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Climate Change Vulnerability and Adaptation in the Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest

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Editors

Jessica E. Halofsky is the director, U.S. Department of Agriculture, Forest Service, Western Wildland Environmental Threat Assessment Center and Northwest Climate Hub Pacific Northwest Research Station, 3625 93rd Avenue SW, Olympia, WA 98512; **David L. Peterson** is a research biological scientist (emeritus), U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, 400 N 34th Street, Suite 201, Seattle, WA 98103; **Rebecca A. Gravenmier** is a science coordinator and regional climate change coordinator (retired), U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station and Pacific Northwest Region, 1220 SW 3rd Avenue, Portland, OR 97204.

Cover: View of the Bull Run Watershed, Bull Run Lake, and Mount Hood, located on Mount Hood National Forest. Photo credit: Portland Water Bureau.

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Jessica E. Halofsky, David L. Peterson, and Rebecca A. Gravenmier, Editors

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Abstract

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A science-management adaptation partnership was developed among the Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest, and other organizations (hereafter referred to as CMWAP) to identify climate change issues relevant for resource management in central Oregon and southern Washington). This partnership assessed the vulnerability of natural resources to climate change and developed adaptation options that minimize negative impacts of climate change and facilitate transition of ecosystems and organizations to a warmer climate. The vulnerability assessment focused on water resources and infrastructure, fisheries, vegetation, wildlife, recreation, and ecosystem services.

The vulnerability assessment shows that the effects of climate change on hydrology in the CMWAP assessment area will be significant, primarily because decreased snowpack and earlier snowmelt will shift the timing and magnitude of streamflow; peak flows will be higher, and summer low flows will be lower. Projected changes in climate and hydrology will affect aquatic and terrestrial ecosystems, especially as frequency of extreme climate events (drought, low snowpack) and ecological disturbances (flooding, wildfire) increase.

Distribution and abundance of coldwater fish species are expected to decrease in response to higher water temperature, although effects will vary as a function of local habitat and competition with nonnative fish. Higher air temperature, through its influence on soil moisture, is expected to cause gradual changes in the distribution and abundance of plant species, with drought-tolerant species becoming more dominant. Increased frequency and extent of wildfire (and in some cases insects) will facilitate vegetation change, in some cases leading to altered structure and function of ecosystems, although the frequency and extent of disturbances are uncertain. Vegetation change will alter wildlife habitat, with both positive and negative effects depending on animal species and ecosystem. Animal species with a narrow range of preferred habitats (e.g., riparian systems, old forest) will be the most vulnerable to more disturbance and large-scale shifts in flora.

The effects of climate change on recreation activities are difficult to project, although higher temperatures are expected to create more opportunities for warm-weather activities (e.g., hiking, camping, water-based recreation) and fewer opportunities for snow-based activities (e.g., skiing, snowmobiling). Recreationists modify their activities according to current conditions, but recreation management by federal agencies has generally not been so flexible. Of the ecosystem services considered in the assessment, (1) timber supply and carbon sequestration may be affected by lower productivity and higher frequency and extent of disturbances, (2) native pollinators may be affected by altered vegetation distribution and phenological mismatches between insects and plants, and (3) decreased salmon populations will reduce the availability of an important first food for tribes in the assessment area.

CMWAP resource managers developed adaptation options in response to the vulnerabilities of each resource, including high-level strategies and on-the-ground tactics. Many adaptation options are intended to increase the resilience of aquatic and terrestrial ecosystems, or to reduce the effects of existing stressors (e.g., removal of nonnative species). In aquatic systems, a dominant theme is to restore the structure and function of streams to retain cold water for fish and other aquatic organisms. In forest systems, dominant themes of adaptation are to decrease stand density and increase structural and genetic diversity to confer resilience to drought. Many adaptation options can accomplish multiple outcomes; for example, restoring the hydrologic function of streams and wetlands will benefit coldwater fish species and riparian wildlife species as well as reduce impacts on infrastructure. Many existing management practices are already “climate smart” or require minor adjustment to make them so. Long-term monitoring is needed to detect climate change effects on natural resources and evaluate the effectiveness of adaptation options.

Keywords: Adaptation, aquatic ecosystems, climate change, climate-smart management, ecosystem services, fisheries, hydrology, infrastructure, recreation, science-management partnership, Oregon Cascade Range, terrestrial ecosystems, vegetation, wildfire, wildlife.

Summary

A science-management adaptation partnership was implemented among the U.S. Department of Agriculture, Forest Service Columbia River Gorge National Scenic Area and the Mount Hood and Willamette National Forests, Pacific Northwest Research Station, Pacific Northwest Region, Office of Sustainability and Climate; and the University of Washington (hereafter CMWAP). These organizations worked in collaboration with stakeholders over a period of 2 years to identify climate change issues relevant to resource management and to find solutions that can minimize undesirable effects of climate change and facilitate transition of ecosystems and organizations to a warmer climate.

Mean annual temperatures in the assessment area have increased by 1.2 to 1.4 °C since 1895, while annual precipitation has not changed. Global climate models for a high-end greenhouse gas emission scenario (Representative Concentration Pathway [RCP] 8.5; comparable to the current trajectory of emissions) project that warming will continue throughout the 21st century. Compared to observed historical temperature, mean annual temperature is projected to increase 4.5 °C by the end of the 21st century (2070–2099). Precipitation may increase slightly in winter, although the magnitude is uncertain.

Higher temperatures will result in more precipitation falling as rain at high elevations, a substantial decline in mountain snowpack, earlier snowmelt, and decreases in summer streamflow. Below 1800 m, the growing season could become year-round, with freeze events rare to nonexistent. Even at the highest elevations within the assessment area, the growing season could extend to nearly 9 months in areas where snow cover and alpine tundra currently exist.

Conclusions reached by the vulnerability assessment and adaptation options for the CMWAP assessment area are discussed in the following sections.

Water Resources and Infrastructure

Effects—

Climate change will affect physical hydrological processes and resource values that are influenced by hydrology, including water available for human uses, water quality, roads, and developed infrastructure. Climate change is likely to alter the amount, timing, and type of precipitation, leading to less snow, receding glaciers, more winter precipitation as rain, earlier snowmelt, and fewer summer precipitation events. Anticipated streamflow changes include higher winter peak flow events associated with increased rain and rain-on-snow in mid to higher elevations, and overall declines in summer baseflows. Slower groundwater recession in areas with permeable volcanic rocks may dampen peak-flow increases and summer low-flow declines.

Increasing temperature and changes in the amount and timing of precipitation and runoff will also affect water quality, water availability, soils, and vegetation. Roads and trails that were built decades ago are highly sensitive to climate change because of declining condition. Culverts remaining in place beyond their design life are less resilient to high flows and bed load movement and have a higher likelihood of structural failure. In the face of higher severity storms, aging infrastructure and outdated design standards can lead to increased incidents of road failure.

Adaptation options—

In-stream restoration techniques (e.g., adding wood to streams) will improve hydrologic connectivity in floodplains and increase water storage capacity. Reintroducing or supporting populations of American beaver (*Castor canadensis* Kuhl) may also help to slow water movement and increase water storage. Working across boundaries on water protection plans and water conservation will help ensure adequate water supplies. Sediment delivery to streams from roads can be reduced by disconnecting ditch lines from streams during watershed restoration, timber projects, vegetation management, and road management. Landslide risk will be reduced by stabilizing slopes, mapping landslide risk, locating or relocating roads in areas that are less vulnerable to landslides, and decommissioning roads in vulnerable locations. Streamflow projections that consider climate change can inform decisions on structure type and sizing at stream crossings, as well as decisions about travel management and restoration. Increasing resilience of recreation facilities, stream crossings, historical and cultural sites, and points of diversion to peak flows will improve public safety.

Fisheries and Aquatic Habitat

Effects—

Decreased summer streamflows (22 to 43 percent in the 2040s and 38 to 58 percent in the 2080s) and warmer water temperature will reduce habitat quality for coldwater fish species, especially at lower elevations. Lower flows and higher temperatures will make coldwater refugia rarer, particularly for species with long-term freshwater residency, such as coho salmon (*Oncorhynchus kisutch* Walbaum), stream-type Chinook salmon (*O. tshawytscha* Walbaum in Artedi), and bull trout (*Salvelinus confluentus* Suckley). Changes in flow and temperature can affect habitat, survival, and outmigration timing for spring-spawning fishes such as steelhead trout (*O. mykiss* Walbaum), redband trout (*O. m. gairdneri*), coastal cutthroat trout (*O. clarkia* Richardson), and Pacific lamprey (*Entosphenus tridentatus* Richardson). Projected reductions in flow by the end of the century could decrease population sizes of fall-spawning fishes such as bull trout, coho salmon, Chinook salmon, and chum salmon (*O. keta* Walbaum in Artedi) by intensifying competition for food and space. Higher winter flows may destabilize redds for fish that spawn early, although spring-spawning fish are generally less susceptible to high flows. Warmwater fishes (e.g., sunfish, bass) will likely become more abundant in the assessment area and may increase native fishes' exposure to nonnative diseases, competition, and predation.

Adaptation options—

Conserving existing habitat and restoring degraded habitat to allow for fish passage and to provide refuge from warm water will be essential for maintaining resilient populations of coldwater and anadromous fish species. Increasing habitat connectivity across management boundaries and between riparian and aquatic ecosystems will maximize access to coldwater refugia, increase biological and genetic diversity, and help restore natural ecosystem processes and function to historically degraded habitats. Managers can improve the resilience of coldwater fish populations by maintaining or improving critical habitat and connectivity, reestablishing natural processes (e.g., fire, sedimentation, streamflow), reducing negative impacts of invasive species, and leveraging partnerships to increase and expand efforts across management boundaries. Potential tactics that can support these strategies include implementing watershed-scale restoration projects with neighboring partners, coordinating monitoring efforts between state and federal agencies, and increasing education and outreach to stakeholders and water users.

Vegetation

Effects—

Higher air temperature, through its influence on soil moisture, is expected to cause gradual changes in the abundance and distribution of vegetation species, with drought-tolerant species being more competitive. Ecological disturbance, especially increased frequency and extent of wildfire and insect outbreaks, will be the primary facilitator of vegetation change, and future forest landscapes may be dominated by younger age classes and smaller trees.

***Moist forests*—**Moist forests will likely continue to be dominated by Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco). Fire- and drought-intolerant species such as western hemlock (*Tsuga heterophylla* [Raf.] Sarg.), Pacific silver fir (*Abies amabilis* [Douglas ex Loudon] Douglas ex Forbes), and western redcedar (*Thuja plicata* Donn ex D. Don) may decrease in abundance, reducing stand density and canopy layering. Hardwoods are likely to be favored by increasing fire frequency in lower elevation forests in the western part of the assessment area. Productivity could increase as a result of a longer growing season and higher atmospheric carbon dioxide, although moisture may become limiting for tree establishment and growth on drier sites with summer water deficits. Noble fir (*Abies procera* Rehder) and Pacific silver fir in middle elevations may, in some cases, be replaced by species from lower elevations (especially Douglas-fir).

Cold forests—Cold forests at upper elevations may experience a decrease in the abundance and distribution of some species such as subalpine fir (*A. lasiocarpa* [Hook.] Nutt.), mountain hemlock (*Tsuga mertensiana* [Bong.] Carrière), and Engelmann spruce (Parry ex Engelm), in some cases, facilitated by competition from lower elevation tree species. Disturbance will be a major factor. Increased frequency and extent of wildfire could not only kill subalpine species across large landscapes but also make regeneration difficult. An expanded range of some insect species, especially mountain pine beetle (*Dendroctonus ponderosae* Hopkins), would be a major stressor, compounding ongoing stress from pathogens, especially white pine blister rust (*Cronartium ribicola*) in whitebark pine (*Pinus albicaulis* Engelm.).

Dry forests—Dry coniferous forest and woodlands will probably maintain their current geographic distribution in the future, although they will experience increased exposure to fire, which may affect composition and structure. Ponderosa pine may shift to higher elevations and become more dominant relative to grand fir and Douglas-fir. Growth of dry forest species is expected to decrease. Tree mortality may also increase in some locations because of interactions among drought, disturbance, and insects. Shifts from dry forest to woodlands or shrublands may occur in the driest portions of the current dry forest range, especially if drought and frequent fire limit regeneration. Invasive annual grasses may facilitate more fires and compete with tree seedlings for soil moisture.

Special habitats—**Oak woodlands** are greatly reduced in extent and highly fragmented by non-climatic stressors (land development, increased density of conifers, invasive species, urban recreation). They may benefit from more frequent fire if conifer encroachment is reduced, but invasive annual grass species may also increase. **Meadows** will decrease in area and abundance if decreased snowpack accelerates establishment of woody vegetation, compounding meadow loss over the past century. Large patches of high-severity fire may restore some meadow vegetation by killing recently established trees. **Riparian areas** may be increasingly sensitive to drought, higher evapotranspiration, and lower summer streamflows, decreasing the extent of the riparian zone and altering plant community composition. Drier conditions and more frequent fire in riparian areas may favor conifers over species typically associated with riparian areas (e.g., deciduous hardwoods). **Wetlands and groundwater-dependent ecosystems** will be affected by the same stressors as in riparian areas, thus altering hydrology and reducing the duration and depth of standing water. This could affect local distribution and abundance of plant species and aquatic fauna, especially in ephemeral wetlands.

Adaptation options—

Minimizing the incidence of high-severity, stand-replacing disturbance events and maintaining spatial diversity of forest stands and age classes will help maintain resilience to fire, drought, and insects, thus supporting functional forest ecosystems. Reducing stand density with thinning can decrease inter-tree competition and forest drought stress, thus increasing tree growth and vigor. Implementing fuel treatments in dry forests can help minimize stand-replacement fire. Mapping current and potential mixed oak/pine refugia as well as the current distribution of invasive plants will help prioritize locations for treatment and protection. Favoring drought-tolerant genotypes and species may help increase survival following disturbances. In riparian areas, wetlands, and groundwater-dependent ecosystems, managers can plan for more frequent flooding in winter and drier soils in summer.

Wildlife

Effects—

Ecosystem responses to climate change will affect animal species through altered food availability, competition, predator-prey dynamics, and availability of key habitat features (e.g., nesting or resting structures and ephemeral water sources). Despite the flexibility and adaptive capacity of many species, widespread shifts in animal ranges and local extirpation of some species may result from climate change in combination with other stressors. Potential effects of climate change on focal habitats include the following:

***Oak woodlands*—**The greatly reduced extent and fragmented nature of oak woodlands makes them and the wildlife species they support highly sensitive to the effects of climate change.

Projected increases in fire frequency are likely to favor oaks. However, disconnected habitat patches make it difficult for animal populations to rely on dispersal and metapopulation dynamics to shift distributions or recolonize locally extirpated habitats. Western gray squirrel (*Sciurus griseus*), woodpeckers that use acorns, and rare butterfly species may be particularly sensitive to changes in oak habitat.

Coniferous forests/western hemlock zone**—**The future distribution and characteristics of these habitats will be shaped by the interplay and spatial dynamics of natural disturbances, management actions, and regeneration dynamics. **Habitat features that require decades or centuries to develop** (large snags, coarse woody debris, large trees) will be a limiting factor for animals associated with old-growth forests (e.g., northern spotted owl [*Strix occidentalis caurina*]). **Species with restricted dispersal distances or abilities** will have reduced capacity to disperse to suitable areas (e.g., red tree voles [*Arborimus longicaudus*], northern flying squirrels [*Glaucomys sabrinus*]), especially where habitat fragmentation is high. A mismatch between habitat features and thermal suitability could occur in the future, if climatically suitable habitat is precluded by a warmer climate (e.g., bat species may not have roosting snags [thermal refugia] in locations with appropriate air temperatures).

Coniferous forests/Pacific silver fir zone**—**Warmer and drier low-elevation portions of the silver fir zone may transition to climates with reduced snowfall, more supportive of western hemlock zone species. Wildlife populations in isolated patches are likely to experience declines owing to loss of connectivity among subpopulations. Snowpack and subnivean habitats could be degraded or lost, depending on disturbance patterns, large trees, and standing and down dead wood. American martens (*Martes americana*) are projected to experience stress through direct loss of fir habitat, in some cases through increased fire frequency and extent. In some cases, fishers (*Pekania pennanti*) may compete with martens. A wide range of bird species may also be sensitive to climate-induced habitat change.

Subalpine forests**—**Subalpine habitats in the assessment area are mostly small and isolated, supporting correspondingly small populations of associated species. Contraction and disappearance of patches of subalpine habitat would increase the fragmentation and isolation of these populations. Subalpine areas used for recreation are already experiencing stress from heavy recreational use. Whitebark pine, an important food source for numerous species, is already under stress from white pine blister rust, and further loss of whitebark pine stands would reduce habitat for Clark’s nutcrackers (*Nucifraga columbiana*) and other species dependent on seeds from cones.

East-side forests and mixed woodlands**—**Wildlife associated with old-growth ponderosa pine and mixed-conifer forest may lose remnant, lower elevation stands to drought and high-severity fire, and reduced tree growth from climate change may slow the recovery and development of old-growth habitat structure. Increasing drought will create stress for moisture-limited species such as mollusks and amphibians. Reduced tree cover from past and ongoing timber harvest is likely to interact with warming trends. Available habitat for riparian-associated and moisture-dependent east-side species is already reduced, increasing the sensitivity of these species as groundwater resources decline and severe droughts increase.

***Shrub, grass, and rock*—**Because these habitats are found across the assessment area and across a broad range of elevations, the degree of exposure to climate change will differ but is not explicitly addressed by vegetation modeling. Shrub and grass communities are often linked to fire dynamics and fire-return intervals, which may change in a warmer climate. Where grass communities are maintained by specific soil-hydrology characteristics (e.g., in forest or alpine meadows), higher evapotranspiration and drying may lead to increased tree recruitment in areas that were previously too wet. Riparian-associated snails that rely on talus will be sensitive to hydrologic change owing to climate change. Potential changes include increased severity of droughts and floods, reduced flow arising from reduced snowpack, increased siltation, and increased air and water temperatures.

***Early-seral habitat*—**The amount of early-seral forest is expected to increase as fire frequency increases. The exposed physical characteristics of early-seral forests, with few standing structures to provide shade, moisture, and shelter, will cause fauna to be more exposed to direct changes in temperature and moisture. Species associated with early-seral forests tend to have traits that may reduce their sensitivity to climate change, including good dispersal abilities and high reproductive rates, helping populations shift spatially or otherwise adapt to new climatic conditions. If fire severity increases or fires re-burn frequently, biological legacies (snags, logs) may decrease. Fauna that depend on specific plant species (e.g., butterflies with specific hosts) or will be sensitive to phenological mismatches (e.g., from migration timing and resource availability) are more likely to be affected by climate change.

***Riparian, wetlands, and water*—**Drivers of heat budgets for water bodies are complex and include air temperature, groundwater inputs, solar radiation, and shade from vegetation, making projections of climate change uncertain at fine scales. Climate change may be increasing the synchrony of the timing of peak temperatures and low streamflows, both stressful factors for aquatic biota. Higher water temperatures can enable invasive aquatic species to displace species of conservation concern. Springs, small streams, riparian areas, and wetlands are likely to have decreased size and periods of inundation as a result of decreased magnitude and duration of snowpack. In drier areas, warmer temperature and drier soil may lead to more drought-tolerant conifers replacing riparian hardwoods.

By increasing stream temperatures and reducing water storage, climate change will fragment coldwater habitat, reducing genetic and population connectivity for species associated with cold water.

Adaptation options—
Management plans that increase habitat connectivity at large spatial scales, especially across different land ownerships, will enhance the long-term persistence of mobile species. Mapping and surveying areas where habitat connectivity is threatened by repeated disturbances can be coordinated with mapping and surveying the distribution of populations that can potentially colonize or repopulate habitats affected by disturbance. Resilience of late-successional habitat can be enhanced by increasing the heterogeneity of forest structure at multiple spatial scales. Managers can help protect water-associated habitats by reducing the spread of invasive species, restoring the hydrologic function of streams and wetlands, and minimizing the effects of wildfire by reducing fuels where appropriate. Reconnecting channels and restoring stream structure can increase habitat connectivity, coldwater refugia, and establishment of riparian vegetation. Encouraging American beaver colonization increases water retention and groundwater recharge Managers can also consider maintaining forest stands at specific densities to increase rates of snow deposition and retention.

Recreation

Effects—
Summer recreation (hiking, camping, bicycling) will benefit from a longer period of suitable weather without snow, especially during spring and autumn shoulder seasons. Snow-based recreation (skiing, snowmobiling) will be negatively affected by a warmer climate because of less and more transient snow. Ski areas and other facilities at lower elevations will be especially vulnerable. Hunting may be sensitive to temperature and timing and amount of snow during the designated hunting season. Fishing will be sensitive to streamflows and stream temperatures associated with target species; if summer flows are very low, some streams may be closed to fishing. Water-based recreation (swimming, boating, rafting) will be sensitive to lower water levels during drought years. Gathering forest products for personal and commercial use (e.g., huckleberries [*Vaccinium* spp.], mushrooms) may be somewhat sensitive if climatic conditions alter the distribution and abundance of items being collected.

Adaptation options—

Redirecting recreational use to optimize recreational opportunities, as well as protecting areas that are vulnerable to damage by recreationists will help maintain the quality of recreation experiences. Adaptation tactics focus on adjusting the capacity of recreation sites and increasing flexibility of the availability of those sites based on weather conditions from year to year. Efforts are needed to identify recreation sites that are likely to incur heavier use in a warmer climate, then ensure that infrastructure and staffing are sufficient to support that use, or consider dispersing access to locations that can sustain more use. Access to some areas may need to be restricted to protect resources, especially when roads, trails, and facilities are not yet open (and may not be safe) in years when snow melts early. Following wildfires, managers will need to raise public awareness about hazard trees, and in some cases, implement tree removal and control public access to unsafe areas. Flexibility in the seasonality of staffing, permitting, and concessionaire contracts will help adjust to altered recreation demands and opportunities.

Ecosystem Services

Effects—

Higher temperature and increased frequency and extent of disturbances will alter forest structure and growth, thus affecting timber supply, carbon sequestration, and access and availability of special forest products. Increased frequency and extent of drought and wildfire will affect both forest systems and human communities. Livestock grazing will likely be affected by altered plant species composition and productivity, especially if nonnative annual grasses spread as expected. The ability of forests to sequester carbon will likely decrease if warmer climate increases physiological stress in trees and increases the frequency and extent of disturbances. A warmer climate may also affect the physiology and behavior of some insect pollinators, possibly creating a phenological mismatch in timing of flowering and pollinator emergence. Some pollinators may shift their range to find new food sources, depending on habitat connectivity. Climate change may also affect biophysical structures, processes, and functions related to cultural resources, potentially decreasing the availability of some first foods (e.g., salmon, huckleberries) valued by American Indians and others. Quantity and quality of water supplies may become less reliable for both people and aquatic systems because of extreme weather and climate (flooding, dry periods).

Adaptation options—

Sustainability of forest products can be maintained by keeping forests healthy through stand density management. In dry forests, surface fuels can be reduced to prevent high-intensity wildfires, thus increasing resilience in forest systems and the wildland-urban interface. Long-term stability of carbon sequestration can be maintained using this same approach. Productive grazing can be ensured by developing adaptive grazing strategies to respond to changing conditions, and mitigating impacts of wildfire, nonnative species, and drought. Adaptation options for native pollinators include protecting pollinator habitat, maintaining a diversity of native species, and increasing agency and public awareness of the importance of native pollinators. Sustainability of cultural resources can be improved by reducing non-climate stressors and applying restoration practices in locations where production of first foods can be enhanced. For all ecosystem services, managing public expectations for landscape change and disturbance will facilitate long-term adjustment to new conditions.

The CMWAP climate change vulnerability assessment and adaptation project achieved specific elements of national climate change strategies for federal agencies, providing a new scientific context for resource management, planning, and ecological restoration in northern Oregon and southern Washington. The large number of adaptation options, many of which are a component of current management practices, provide a pathway for slowing the rate of deleterious change in resource conditions. Rapid implementation of adaptation in resource planning and management will help maintain critical structure and function of aquatic and terrestrial ecosystems and improve transitions by land management organizations and the general public. Long-term monitoring will help detect potential climate change effects on natural resources and evaluate the effectiveness of adaptation options that have been implemented.

Contents

Chapter 1: Introduction

Benjamin S. Soderquist and Robin Z. Shoal[1]

The Columbia River Gorge Natural Scenic Area (CRGNSA) and Mount Hood and Willamette National Forests (NFs) Adaptation Partnership (CMWAP) was initiated in 2018 to assess the vulnerability of natural resources and ecosystems to climate change and develop adaptation options that address climate change effects. The three management areas, located in west-central Oregon and southern Washington (fig. 1.1), encompass a variety of ecosystems that provide many natural resources, ecosystem services, and other benefits to local communities and residents of the Pacific Northwest.

The CMWAP assessment area comprises a mix of federal, state, private, and other lands. Management practices and legacies differ depending on resource availability, historical land use practices, and current management objectives. In the coming years, the effects of climate change on ecosystems and natural resources will differ spatially and temporally. Therefore, future management actions to address these effects will need to be increasingly collaborative and span management boundaries.

The CMWAP builds on previous adaptation partnerships established to assess climate change vulnerabilities across Oregon, Washington, and the larger Pacific Northwest region (Halofsky and Peterson 2017; Halofsky et al. 2018a, 2019). Climate change vulnerability assessments developed from these partnerships are particularly relevant for land management planning on federal lands managed by the U.S. Department of Agriculture, Forest Service (Forest Service). Specifically, the vulnerability assessment process used by the CMWAP and previous assessments supports four strategic goals of the Forest Service Strategic Plan for 2015–2020 (USDA FS 2015a): (1) sustain our nation's forests and grasslands, (2) deliver benefits to the public, (3) apply knowledge globally, and (4) excel as a high-performing agency. Working toward these goals helps the Forest Service "to sustain the health, diversity, and productivity of the Nation's forests and grasslands to meet the needs of present and future generations."

Although findings from the CMWAP vulnerability assessment are useful for federal land managers, the partnership also engaged a diverse group of natural resource professionals. Because of this collaborative emphasis, the assessment findings are relevant to other groups or organizations interested in climate change adaptation, including state agencies, nongovernmental organizations, industry professionals, and private landowners.

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[1] **Benjamin S. Soderquist** is a natural resource specialist, Intermountain Region, 324 25th Street, Ogden, UT 84401; and **Robin Z. Shoal** is a planning/natural resources staff officer, Olympia National Forest, 1835 Black Lake Boulevard SW, Olympia, WA 98512.

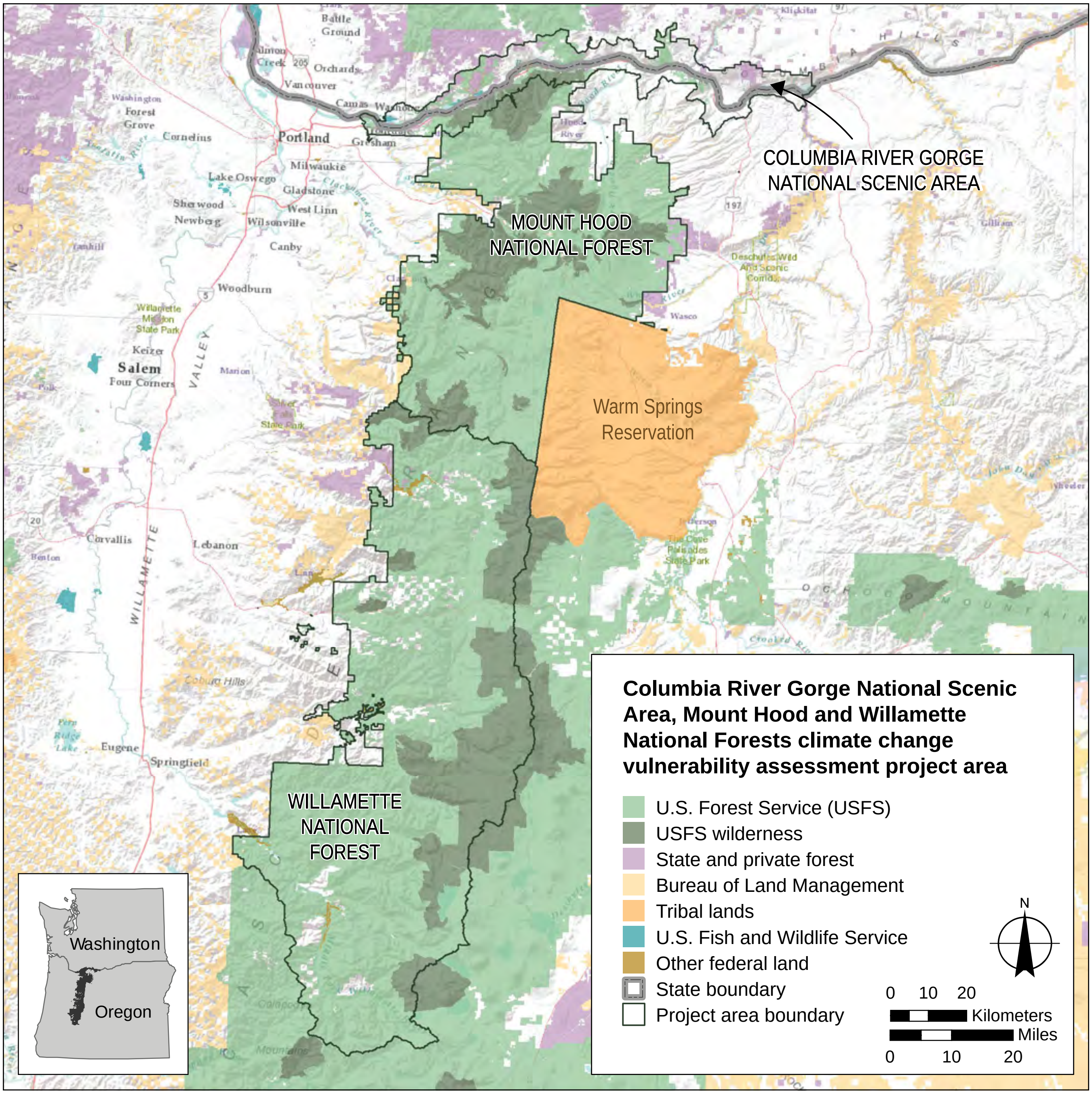


Figure 1.1—Assessment area for the Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest Adaptation Partnership.

Responding to Climate Change in the U.S. Forest Service

In recent decades, climate change has been a growing concern for federal land management agencies like the Forest Service, and guidance for resource managers has evolved significantly. Beginning in 2008, Forest Service administrative units across the National Forest System were issued a first set of directions on how to respond to climate change (USDA FS 2008). In the following years, the Forest Service expanded this effort by developing the National Roadmap for Climate Change (USDA FS 2010) and implementing the Performance Scorecard for Implementing the Forest Service Climate Change Strategy (USDA FS 2010). These nationally focused efforts have helped managers assess climate change programs and report their progress under four broad themes: (1) increasing organizational capacity; (2) partnerships, engagement, and education; (3) adaptation; and (4) mitigation and sustainable consumption.

Climate change effects on vulnerable resources will affect landscapes that span multiple management boundaries. Because of different management roles and objectives, the responsibilities of private, state, federal, and tribal land managers often differ, leading to potential differences in the scope, scale, and goals of management responses to climate change. Developing and maintaining partnerships is a critical first step toward developing collaborative, all-lands approaches to climate change adaptation.

The CMWAP builds on a network of previous climate adaptation partnerships established across the Pacific Northwest. Beginning in 2008, one of the first climate change vulnerability assessments was conducted for the Olympic National Forest and Olympic National Park (Halofsky et al. 2011). Over the following decade, this approach was replicated across other ecoregions in Oregon, Washington, and the inland Northwest (Halofsky and Peterson 2017; Halofsky et al. 2018a, 2018b).

For each of these efforts, assessment areas typically included lands managed by the Forest Service; U.S. Department of the Interior Bureau of Land Management and National Park Service; state agencies; and private landowners. Representatives from federal and state management agencies, research institutions, and nongovernmental organizations participated in the assessment development, adaptation workshops, and assessment review. By prioritizing collaboration at the beginning of the assessment process, the CMWAP and similar partnerships provide a consistent and comprehensive overview of locally relevant climate change information to a large group of managers, so that assessments can inform adaptation actions.

Adapting to Climate Change in the CMWAP Assessment Area

Vulnerability to climate change is described in terms of resource exposure, sensitivity, and adaptive capacity (Parry et al. 2007), where exposure is the degree to which the system is exposed to changes in climate, sensitivity is an inherent quality of the system that indicates the degree to which it could be affected by climate change, and adaptive capacity is the ability of a system to respond and adjust to the exogenous influence of climate. Adapting to climate change involves a four-step process in which stakeholders (1) become aware of basic climate change science and integrate that understanding with knowledge of local conditions and issues (review), (2) evaluate sensitivity of natural resources to climate change (rank), (3) develop and implement options for adapting resources to climate change (resolve), and (4) monitor the effectiveness of on-the-ground management (observe) and adjust as needed (Peterson et al. 2011). The CMWAP is focused on implementing principles and practices from each of these steps.

Conducting a vulnerability assessment typically precedes the implementation of climate change adaptation actions. The CMWAP assessed climate change vulnerabilities for several key resources across the assessment area: hydrology and water resources (chapter 3), fish and aquatic ecosystems (chapter 4), vegetation and disturbance (chapter 5), wildlife and wildlife habitat (chapter 6), recreation (chapter 7), and ecosystem services (chapter 8). For each resource area, assessment teams were assigned to (1) synthesize the current science describing resource climate sensitivities, risk of exposure, and adaptive capacities; (2) conduct additional analyses using downscaled climate projections, simulation models, datasets, and other resources that could provide locally relevant information; and (3) summarize all information into resource chapters that provide an overview of current management practices, resources sensitivities, and projected climate change effects. Vulnerability assessments structured around this framework provide a scientific foundation from which climate change information can be integrated into land management planning and project design.

For climate change adaptation to occur, information from vulnerability assessments must be used to develop adaptation strategies and tactics that guide management actions (Peterson et al. 2011). This was accomplished during a 2-day workshop held in May 2019 in Salem, Oregon. During the workshop, assessment teams, resource managers, and stakeholders representing the CMWAP assessment area convened to review and discuss the results of each vulnerability assessment chapter. Using this information, workshop participants then collaboratively developed resource-specific adaptation options based on the climate change projections and vulnerabilities presented earlier. Worksheet exercises adapted from Swanston and Janowiak (2012) helped attendees identify high-priority climate change stressors, define broader adaptation strategies, and develop specific adaptation tactics that can be implemented in the future. The results of the workshop discussions and worksheet exercises are summarized and discussed in chapter 9.

Assessment Area Description

The CMWAP focused on three distinct management areas: the CRGNSA, the Mount Hood NF, and the Willamette NF. The combined assessment area covers 1.1 million ha, with most lands located in west-central Oregon (fig. 1.1). The CMWAP assessment area contains diverse landscapes and ecosystems dry mixed-oak and pine woodlands, moist coniferous forests, and high-elevation alpine ecosystems (chapter 5). Climatic conditions differ across the landscape and are influenced by large landscape features, local topography, and environmental gradients. We provide a brief overview of each management area below.

Columbia River Gorge National Scenic Area

The CRGNSA is the northernmost management unit in the CMWAP assessment area, encompassing 1200 km^2 across six counties in southern Washington and northern Oregon. The CRGNSA spans the Columbia River between its confluence with the Sandy River just east of the Portland metropolitan area and the confluence with the Deschutes River about 135 km to the east. The landscape is a complex mosaic of land ownerships, including federal lands (National Forest System and other federal agencies), state land, county land, tribal land, and private land. Over 50,000 people live in the urban areas and rural communities within the scenic area boundary. Two major highways and two mainline railways run the east-west length of the scenic area. Two large hydroelectric dams (Bonneville Dam, The Dalles Dam) are located on the Columbia River, and multiple high-voltage transmission corridors traverse the scenic area.

The CRGNSA was established by Congress in 1986 through the National Scenic Area Act (USC 16 §544-544p). The act authorized the states of Oregon and Washington to create the Columbia River Gorge Commission (Gorge Commission). As directed by the act, the Gorge Commission and the Forest Service developed a management plan that guides land use and development on all lands within the congressionally designated boundary, except for the 13 urban areas designated in the act. The plan and associated ordinances guide land use and development throughout the scenic area. This land management structure requires cooperation between the Forest Service, Gorge Commission, and counties. The Forest Service and Gorge Commission share responsibility for implementing the act and the management plan.

Land use designations within the national scenic area include agriculture, forest, open space, public recreation, residential, and commercial. National Forest System lands, which comprise about a third of the land base within the scenic area boundary, are primarily in the open space, forest, agriculture, and recreation designations. Management of National Forest System lands emphasizes recreation, scenic values, natural and cultural resource conservation, and fuels management.

Mount Hood National Forest

Mount Hood NF encompasses 650 000 ha south of the CRGNSA and is located 32 km east of Portland, Oregon. Its proximity to Portland and the surrounding area's large population makes it one of the most visited national forests in the country (chapter 7). Year-round recreational opportunities on the Mount Hood NF are a substantial economic driver for the region. The Mount Hood National Recreation Area was established in 2009 to help sustainably manage the area's recreational resources. The Mount Hood NF also contains eight wilderness areas that cover more than 120 000 ha and encompass a variety of lower elevation riparian corridors, high-elevation subalpine forests, and glaciated alpine ecosystems.

Mount Hood is currently home to 11 active glaciers, several of which drain to the nearby Hood River. Across the Mount Hood NF, at least 15 watersheds provide drinking water to downstream municipalities. The Bull Run watershed, located northwest of Mount Hood, is primarily rainfed and provides drinking water to the greater Portland metropolitan area.

Both the Mount Hood and Willamette NFs (below) are in the region managed under the broader Northwest Forest Plan, which was adopted in 1994. This regional planning approach spans federal management boundaries across western Washington and Oregon as well as parts of northern California. The goals of this plan are to ensure the sustainable management of Northwest forests, while balancing the needs of sensitive wildlife and the continued production of forest products.

Willamette National Forest

The Willamette NF is the southernmost management unit in the CMWAP assessment area, extending over 160 km along the western slope of the Cascade Range. The Willamette NF is similar in size to the Mount Hood NF, covering more than 650 000 ha. The Willamette NF has eight wilderness areas that cover more than 150 000 ha within the national forest boundary. Rivers in the Willamette NF flow along steep elevation gradients and are fed by large amounts of seasonal precipitation. The Mackenzie River and the North Fork of the Willamette River flow through the Willamette NF and are protected under the Wild and Scenic Rivers Act. The natural attractions of the Willamette NF, including rivers, lakes, and protected old-growth forest stands, provide scenic and recreational opportunities to local residents and visitors from across the world.

The Willamette NF is dominated by highly productive conifer forests at low elevation as well as subalpine forest at high elevation. Timber harvesting was practiced widely across most of the forest during much of the 20th century. However, pockets of old-growth forest remain and provide critical habitat for species dependent on late-seral forest (chapter 6).

In 1948, the H.J. Andrews Experimental Forest was established on the west side of the Willamette NF. Since then, this 6475-ha research site has provided extensive long-term monitoring and scientific research on the hydrology, ecology, and disturbance regimes of old-growth and maritime forests typical of the western Cascades. Research conducted in the H.J. Andrews Experimental Forest has guided science-based forest management across the Pacific Northwest.

Labor Day Fires of 2020

In September of 2020, several large wildfires affected the CMWAP assessment area (box 1.1) by which time the peer review process for this assessment was complete. Because of this, the effects of the fires on the assessment area are addressed in only a limited way in some chapters. However, we acknowledge the significant effects of these fires on natural resources and communities in the region.

Using the CMWAP Climate Change Vulnerability Assessment

Information from these chapters can be used in several ways. First, the vulnerability assessment is a peer-reviewed document that synthesizes the best available science for specific resources at spatial and temporal scales that are relevant for resource management across the assessment area. The document is structured so that it can be referenced and cited during land management planning, National Environmental Policy Act analyses, and project design. Although the adaptation options are focused primarily on public lands, the assessment can also be a useful resource for nongovernmental entities (e.g., fish and wildlife organizations, watershed stewardship groups), that may want to coordinate with federal or state agencies or develop climate-smart management strategies of their own.

Engagement with regional partners in the early stages of the adaptation process (raising awareness and assessing vulnerabilities) is critical when responding to climate change effects that will likely influence large landscapes. Acknowledging this need, climate change strategies adopted by the Forest

Service frequently emphasize the importance of partnerships and collaboration to achieve climate adaptation goals across larger landscapes. Providing resource managers, neighboring partners, and local stakeholders with consistent climate change information will help facilitate broader collaboration and increase

Box 1.1

Ecosystem services, smoke, and the 2020 fire year

The 2020 fire year was unprecedented in recent decades for the Pacific Northwest. Multiple fires burned about 289 000 ha, much more than at any other time in living memory of most residents, but similar to fires documented in the early 20th century (e.g., 1902 Yacolt Burn, 1933 Tillamook Burn) (see chapter 5, fig. 5.5). A powerful dry east wind event starting on September 7th triggered the onset of several large wildfires. The resulting Riverside (55 828 ha), Beachie Creek (78 224 ha), Lionshead (84 552 ha), and Holiday Farm (70 086 ha) Fires burned an extensive area of forest land within and adjacent to the assessment area, much of it at high severity. Lives were lost, and numerous homes, businesses, and critical facilities were damaged or destroyed. The full impacts on the social, cultural, and economic life of the region's residents will take some time to fully assess.

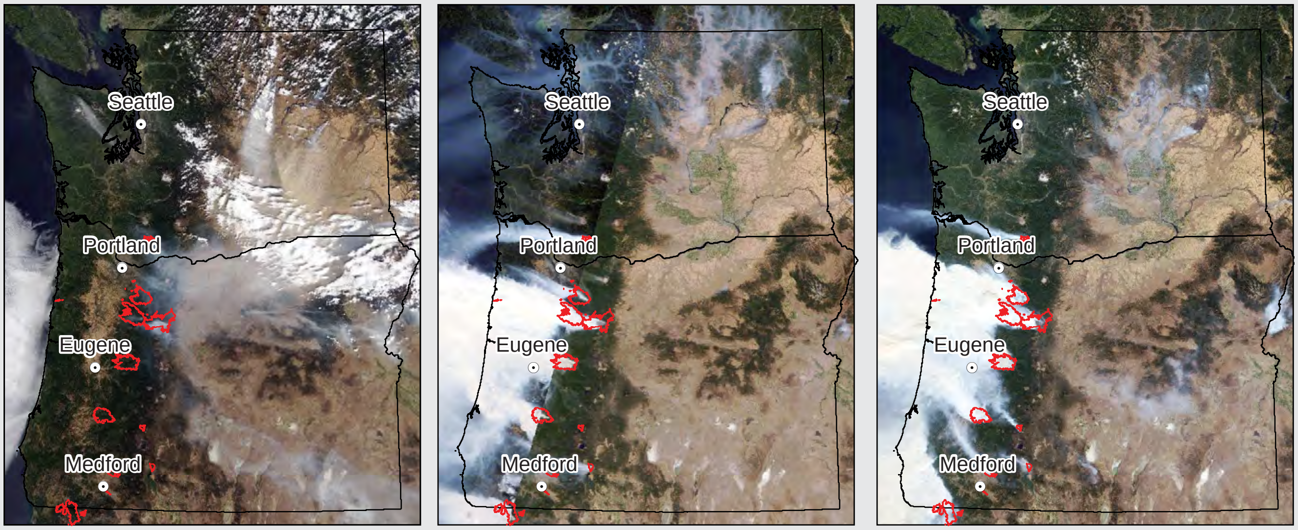
Many ecosystem services provided by these forests were affected by the wildfire events, including municipal drinking water supplies for large urban centers in the Willamette Valley. As described in chapter 7, there were years previous to 2020 where fire and smoke disrupted recreation and caused lasting damage to infrastructure, and the fires of 2020 will also cause lasting impacts to recreation in the assessment area. Large-scale fires such as these will also very likely trigger significant changes in supplies of both timber and nontimber forest products.

Beyond the wildfire boundaries, extreme levels of smoke blanketed the region, lingering a week or longer throughout western Oregon (fig. box 1.1). For multiple days, Portland's air quality was rated the worst among major cities for the entire planet. The concentration of particulate matter of 2.5 microns or less (PM2.5) exceeded the highest rating for air quality health impacts, with other nearby population centers experiencing similar PM2.5 levels. Wildfire smoke has been linked to respiratory diseases and increasingly with all causes of morbidity (Reid et al. 2016), and smoke represents a major hazard for vulnerable populations. Air quality during the 2020 fires was so degraded as to be hazardous for every segment of the population, forcing many to remain indoors and causing closures of businesses and public spaces.

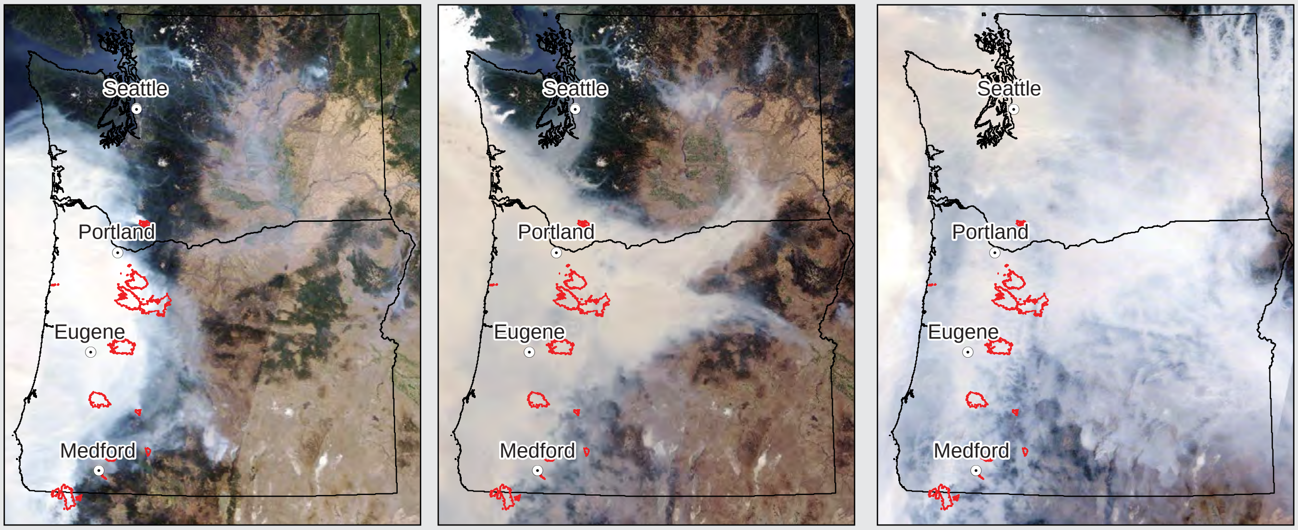
Current evidence points to dry east winds rather than broader climate change trends as the main driver of this fire event. Nevertheless, it serves as an example of the potential effects of large, severe fires on human health and economies on the west side of the Cascade Range. Large fire events will likely become more frequent in the assessment area with climate change (chapter 5).

the pace of adaptation actions across management boundaries. The CMWAP vulnerability assessment can serve as a resource for resource managers who want to communicate risks, coordinate resources, and share knowledge as they work to increase the resilience of local ecosystems in a changing climate.

Smoke effects from the September 7 and 8, 2020, wildfire event



A September 7, 2020 **B** September 8, 2020 **C** September 9, 2020



D September 10, 2020 **E** September 11, 2020 **F** September 12, 2020

Literature Cited

Halofsky, J.E.; Peterson, D.L., eds. 2017. Climate change vulnerability and adaptation in the Blue Mountains. Gen. Tech. Rep. PNW-GTR-939. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 331 p.

Halofsky, J.E.; Peterson, D.L.; Dante-Wood, S.K. [et al.]. 2018a. Climate change vulnerability and adaptation in the Northern Rocky Mountains. Gen. Tech. Rep. RMRS-GTR-374. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. Parts I and II.

Halofsky, J.E.; Peterson, D.L.; Ho, J.J., eds. 2019. Climate change vulnerability and adaptation in south-central Oregon. Gen. Tech. Rep. PNW-GTR-974. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 473 p.

Halofsky, J.E.; Peterson, D.L.; Ho, J.J.; Little, N.J.; Joyce, L.A., eds. 2018b. Climate change vulnerability and adaptation in the Intermountain Region. Gen. Tech. Rep. RMRS-GTR-375. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 513 p.

Halofsky, J.E.; Peterson, D.L.; O'Halloran, K.A.; Hoffman, C.H. 2011. Adapting to climate change at Olympic National Forest and Olympic National Park. Gen. Tech. Rep. PNW-GTR-844. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 130 p.

Parry, M.L.; Canziani, O.F.; Palutikof, J.P. [et al.], eds. 2007. Climate change 2007: impacts, adaptation and vulnerability: a contribution of working group II to the fourth assessment report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom: Cambridge University Press. 976 p.

Peterson, D.L.; Millar, C.I.; Joyce, L.A. [et al.]. 2011. Responding to climate change in national forests: a guidebook for developing adaptation options. Gen. Tech. Rep. PNW-GTR-855. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 109 p.

Reid, C.E.; Brauer, M.; Johnston, F.H. [et al.]. 2016. Critical review of health impacts of wildfire smoke exposure. Environmental Health Perspectives. 124: 1334–1343.

Swanston, C.W.; Janowiak, M.K., eds. 2012. Forest adaptation resources: climate change tools and approaches for land managers. Gen. Tech. Rep. NRS-GTR-87. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 121 p.

U.S. Department of Agriculture, Forest Service [USDA FS]. 2008. Forest Service strategic framework for responding to climate change. Version 1.0. Washington, DC: Climate Change Advisor's Office. https://www.fs.fed.us/climatechange/documents/strategic-framework-climate-change-1-0.pdf. (9 April 2021).

U.S. Department of Agriculture, Forest Service [USDA FS]. 2010. A performance scorecard for implementing the Forest Service climate change strategy. Washington, DC: Climate Change Advisor's Office. https://www.fs.fed.us/climatechange/pdf/performance_scorecard_final.pdf. (9 April 2021).

U.S. Department of Agriculture, Forest Service [USDA FS]. 2015. USDA Forest Service strategic plan: FY 2015–2020. Washington, DC: 53 p. https://www.fs.fed.us/sites/default/files/strategic-plan%5B2%5D-6_17_15_revised.pdf?utm_medium=email&utm_source=govdelivery. (9 April 2021).

Chapter 2: Historical and Future Climate

James A. Miller, John B. Kim, and Becky K. Kerns[1]

Regional Climate Overview

The Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest Adaptation Partnership (CMWAP) assessment area encompasses more than 1.1 million ha, extending roughly 250 km north to south and about 60 to 100 km west to east. About a quarter of the region is federally protected wilderness, spread among 16 wilderness areas, 5 of which are designated Class I (meaning they are given special air quality protections under the Clean Air Act).

The CMWAP assessment area is characterized by a diverse set of physical landscapes and climates, owing to a large elevation range and longitudinal extent spanning the west and east sides of the Cascade Range. As illustrated in figure 2.1A, the lowest elevations of the CMWAP assessment area are near sea level, and Mount Hood and Mount Jefferson both rise above 3000 m. However, elevation generally ranges between 1000 and 2000 m within the area's core.

The CMWAP assessment area contains three climate divisions classified by the National Centers for Environmental Information, Oregon climate divisions 2, 4, and 6. The Cascade Range foothills and major river drainages are mostly within Oregon climate division 2 (Willamette Valley), whereas the higher terrain of the area lies within Oregon climate division 4 (northern Cascades). The eastern portion of the Columbia River Gorge National Scenic Area is in Oregon climate division 6 (north central).

The CMWAP assessment area has an annual mean temperature of about 7 °C, although there is considerable temperature variability because of Cascade Range effects on regional air masses and the wide elevation range of the area. Summer maximum temperatures average around 30 °C in the hottest parts of the assessment area near The Dalles (fig. 2.1C), whereas the area near the peak of Mount Hood has average winter minimum temperatures as low as -9 °C (fig. 2.1D). However, both the maritime influence of the Pacific Ocean and the Cascade Range moderate temperature extremes on the west side of the mountains, resulting in relatively mild conditions throughout the region. Typical winter daytime high temperatures average around 4 °C, with winter low temperatures a few degrees below freezing.

Although winter minimum temperatures commonly fall below freezing, the length of the freeze-free season varies greatly owing to the differences in elevation

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[1] **James A. Miller** is an air quality specialist (currently with the Bureau of Land Management in Salt Lake City, Utah), Pacific Northwest Region, 1220 SW 3rd Avenue, Suite 1600, Portland, OR 97204; **John B. Kim** is a biological scientist and **Becky K. Kerns** is a research ecologist, Pacific Northwest Research Station, Forestry Sciences Laboratory, 3200 SW Jefferson Way, Corvallis, OR 97331.

and maritime influence. Low-elevation locations on the west side of the Cascades average 30 to 60 days below freezing per year, whereas higher elevation locations average over 150 freezing days annually. Areas east of the Cascades experience

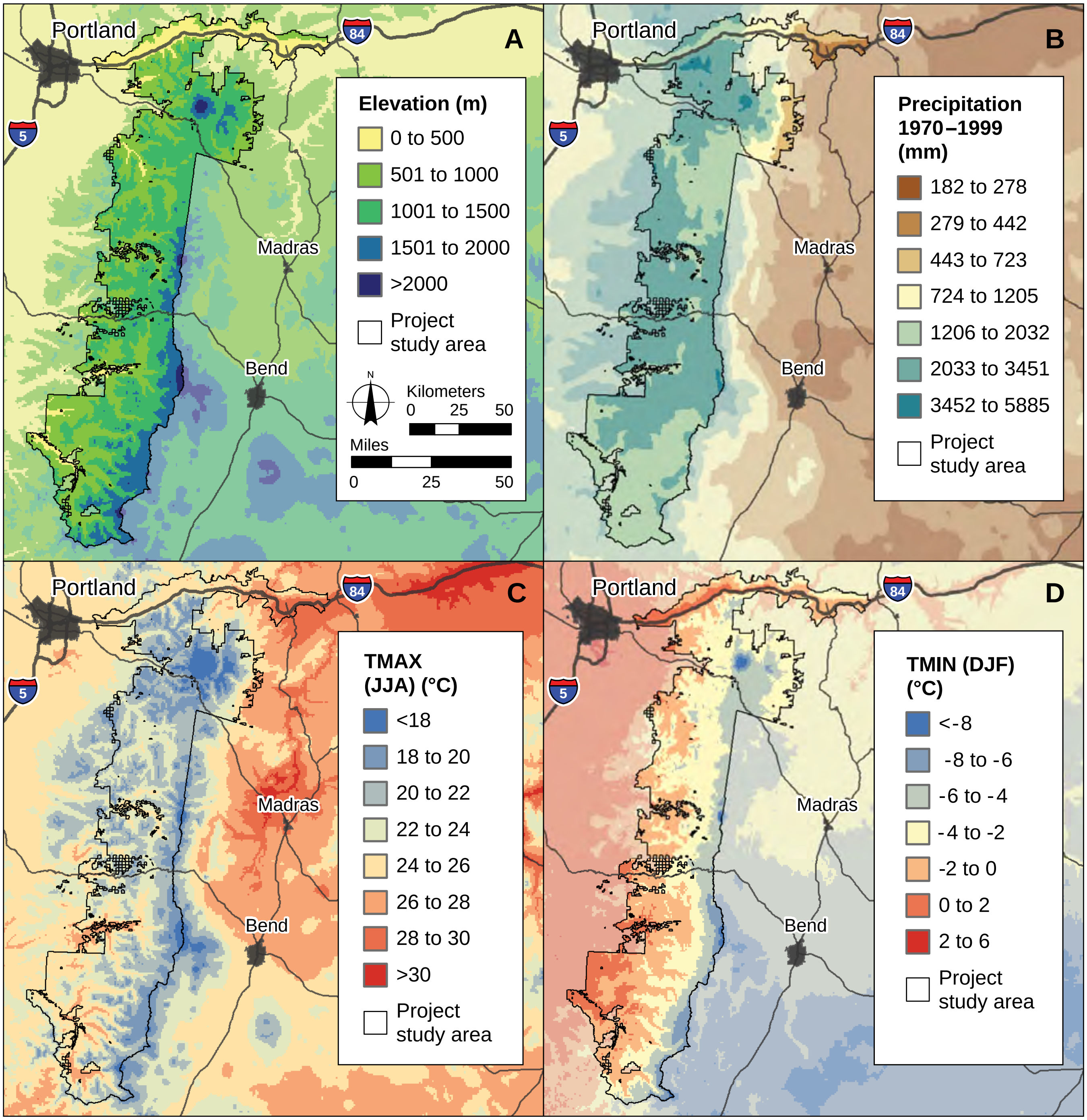


Figure 2.1—Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest assessment area elevation and climate for 1970–1999. PRISM data (Daly et al. 2008) were used to plot (A) elevation; (B) mean annual precipitation; (C) mean daily maximum temperature (TMAX) for June, July, and August (JJA); and (D) mean daily minimum temperature (TMIN) for December, January, and February (DJF).

a freeze-free season roughly 2 months shorter than areas at the same elevation on the west side. Summer maximum temperatures generally average between 20 and 22 °C with minimum temperatures between 7 and 10 °C, though summer maximum temperatures are about 5 °C higher at The Dalles (elevation 33 m) than locations on the west side of the mountains at the same elevation. Overall, there is about a 15 °C difference in average temperature between winter and summer for most locations within the CMWAP assessment area.

A mediterranean precipitation pattern marked by wet winters and dry summers occurs throughout the CMWAP assessment area, with about 70 percent of annual precipitation observed from November to March (fig. 2.2). Summers are dry, with less than 10 percent of annual precipitation occurring between June and August. The regional average annual precipitation is about 2000 mm but varies greatly throughout the region because of a strong orographic influence on winter storms and the broad range of elevation. As demonstrated in figure 2.1B, the mountains create a large precipitation gradient, with over 3000 mm of annual precipitation possible on the windward slopes of the Cascade Ranges; as little as 300 mm of

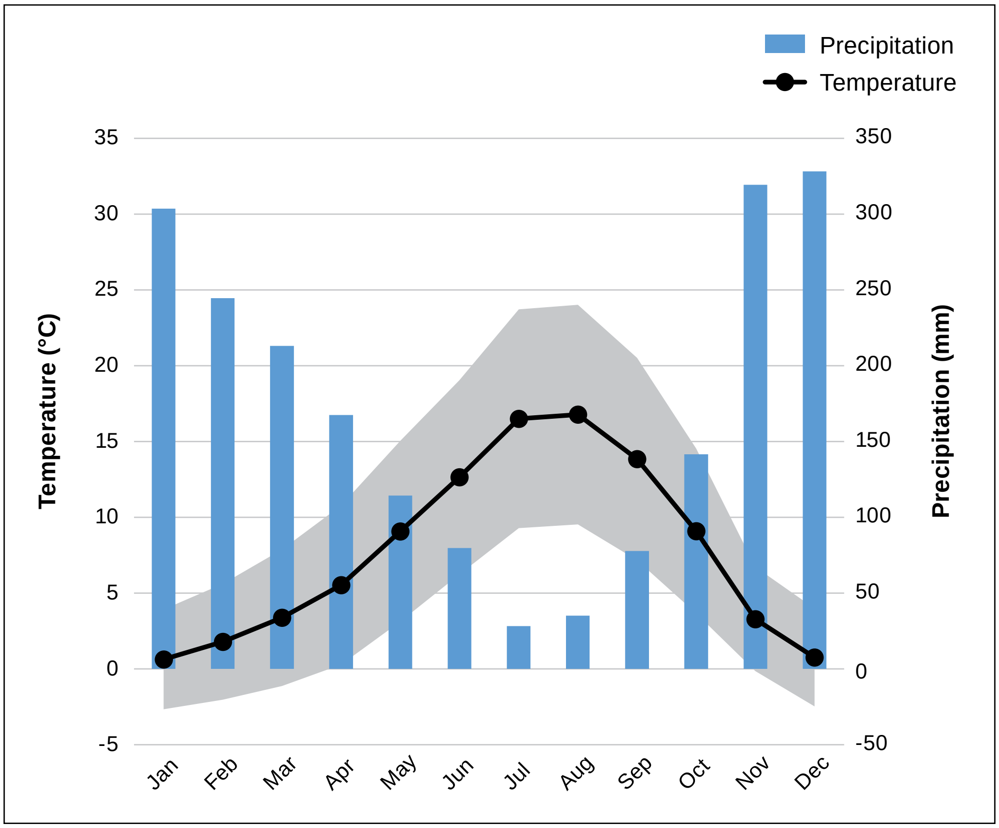


Figure 2.2—Mean monthly temperature and precipitation for 1970–1999 in the Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest assessment area from the PRISM dataset. The mean monthly minimum and maximum temperatures are represented by the shaded area, with the mean monthly temperature identified by the black line.

precipitation falls annually in the easternmost locations of the Columbia River Gorge National Scenic Area near The Dalles (just 50 km to the east).

Regional precipitation on yearly to centennial time scales is strongly influenced by tropical Pacific Ocean circulation and temperatures (Cobb et al. 2003, Redmond and Koch 1991). On interannual time scales, regional precipitation is modulated in part by the El Niño Southern Oscillation (ENSO), an atmospheric-oceanic teleconnection that alternates between cold and warm phases lasting from about 8 to 15 months with irregular return intervals and occasional neutral periods (McPhaden et al. 1998). Cold phases of ENSO (La Niña) are typically associated with anomalously wet conditions in the Pacific Northwest, whereas warm phases (El Niño) often result in drier than average conditions (Redmond and Koch 1991). Although there is some evidence (e.g., McCabe and Dettinger 1999, Mote et al. 2003) that the low-frequency Pacific Decadal Oscillation (PDO) modifies ENSO impacts in the region, PDO-ENSO analysis is limited by the small number of observed PDO cycles. The PDO is currently thought of as a slow North Pacific response to ENSO forcing and not as a single phenomenon, but rather, a response to three distinct ocean-atmosphere feedbacks (Newman et al. 2016). Although tropical Pacific conditions are a primary control on regional precipitation, Miller and Goodrich (2007) demonstrate that there are important subregional patterns, each with distinct trends and teleconnections. As such, the strength of precipitation-teleconnection relationships differs significantly across the Pacific Northwest.

Recent Climate Trends in the CMWAP Assessment Area

To examine regional temperature changes since 1895, we analyzed Oregon climate divisions 2, 4, and 6 (Guttman and Quayle 1996), which overlap with the CMWAP assessment area. Overall, there are negligible differences among the three climate divisions, with each indicating that mean annual temperatures increased by about 1.2 to 1.4 °C since 1895 (fig. 2.3). Because there were minimal differences among the three climate divisions analyzed in this report, the data were area weighted to create one regional time series. We also examined trends from the parameter-elevation regressions on independent slopes model (PRISM) dataset (Daly et al. 2008). Although its developers specifically caution against using PRISM for long-term trend analysis, we include it for comparison to results from recent Pacific Northwest climate change research (e.g., Abatzoglou et al. 2014).

Modest differences in seasonal temperature trends with the climate division data indicate that summer, fall, and winter temperatures each increased by about 1.4 °C since 1895, whereas spring temperatures increased by about half that amount. Notably, Abatzoglou et al. (2014) found that Pacific Northwest spring temperatures declined from 1980 to 2012, while the other three seasons each warmed at an

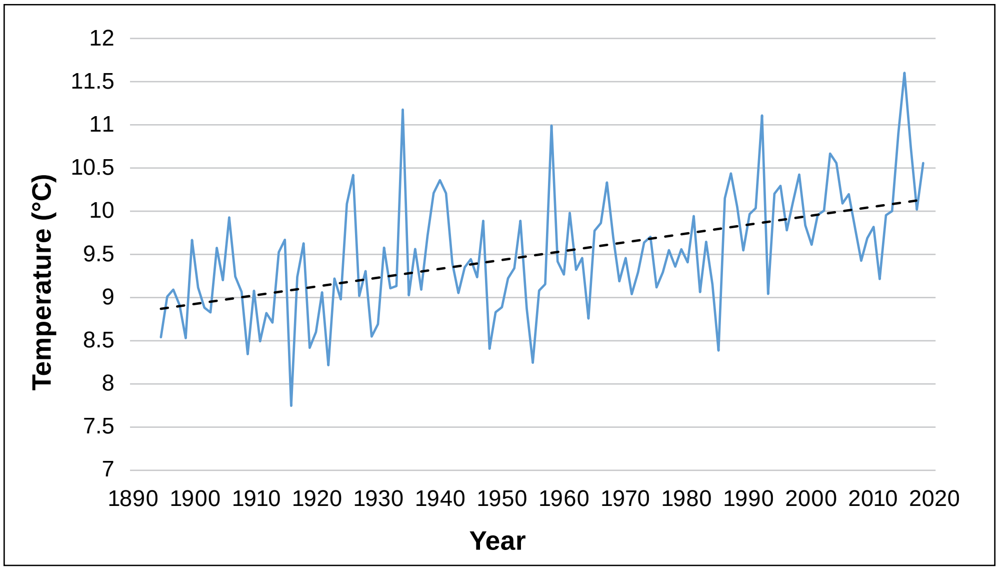


Figure 2.3—Mean annual temperature within the Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest assessment area since 1895, represented by an area-weighted average of Oregon climate divisions 2, 4, and 6. An 11-year moving average was applied to the time series.

accelerated rate compared to 1900 to 1980. Both temperature datasets examined indicate a similar pattern. Despite the moderated spring temperature trend, 6 of the 10 hottest years recorded have occurred since 2003, with the hottest summer (2015) and year (2015) also observed during that time. Moreover, despite moderate spring temperature trends, the fourth and fifth hottest spring seasons occurred in 2016 and 2015, respectively.

Although maximum and minimum temperatures increased by about the same amount since 1950, slightly more warming was observed in minimum temperature dating back to 1895. Despite similar temperature increases for both maximum and minimum temperatures, Bumbaco et al. (2013) found that extreme maximum and minimum temperatures changed at different rates. They observed that the frequency of hot overnight temperatures (nighttime minimum temperatures exceeding the 99th percentile) in June to September increased markedly in western Washington and Oregon over the past century, though there was no trend in the frequency of daytime temperatures exceeding the 99th percentile. In general, temperature trends in the CMWAP assessment area broadly match global findings reported in Vose et al. (2005) and Pacific Northwest regional results documented by Abatzoglou et al. (2014).

Climate change may be occurring differentially by elevation (e.g., Diaz and Eischeid 2007, Pepin and Lundquist 2008, Rangwala and Miller 2012, Vuille and Bradley 2000), but a lack of long-term data from high-elevation weather stations makes conclusions equivocal. Pepin et al. (2015) provided a comprehensive review of elevation-dependent climate trends as well as the ambiguity and challenges in characterizing climate trends in mountainous regions. Poor spatial coverage, variable data quality, and short periods of record are common issues in assessing climate change in mountainous regions. For instance, there is evidence that the snow telemetry (SNOTEL) network, a primary source of climate data in mountainous regions of the Western United States, produced artificially inflated high-elevation temperature trends over the past 30 years (Oyler et al. 2015). In addition, Strachan and Daly (2017) highlight inconsistent sensor installation within the SNOTEL network, including varying instrument heights and vegetation coverage that can introduce biases within gridded products. The remote automated weather stations (RAWS) network provides vital weather information to assist with fire weather forecasts and fire management across the United States (Zachariassen et al. 2003), but its use in long-term climate studies is limited because of its relatively short period of record. Moreover, stations within the RAWS network are typically located on dry ridgetops and southwest aspects, which may not be representative of other locations.

Within the CMWAP assessment area, a relatively well-studied region of complex terrain is the H.J. Andrews Experimental Forest, a long-term ecological research site on the western slope of the central Cascade Range. For the H.J. Andrews site, Daly et al. (2009) observed different temperature trends between valley/hilltop/ridgeline locations, with the latter strongly correlated to trends in free atmosphere temperature. Overall, climate models suggest warming will be greater at higher elevations because of snowpack losses (lowering surface albedo—the “whiteness” of a surface—resulting in increased shortwave radiation gain) (Rangwala et al. 2013).

Neither the PRISM nor climate division datasets indicate long-term trends in annual precipitation within the CMWAP assessment area (figs. 2.4B and 2.5). This agrees with Mote et al. (2003) and Abatzoglou et al. (2014) for the broader Pacific Northwest. Throughout the CMWAP assessment area, the highest average annual precipitation occurred during the mid-1940s until the mid-1950s. Before this time, an especially dry period occurred during the late 1920s to early 1940s, commonly referred to as the Dust Bowl years within the continental United States. Tropical Pacific sea-surface temperatures are thought to be a major control on Western U.S. long-term droughts, such as those that occurred during the Dust Bowl era (Seager et al. 2005). Luce et al. (2013) observed that orographic precipitation in the Pacific Northwest decreased since 1950 because of a weakening of tropospheric westerly winds. However, because of a lack of high-elevation weather stations with reliable long-term records, we were unable to corroborate that finding within the CMWAP assessment area.

Although annual precipitation has not changed significantly in the past century, evidence suggests that spring precipitation has increased. Overall, regional spring precipitation in the most recent 30-year period, 1989–2018, was about 15 percent higher than that observed for the period 1895–1988. This mirrors a chief finding of Abatzoglou et al. (2014), who noted that spring precipitation increased during the period 1901–2012, though they also found that summer and autumn precipitation decreased since 1901, a result not revealed in the climate division data.

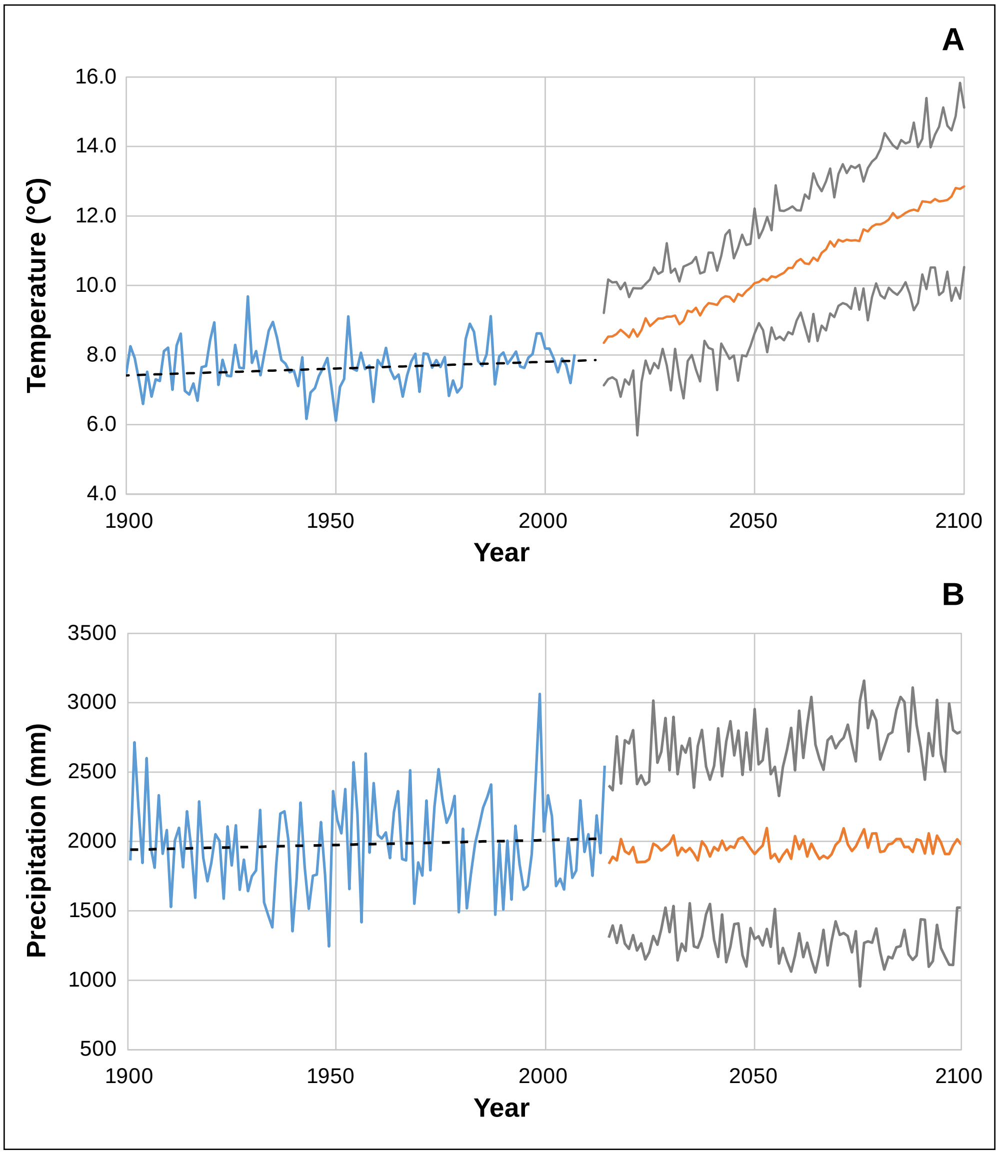


Figure 2.4—Historical and projected annual temperature (upper) and precipitation (lower) under the RCP 8.5 emission scenario for the Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest assessment area. Historical values were calculated from PRISM (Daly et al. 2008). Future projections were calculated from 31 global climate models (GCMs) in the NASA NEX-DCP30 downscaled climate dataset (Thrasher et al. 2013). Future projections are shown as a range, with orange lines representing the mean of the 31 GCMs.

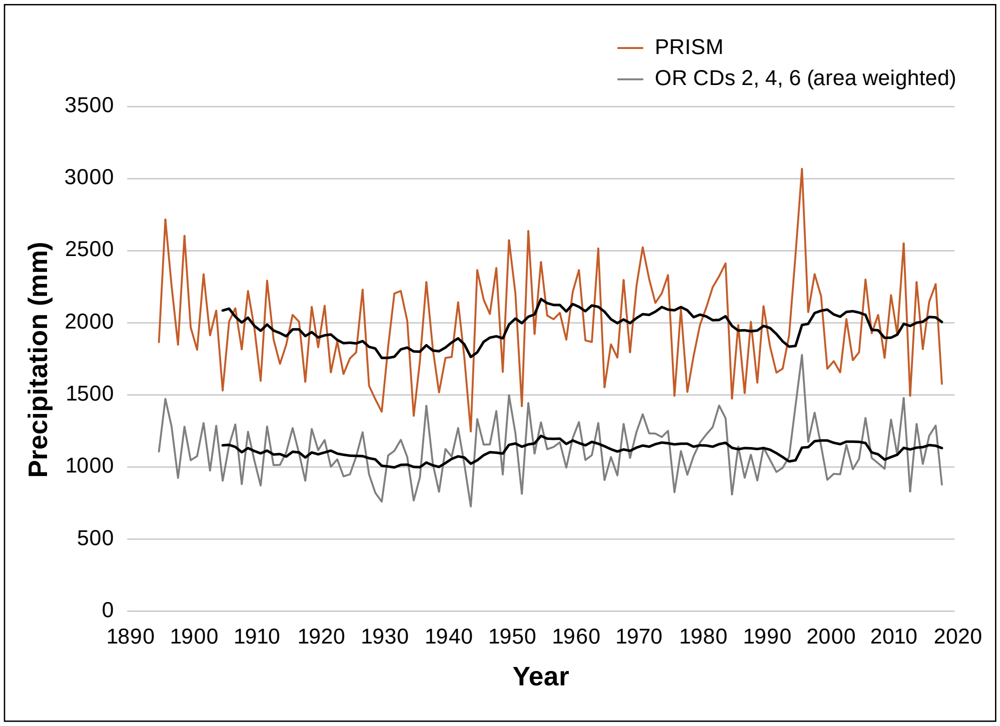


Figure 2.5—Mean annual precipitation within the Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest assessment area since 1895, represented by an area-weighted average of Oregon Climate Divisions (OR CDs) 2, 4, and 6 (gray) and PRISM data (Daly et al. 2008) (orange). An 11-year moving average was applied to the time series.

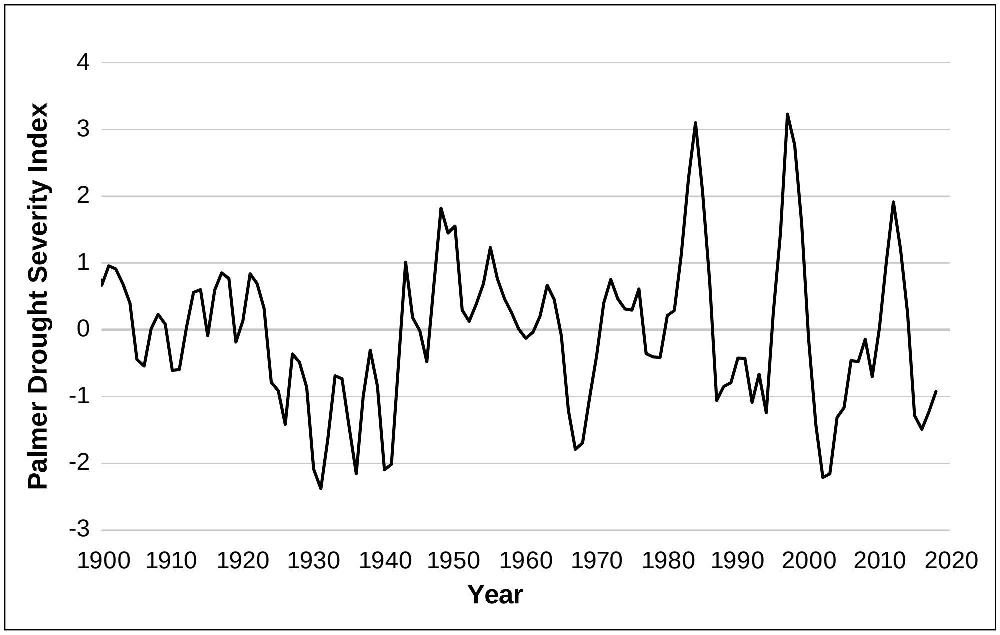


Figure 2.6—Three-year moving average of the Palmer Drought Severity Index for Oregon Climate Divisions 2, 4, and 6 (area-weighted). Positive values indicate wetter conditions, and negative values indicate drier conditions.

Another method to analyze long-term moisture trends is to evaluate drought with the Palmer Drought Severity Index (PDSI), a standardized index that uses precipitation and temperature data to estimate water availability. The index ranges from -10 (dry) to 10 (wet), with values less than -3 indicative of severe drought. As seen in figure 2.6, the PDSI for the three Oregon climate divisions exhibits considerable interannual and interdecadal variability. Overall, there is no long-term trend toward either wetter or drier conditions, though the highest (wettest) and lowest (driest) 36-month running mean PDSI values have each occurred in the past 20 years. For the CMWAP assessment area, the period 1987–2013 was characterized by increased drought severity compared to the period 1960–1986 (fig. 2.7), which is consistent with global assessments and anticipated climate change (Durack et al. 2012). Nevertheless, no droughts since 1895 within the region are thought to be as severe as the mega droughts that occurred during the 16th century (Stahle et al. 2007). Furthermore, Cook et al. (2004) noted that in the context of the past 1,200 years, the 20th century was a relatively wet period for western North America. Climate change may increase the probability of more extreme droughts than those observed in the past century (Lehner et al. 2017).

About half of the runoff in the Western United States derives from mountain snowpack, which typically peaks on or near April 1 (Mote et al. 2018). As such, spring snowpack is an important climate and hydrologic indicator. We analyzed spring snowpack using April 1 snow water equivalent (SWE), a common measure of snowpack used by water resource managers across the Western United States (McCabe and Legates 1995). This information is collected primarily through two networks, the SNOTEL network (with daily measurements) and snow course observations (with monthly measurements). The snow course data in the Pacific Northwest extend back to the 1930s in some cases, though many sites have much shorter periods of record. In Oregon, there are 72 snow course locations available, with only 11 containing records back to the 1930s; more than half of the Oregon snow course locations have records that begin in the 1960s or later. Unfortunately, there are no snow course monitors located within the CMWAP assessment area.

In contrast, of the 91 SNOTEL locations throughout Oregon, at least 25 are located within the assessment area. In addition to analyzing select stations, we examined trends within three hydrologic unit code (HUC) basins and seven HUC subbasins contained within the CMWAP assessment area. The three basins analyzed were the Lower Columbia (HUC 170800), Middle Columbia (HUC 170701), and Willamette (HUC 170900). The seven subbasins we examined include the Clackamas (HUC 17090011), Lower Columbia-Sandy (HUC 17080001), McKenzie (HUC 17090004), Middle Columbia-Hood (HUC 17070105), Middle Fork Willamette (HUC 17090001), North Santiam (HUC 17090005), and South Santiam (HUC 17090006).

Somewhat surprisingly, there were no statistically significant trends in April 1 SWE observed in any of the basins or subbasins as indicated by the SNOTEL data

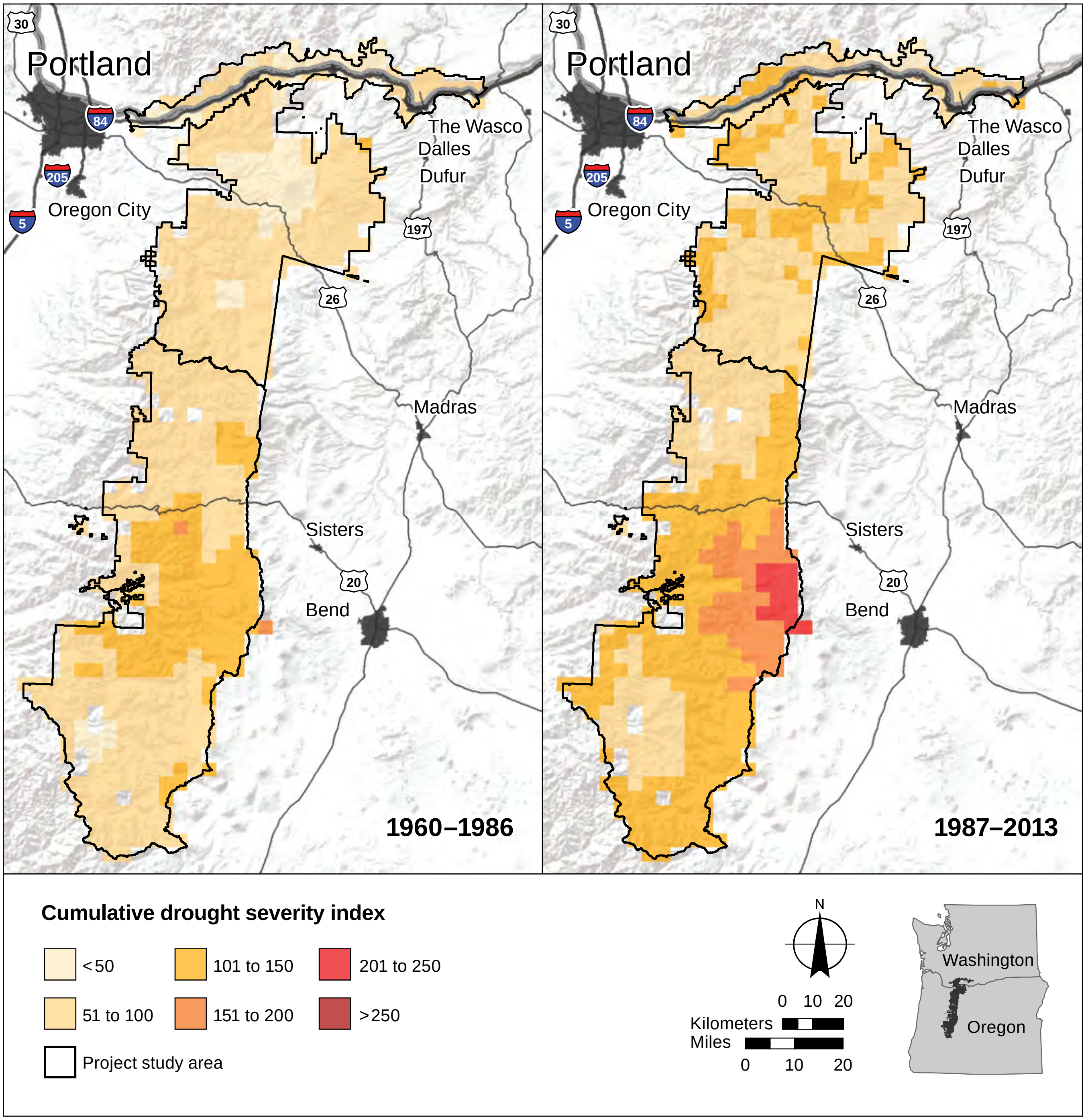


Figure 2.7—A comparison of the cumulative drought severity index in the CMWAP assessment area for two 27-year periods, 1960–1986 and 1987–2013.

(fig. 2.8). The finding of no statistically significant change in regional April 1 SWE since 1980 is corroborated by Siler et al. (2018) and Yan et al. (2019), who both reported that Cascade Range snowpack during the past 40 years has been stable despite recent regional warming. Siler et al. (2018) concluded that atmospheric circulation patterns driven by natural climatic variability explain why April 1 snowpack has been resistant to significant winter warming since 1980. They suggested that snowpack will experience an accelerated decline once the offsetting influence of natural atmospheric circulation variability diminishes. This is quite likely, given our observation that CMWAP assessment area April 1 SWE is most strongly correlated with mean March temperatures, which have either declined or remained the same since 1980. Although moderated spring temperature trends and atmospheric circulation patterns have helped stabilize regional April 1 snowpack, Yan et al. (2019) show that annual peak SWE decreased significantly, with a concomitant increase in rain-on-snow events throughout the Cascades.

Although there has been no significant decrease in April 1 SWE observed in the SNOTEL data since 1980, longer term snowpack studies using snow course data indicate widespread and marked declines since 1950 (Mote 2003, Mote et al. 2018). By comparison, Stoelinga et al. (2010) found that for the greater Pacific Northwest

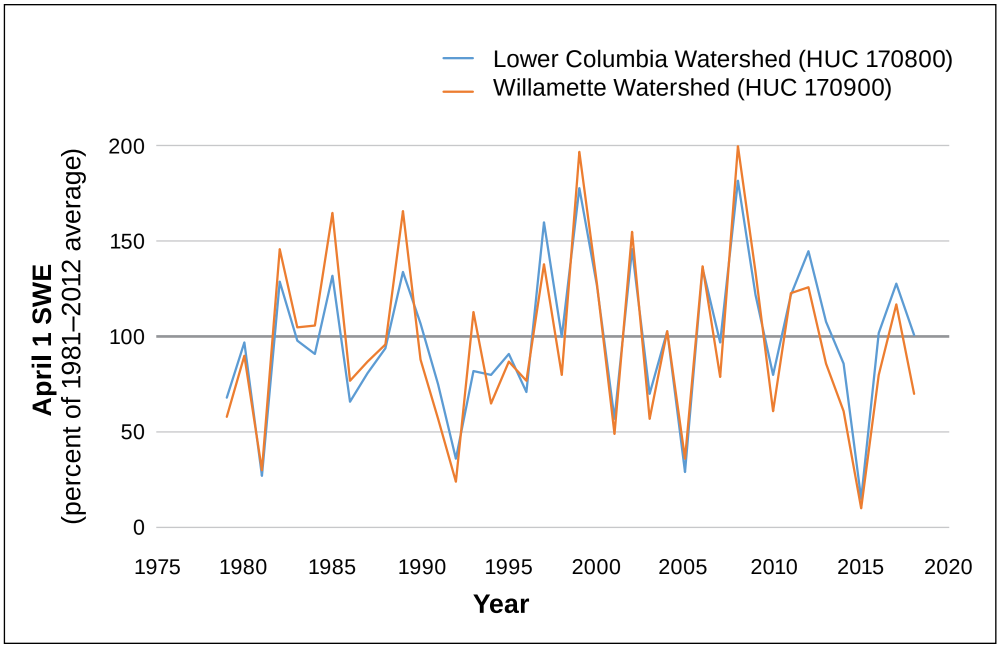


Figure 2.8—Percentage of average April 1 snow water equivalent (SWE) for the Lower Columbia and Willamette watersheds of the Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest assessment area. The snow telemetry SWE data are relative to the base period 1981–2010 and were obtained from the U.S. Department of Agriculture, Natural Resources Conservation Service database.

region, snowpack had declined since the 1930s, but had increased slightly in the period 1976–2007. Mote et al. (2005) also documented a substantial decline in Pacific Northwest snowpack for the period 1950–1997 but reported that Oregon Cascades snowpack had increased modestly in the period 1916–1997, further highlighting that regional snowpack trends are sensitive to the starting year of record and specific location examined.

Mid-20th century years were particularly wet and cold in the Pacific Northwest. Thus, studies that assess snowpack trends starting from 1950 may slightly overestimate 20th-century snowpack decline in the Pacific Northwest. Nevertheless, the consecutive snow drought years of 2014 and especially 2015 are thought to be a preview of future snowpack conditions in the region (Sproles et al. 2017). Moreover, there is strong evidence that snowmelt season is occurring one to three weeks earlier across the Western United States (Stewart et al. 2005). Future regional warming is expected to accelerate this trend (Gergel et al. 2017, Mote et al. 2003).

Projected Future Climate in the CMWAP Assessment Area

To explore possible future climates in the CMWAP assessment area, we used the National Aeronautics and Space Administration (NASA) NEX-DCP30 downscaled climate dataset (Thrasher et al. 2013), which includes climate projections produced by 28 global climate models (GCMs) from the Coupled Model Intercomparison Project phase 5 (Taylor et al. 2012) for two common climate change scenarios: Representative Concentration Pathways (RCP) 4.5 and RCP 8.5 (van Vuuren et al. 2011). NEX-DCP30 uses bias correction-spatial disaggregation to downscale GCM output to 30 arc-second resolution (about 800 m) for the conterminous United States, using PRISM as a reference climate dataset (Thrasher et al. 2013).

Climate models are currently run under several development and energy scenarios, in this instance RCPs, of which there are four: RCP 8.5, RCP 6.0, RCP 4.5, and RCP 2.6 (van Vuuren et al. 2011). These each represent unique global development and energy futures, with the numbers representing change to Earth's atmosphere in radiative forcing, ending with +2.6, +4.5, +6, and +8.5 W m^{-2}, respectively, by year 2100.

RCP 2.6 represents a future in which global greenhouse gases (GHG) peak by 2020, which would likely limit global warming to 1.5 to 2 °C above preindustrial temperatures (Moss et al. 2010). Despite modest reductions in carbon emissions in both the European Union and United States since 2005, global carbon emissions increased by over 20 percent in that timeframe owing to considerable increases from China and other developing nations (Figueres et al. 2018). RCP 4.5 represents a future in which global GHG emissions peak by 2040, with significant reductions thereafter, leading to climate stabilization by year 2100. Under RCP 4.5, warming would be about 2 to 2.5 °C above preindustrial levels (IPCC 2014). RCP 6.0 is also termed a stabilization scenario, with global GHG emissions peaking by 2080 and warming of about 3 °C above preindustrial levels. RCP 8.5 represents a future with no climate change mitigation, high population growth, and an increase in global coal development, leading to increasing GHG emissions throughout the 21st century. By the end of the century, RCP 8.5 would result in atmospheric carbon dioxide (CO_2) concentrations above 1,200 parts per million (ppm), over four times higher than preindustrial levels. GCM projections suggest that global warming under RCP 8.5 would result in more than a 4 °C increase above preindustrial conditions. Although some question the plausibility of RCP 8.5 (e.g., Ritchie and Dowlatabadi 2017, Wang et al. 2017), it remains the benchmark that the Intergovernmental Panel on Climate Change and climate research community use to assess future climate scenarios. Accordingly, for the remainder of this report, we focus primarily on the RCP 8.5 scenario as a high-emissions benchmark.

Each of the 28 GCMs under either the RCP 4.5 or RCP 8.5 scenario suggested that temperatures within the CMWAP assessment area will increase markedly during the 21st century, especially in the latter half (fig. 2.9). The projected temperature increase by the year 2100 for the CMWAP assessment area differs considerably between RCP 4.5 and RCP 8.5. Although temperature projections under RCP 4.5 initially track closely to RCP 8.5, they diverge considerably after 2050, with significantly more warming under the RCP 8.5 scenario by the end of the century. Under RCP 8.5, the mean annual temperature within the CMWAP assessment area is projected to increase by about 4.5 °C above current temperatures, whereas RCP 4.5 suggests regional warming of about 2 °C. Notably, even the model simulating the smallest temperature change under RCP 8.5 projects a larger temperature increase than the model displaying the most warming under RCP 4.5.

The GCMs generally simulate future seasonal warming matching observed seasonal patterns for the past 120 years. The GCMs consistently show the largest temperature increase during summer, with an approximately 6 °C increase projected by the year 2100. Warming during fall is projected to increase by about 5 °C, while the model ensemble average temperature increase for winter and spring is roughly 4 °C. Despite slightly less warming anticipated for winter and spring, the projected temperature increase would greatly affect regional snowpack and water resources (Li et al. 2017) and would likely extend the length of the fire season, which has increased significantly since the 1980s (Westerling et al. 2006).

To place the projected temperature increases in context, the anticipated warming would transform the Portland metropolitan area temperatures to those

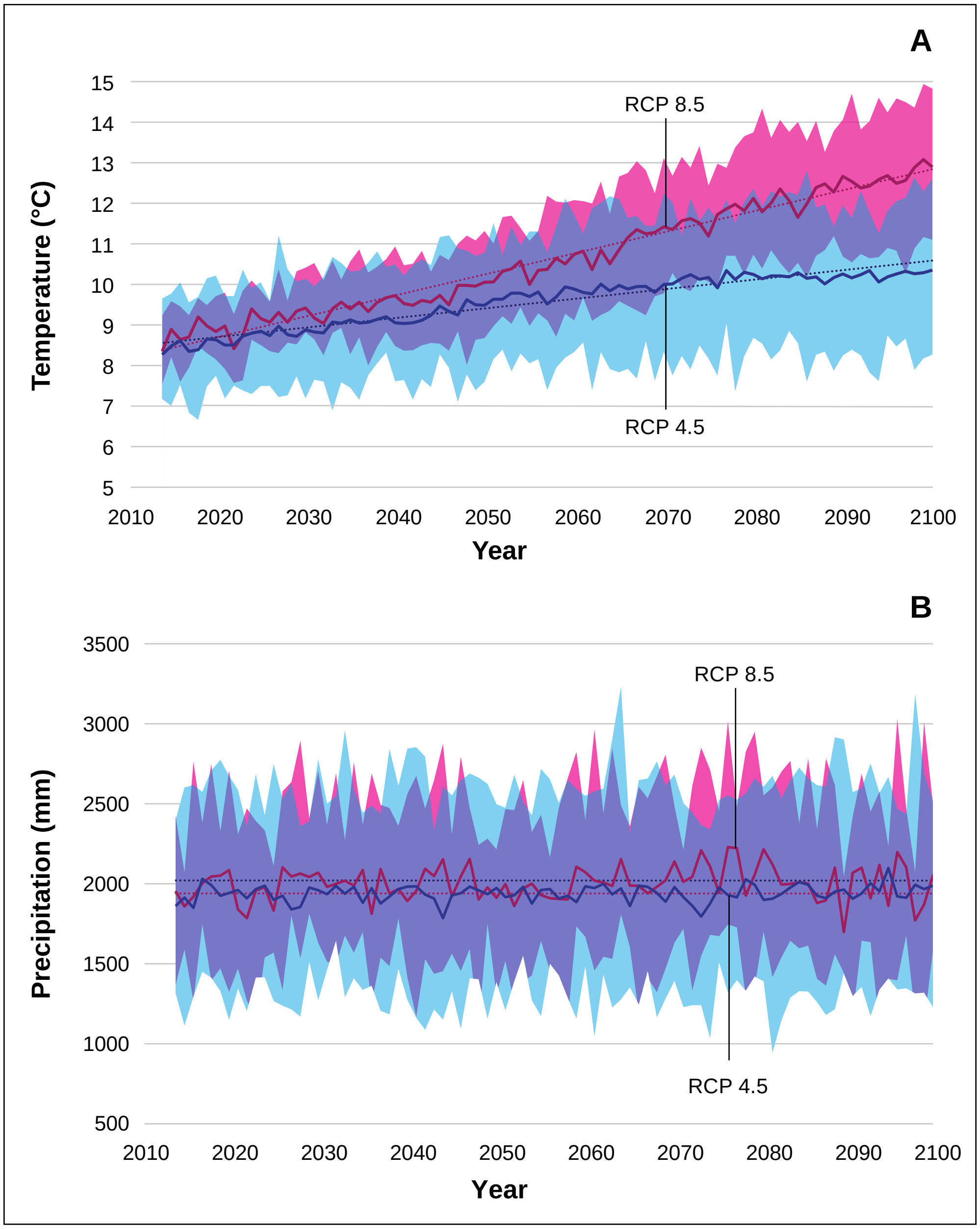


Figure 2.9—A comparison of temperature (A) and precipitation (B) projections under Representative Concentration Pathway (RCP) 4.5 and RCP 8.5 (van Vuuren et al. 2011) for the Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest assessment area. Climate projections were calculated from 31 global climate models in the NASA NEX-DCP30 downscaled climate dataset (Thrasher et al. 2013). Dashed lines are fitted to the annual time series.

more similar to current conditions in California cities like Merced or Sacramento, located over 800 km to the southeast. As another way to illustrate the RCP 8.5 temperature change by century's end, Portland's December and January temperature patterns would be similar to those experienced currently in March. At higher elevation locations, like Government Camp on the south side of Mount

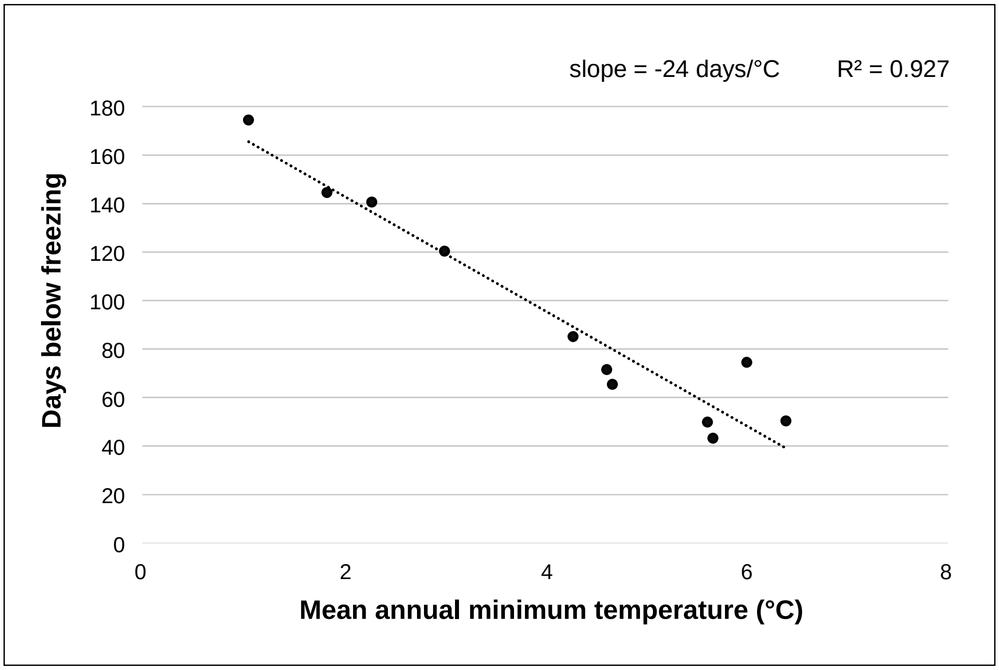


Figure 2.10—Days below freezing at 11 stations within the Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest assessment area versus their respective mean annual minimum temperature. Data are from the Western Regional Climate Center (WRCC 2019).

Hood, projected temperature increases by the end of this century would render Government Camp's summer temperatures comparable to current conditions in Seattle. A 4 °C increase during winter would make the temperatures observed at central Cascade Range pass level (1200 to 1500 m) similar to those currently experienced during winter near sea level. Finally, the mean summer temperature in low-elevation eastern CMWAP assessment area locations, like The Dalles, would increase to almost 28 °C by 2100, which is similar to current summer conditions in the cities of California's southern San Joaquin Valley (e.g., Bakersfield).

The average annual temperature increase of 4.6 °C projected by the GCMs under RCP 8.5 would significantly decrease the number of days below freezing, with a corresponding increase in the length of the freeze-free period. Using climate summary data from the Western Region Climate Center (WRCC 2019) for CMWAP assessment area locations, we found that for every degree Celsius increase in minimum temperature, there are 24 fewer days with a minimum temperature below freezing (fig. 2.10). A similar relationship exists for the freeze-free data; if total warming by 2100 were to exceed 4 °C, the freeze-free season at a high-elevation location, like Government Camp, would increase from 3 months to more than 6 months. Moreover, the regression line in figure 2.10 suggests that freezing days decrease to zero when the average annual minimum temperature of a CMWAP location exceeds 8 °C. Accordingly, a 4.6 °C annual temperature increase would make below-freezing days at low elevations within the CWMAP assessment area rare to nonexistent.

Compared to temperature, GCM precipitation projections are both more variable and much smaller in magnitude. Although 22 of the 28 GCMs suggest an increase in annual precipitation, only 5 of them indicate a greater-than-10-percent increase in the CMWAP assessment area. Moreover, half of the models project less than a 5 percent change in either direction, and only two models simulate more than a 5 percent decrease in annual precipitation by the end of the 21st century. As such, the models generally show either no change in annual precipitation or a negligible increase. However, because of the large temperature increase anticipated, higher evapotranspiration rates would offset any increase in precipitation. Overall, the GCMs show a slight increase in the seasonal amplitude of precipitation, with more winter precipitation (December through February) and less precipitation during the already dry growing season (April through October).

Rupp et al. (2013) noted considerable variability in model performance among the 28 GCMs in the Pacific Northwest. In their study, the GCMs were evaluated and ranked for their ability to replicate various features of recently observed climate within the Pacific Northwest (table 2.1). We analyzed whether models that performed better—those identified by the blue (first quartile) and the green (second quartile) circles in figure 2.11—projected a larger temperature increase

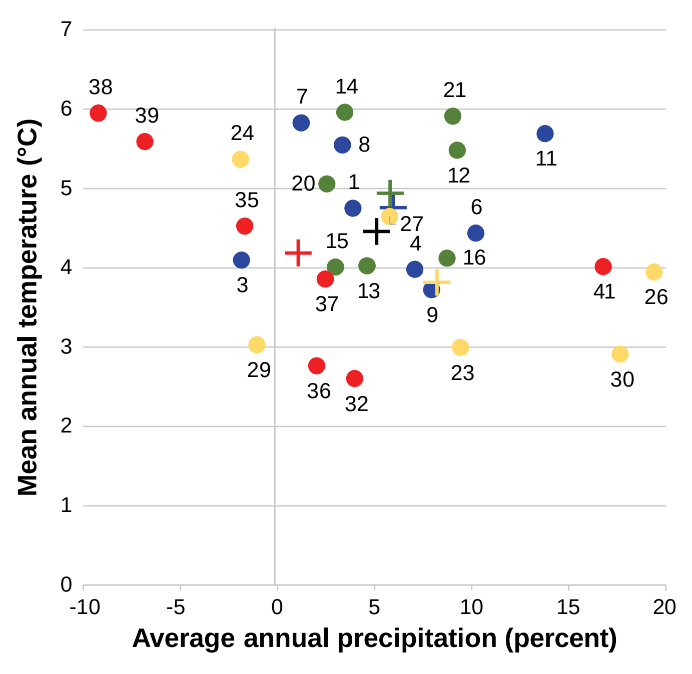
Table 2.1—Ranking of global climate models (GCM) that comprise NEX-DCP30 (Thrasher et al. 2013) according to their skill for simulating historical climate of the Pacific Northwest region (Rupp et al. 2013)[a]

Rank	GCM	Rank	GCM
1	CESM1(CAM5)	22	MPI-ESM-MR
3	CCSM4	23	FIO-ESM
4	CESM1-BGC	24	BNU-ESM
6	CNRM-CM5	25	MPI-ESM-LR
7	HadGEM2-ES	26	FGOALS-g2
8	HadGEM2-CC	27	GFDL-CM3
9	CMCC-CM	29	MRI-CGCM3
11	CanESM2	30	inmcm4
12	IPSL-CM5A-MR	32	GISS-E2-R
13	bcc-csm1-1-m	35	bcc-csm1-1
14	HadGEM2-AO	36	GFDL-ESM2M
15	MIROC5	37	GFDL-ESM2G
16	NorESM1-M	38	MIROC-ESM-CHEM
20	CSIRO-Mk3-6-0	39	MIROC-ESM
21	IPSL-CM5A-LR	41	IPSL-CM5B-LR

[a] ACCESS1-0 was not evaluated in Rupp et al. (2013).

for the CMWAP assessment area than the lower ranked models evaluated in Rupp et al. (2013). The higher ranked models suggest a 4.8 °C increase for the CMWAP assessment area, whereas the lower ranked ones indicate a 4.0 °C increase, a statistically significant difference (p = 0.036). There were no significant differences in projections of future precipitation based on the GCM rankings in Rupp et al. (2013).

To investigate a range of potential climate change effects within the CMWAP assessment area, we selected results from five GCMs as case studies (table 2.2). The case studies cover a variety of future climate states, giving preference to GCMs ranked higher for their ability to simulate past climate of the Pacific Northwest. The CESM1(CAM5), which we classify as the "near mean" model, was selected as the GCM that simulates a future climate nearest the mean of the GCMs with an annual temperature increase of 4.8 °C and no statistically significant change (+4 percent)



Rank	GCM
1	CESM1(CAM5)
3	CCSM4
4	CESM1-BGC
6	CNRM-CM5
7	HadGEM2-ES
8	HadGEM2-CC
9	CMCC-CM
11	CanESM2
12	IPSL-CM5A-MR
13	bcc-csm1-1m
14	HadGEM2-AO
15	MIROC5
16	NorESM-M
20	CSIRO-Mk3-6-0
21	IPSL-CM5A-LR
23	FIO-EDM
24	BNU-ESM
26	MPI-ESM-LR
27	GFDL-CM3
29	MRI-CGCM3
30	inmcm4
32	GISS-E2-R
35	bcc-csm1-1
36	GFDL-ESM2M
37	GFDL-ESM2G
38	MIROC-ESM-CHEM
39	MIROC-ESM
41	IPSL-CM5B-LR

Figure 2.11—Projected change in mean annual temperature and average annual precipitation from 28 global climate models (GCMs) from 1970–1999 to 2070–2099 for the Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest assessment area. Mean annual temperature and average annual precipitation were calculated using the NASA NEX-DCP30 climate dataset (Thrasher et al. 2013). GCMs are ranked according to model skill for simulating historical climate of the Pacific Northwest Region (Rupp et al. 2013). The circles representing GCMs are colored per quartile of model skill: blue, green, yellow, and red circles represent quartiles of ranking from the highest to lowest, respectively. Plus symbols are the means of each quartile group of GCMs. The black plus symbol represents the mean of the entire 28-member set.

in mean annual precipitation. BNU-ESM (termed the “hot” model) projects a temperature increase larger than the ensemble average (+5.4 °C) with no significant change in mean annual precipitation. The CanESM2 (termed the “hot and wet” model) simulates a 5.7 °C temperature increase and a considerable (+14 percent) increase in mean annual precipitation. The MIROC-ESM-CHEM (termed the “hot and dry” model) shows a 6.0 °C temperature increase and a 9 percent decrease in mean annual precipitation. The MRI-CGCM3 (termed the “cool” model) shows a lower amount of warming than the ensemble mean, with a projected 3.0 °C temperature increase and no significant change in annual precipitation.

By the end of the century, each of the selected case study GCMs suggests a much hotter CMWAP assessment area. The largest temperature increases are expected during the hottest time of the year, from June to September (fig. 2.12). For these four months, the average temperature is projected to increase by 6 °C among the five case study GCMs. For the 8-month period from October to May, the models indicate about 2 °C less warming than during the hottest months. However, there are differences among GCMs in the magnitude of anticipated warming. For instance, the CanESM2 temperature increase between June and September is 7.6 °C, with a projected increase of more than 8 °C for July and August. In contrast, the MRI-CGCM3 simulates a 3.6 °C temperature increase for the same 4-month period.

Applying these scenarios to a nearby location like Portland, the hot and wet future presented by the CanESM2 model would produce mid-summer temperatures comparable to those currently experienced in Dallas, Texas. In contrast, if mid-summer warming follows more closely the “cool” MRI-CGCM3 pattern, mid-summer temperatures by 2100 in Portland would be more like those now experienced in Boise, Idaho. Regardless, both climate change futures represent a marked departure from any modern-day climate analog. Using these same mid-summer scenarios on Cascade Range pass locations, like Government Camp

Table 2.2—Five downscaled global climate model (GCM) outputs selected for analysis[a]

GCM	Rank	ΔT (°C)[b]	ΔP (percent)[b]	Representative case[c]
CESM1(CAM5)	1	4.8	4	Near mean
CanESM2	11	5.7	14	Hot-wet
BNU-ESM	24	5.4	-2	Hot
MIROC-ESM-CHEM	38	6.0	-9	Hot-dry
MRI-CGCM3	29	3.0	-1	Cool

[a] Rank is from Rupp et al. (2013) and reflects overall model performance for simulating historical climate of the Pacific Northwest.

[b] Increase in temperature (ΔT) and change in precipitation (ΔP) were calculated as the difference between the climate of 1970–1999 and 2070–2099 for the Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest assessment area under RCP 8.5.

[c] Representative case indicates the relative position of the GCM among the 31 GCMs.

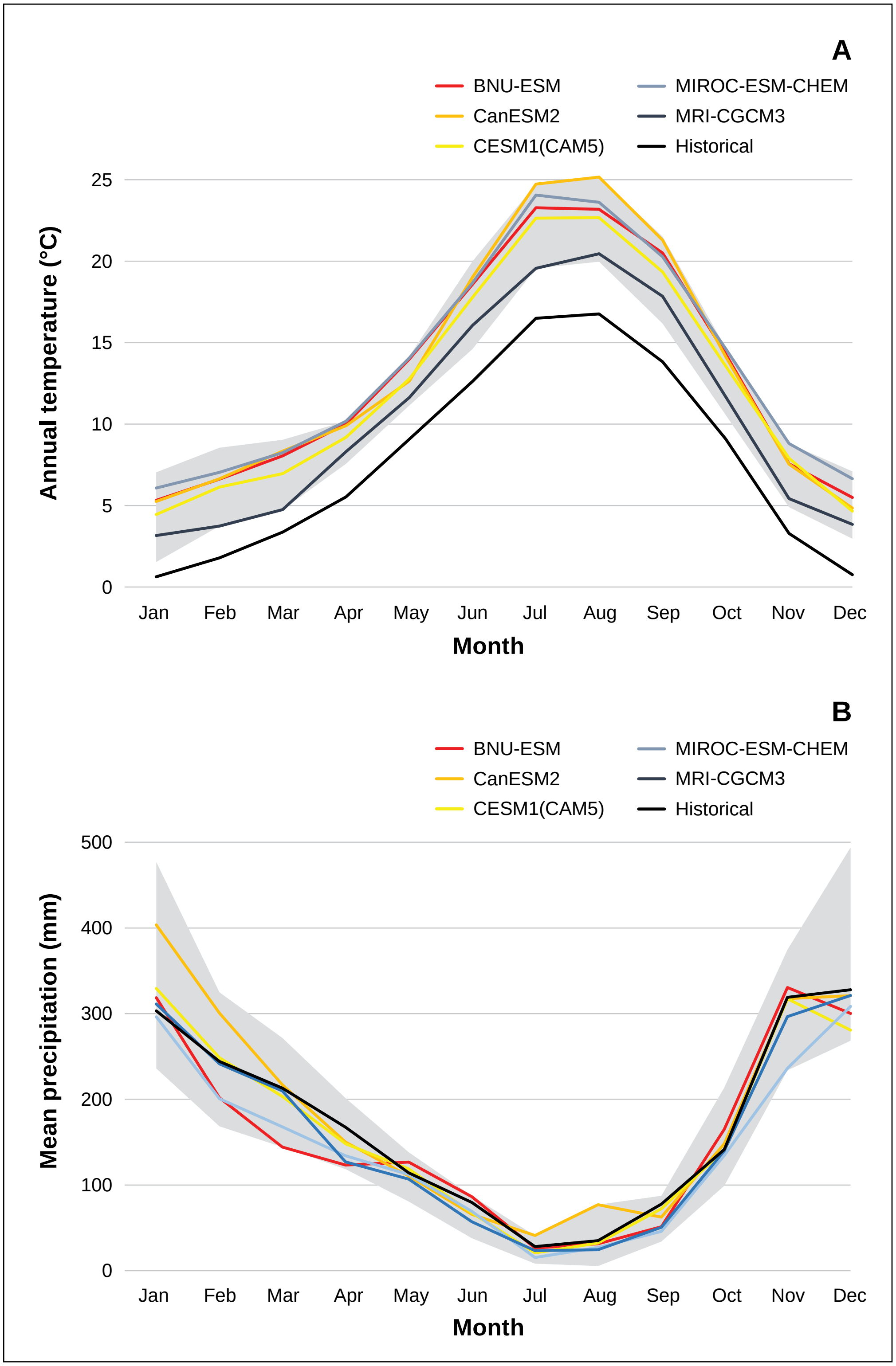


Figure 2.12—Historical and projected monthly mean temperature (A) and mean precipitation (B) patterns under Representative Concentration Pathway (RCP) 8.5 (van Vuuren et al. 2011) for the CMWAP assessment area. Black lines represent historical values, calculated from PRISM (Daly et al. 2008). Future projections were calculated from 28 global climate models (GCMs) from the NASA NEX-DCP30 climate dataset (Thrasher et al. 2013). Gray bands represent the minimum and maximum values across 28 GCMs. The five selected GCMs explored in this chapter are shown as colored lines.

(elevation 1200 m), also illustrates the large difference between the GCMs. The CanESM2 model future would render mid-summer temperatures at pass levels in 2100 similar to current conditions in Portland or Salem. Even the relatively cool MRI-CGCM3 scenario would produce a large change, with Government Camp likely to experience summer temperatures like Vancouver, British Columbia.

Although the temperature increase during the cooler months of the year simulated by the five case study models is about 2 °C less than during the hottest months, the range of warming from 2.5 °C in the MRI-CGCM3 to 4.6 °C in CanESM2 represents a marked change from historical and modern temperatures. All the models simulate later snow accumulation in autumn and winter, with earlier spring melt. These changes would result in a shorter snow season and a reduction in area covered by snow (see chapter 3).

Given that climate change is expected to affect low- and high-elevation regions differently, the five case study models were evaluated for elevation-dependent climate trends. However, for the CMWAP assessment area, the projected change in mean annual temperature differed minimally among the elevation bands (fig. 2.13). Each of the case study GCMs show less than 0.5 °C difference in warming by elevation. Also, there is little suggestion of elevation-dependent change in mean annual precipitation among case study models.

Despite a lack of elevation-dependent temperature or precipitation trends in the five models, the projected change in growing season length (GSL) is anticipated to differ by elevation (figs. 2.13F and 2.14). Each model shows minimal change for the lowest elevations (<1000 m) because the growing season is already nearly year-round. However, at higher elevations, the models indicate considerable increases in GSL. Currently, GSL ranges from about 6 months at 2400 m to around 4.5 months at 3000 m. The relatively cool MRI-CGCM3 indicates the least amount of change in GSL, with a 1-month increase at 1000 m in elevation and a 2-month increase above 2000 m. The other four models simulate greater increases in GSL than the MRI-CGSM3 model, with up to a 4- to 5-month increase projected at the highest elevations. The warmest models suggest that by the end of the century, the GSL at 2400 m would extend to 11 months, similar to the current GSL below 1000 m. Even at the highest elevations within the CMWAP assessment area, the GSL would increase to almost 9 months, a remarkable departure from historical conditions.

Coupled with changes in GSL, growing degree-days (GDD) and wet growing degree-days (WGDD) both increase substantially under the RCP 8.5 scenario (fig. 2.15). GDD is a general index of energy available for plant growth and is calculated as the product of the temperature above zero and the number of days (McMaster and Wilhelm 1997). For example, if every day of a month were 3 °C, then GDD would be 3 degrees × 31 days, or 93 GDD. WGDD is an index of energy available for plant growth while there is significant moisture available, and they are

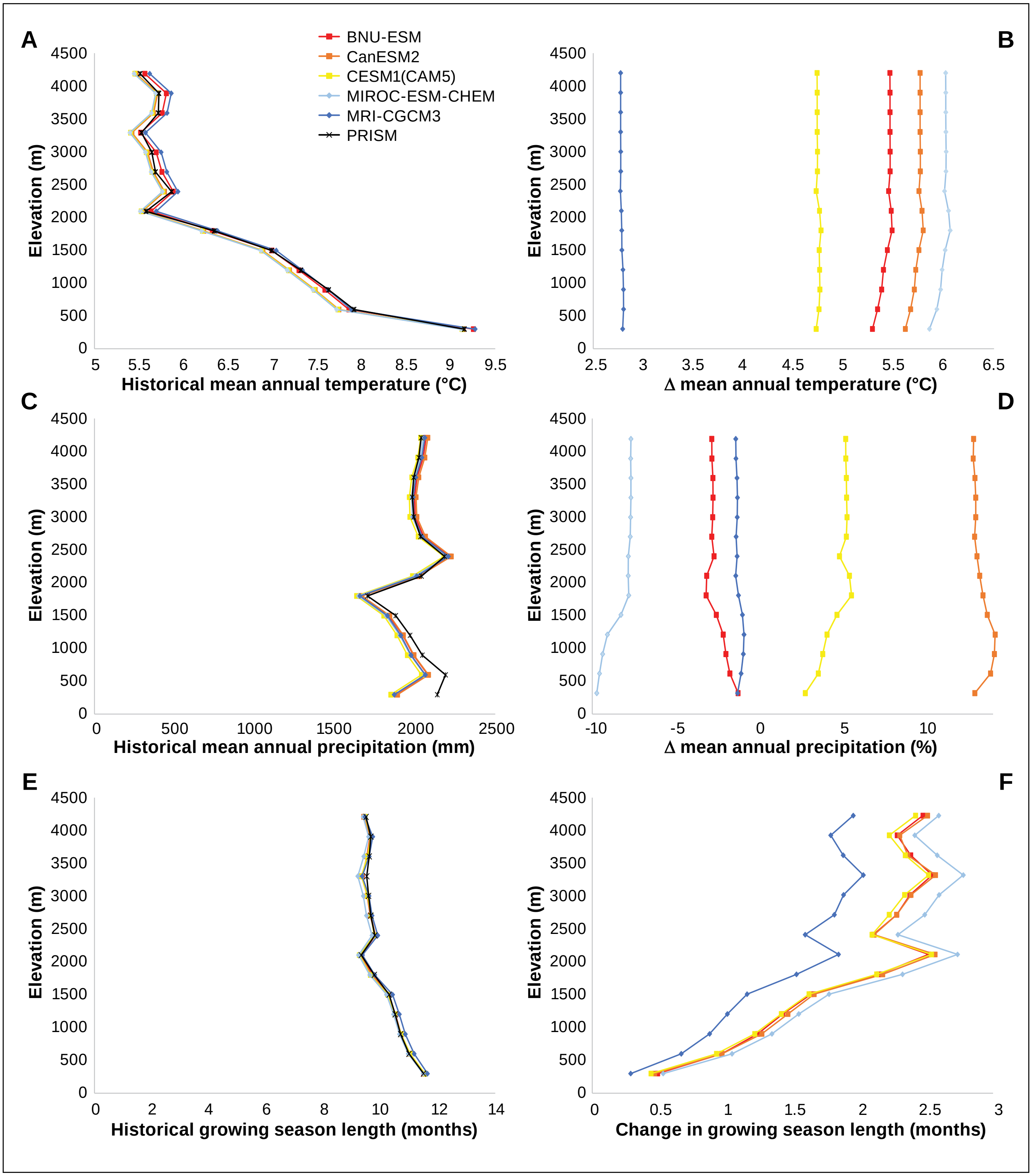


Figure 2.13—(A) Historical mean annual temperature, and (B) projected change; (C) historical mean annual precipitation, and (D) projected change; (E) historical growing season length, and (F) projected change by elevation for the Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest assessment area for five selected global climate models. The historical period is 1970–1999, and changes were calculated for 2070–2099 relative to the historical period. Historical values were calculated from PRISM (Daly et al. 2008), and future projections were calculated from the NASA NEX-DCP30 downscaled climate dataset (Thrasher et al. 2013) for the Representative Concentration Pathway 8.5 emission scenario (van Vuuren et al. 2013). The assessment area was divided into elevation bands in 300-m increments.

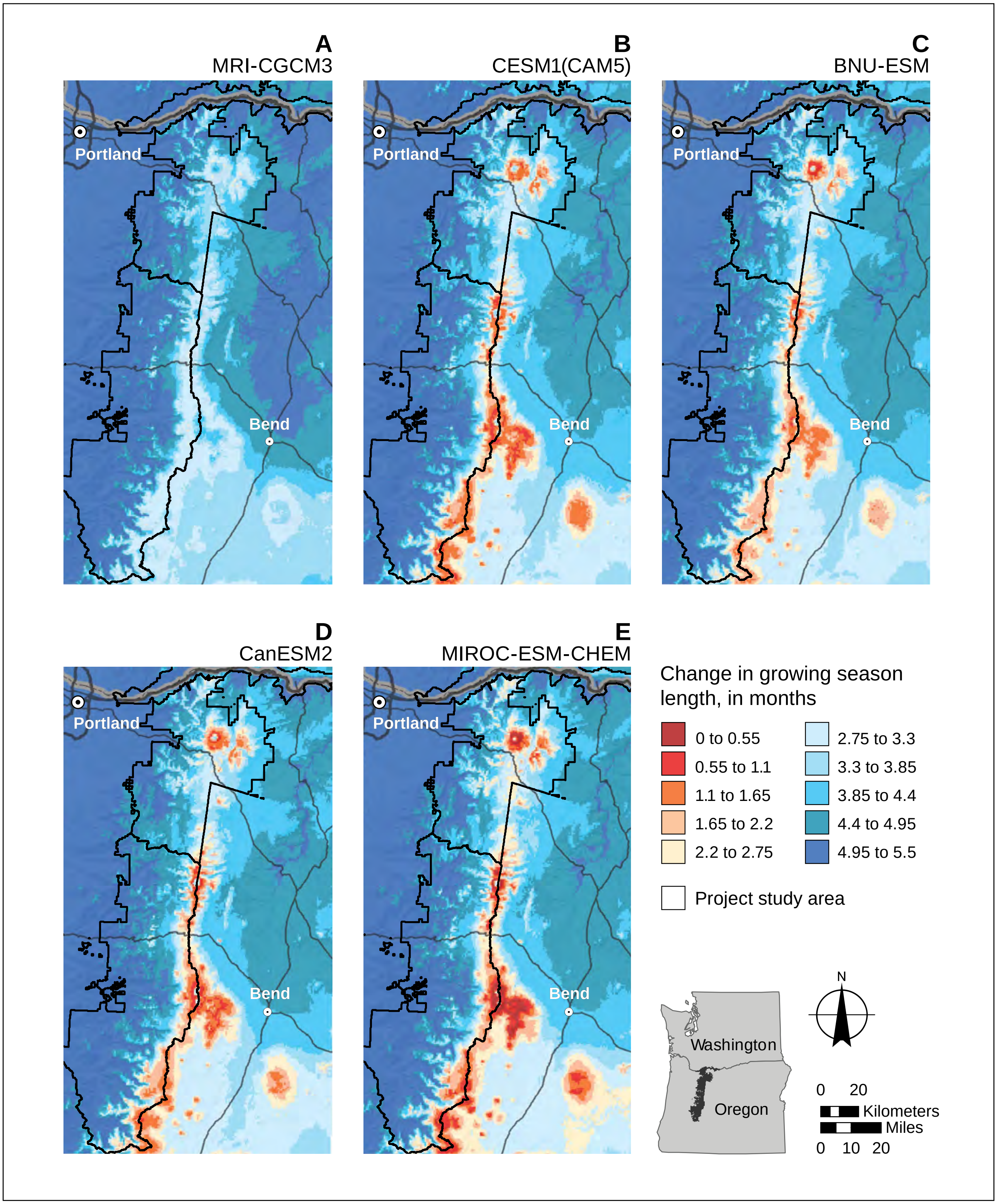


Figure 2.14—Change in growing season length from the historical period (1970–1999) to the end of the century (2070–2099) under the Representative Concentration Pathway 8.5 climate change scenario for five selected global climate models for the Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest assessment area. Growing season includes all months with mean daily minimum temperatures greater than 0 °C.

calculated the same way as GDD, except only for months with precipitation above a selected threshold. GDD is projected to increase most in absolute value during summer, ranging from a seasonal increase of 331 GDD (+24 percent) in the "cool" MRI-CGCM3 model to 734 (+53 percent) GDD in the "hot-wet" CanESM2 model. In percentage terms, the largest change in all models is anticipated in winter, with a doubling or tripling of winter GDD for the period 2070–2099.

Each of the models projects a large increase in WGDD, but differences in projected temperature and precipitation lead to substantial variability in WGDD projections (fig. 2.15). The "near mean" CESM1(CAM5) has the greatest change,

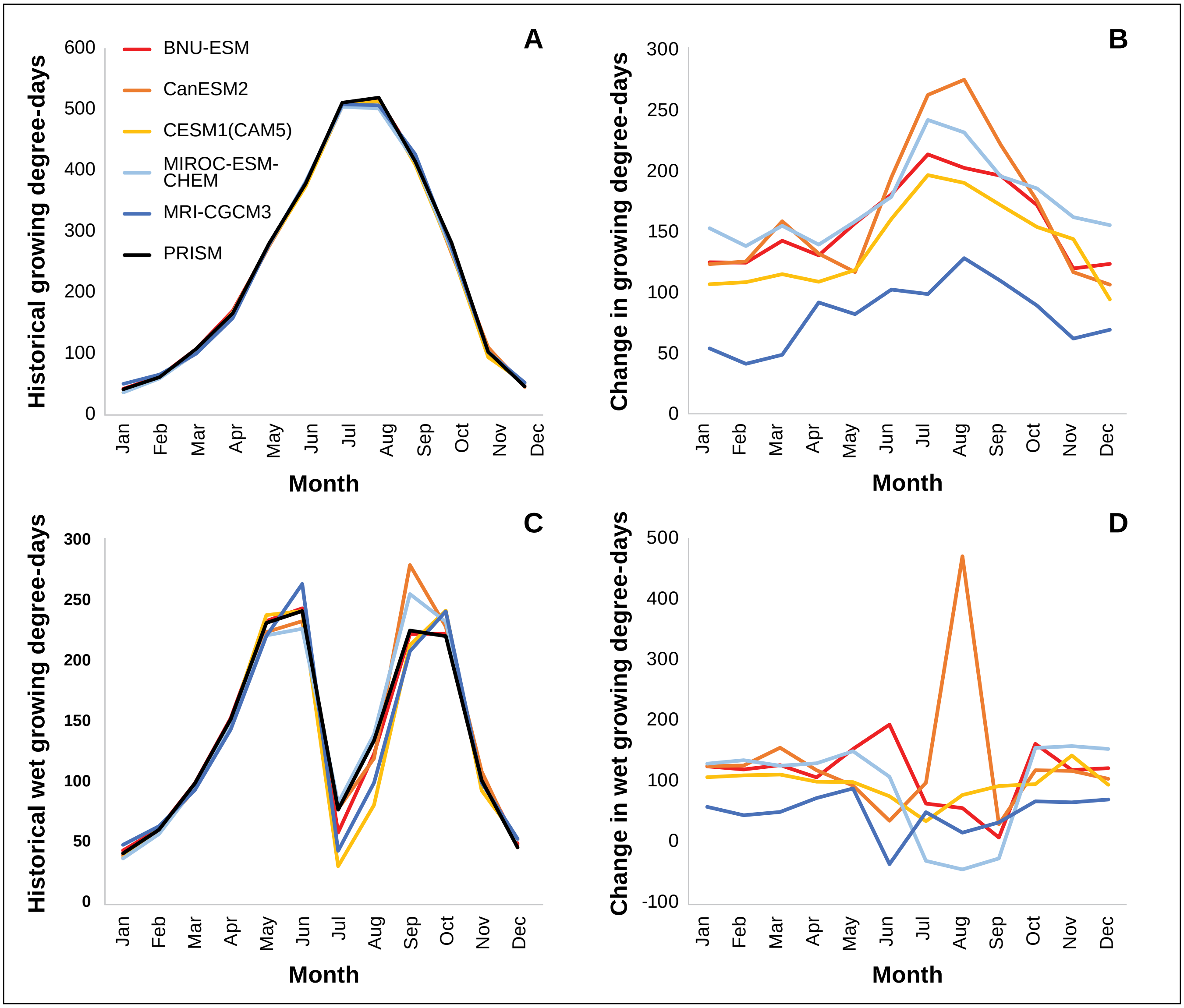


Figure 2.15—(A and B) Monthly growing degree-days (GDD) (C and D) and wet growing degree-days (WGDD) for five selected global climate models for the Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest assessment area. Historical values (A and C) for GDD and WGDD were calculated from PRISM data (Daly et al. 2008) and from MC2 dynamic global vegetation model simulations for 1970–1999. Future projections (B and D) are under the Representative Concentration Pathway 8.5 emission scenario (van Vuuren et al. 2013) for 2070–2099.

with an extra 931 WGDD per year, a 96 percent increase. The “cool” MRI-CGCM3 has the smallest percentage change in annual WGDD, with a 36 percent increase. All models show an increase in WGDD in each season, with the largest absolute changes in spring and fall, but the largest percentage increase in winter. Each model suggests at least a doubling of winter WGDD, with four of the five projecting a tripling of the variable. The only projected decreases in WGDD were negligible and limited to the late summer to early fall in the MRI-CGCM3 model.

The increased GDD and WGDD projected for the CMWAP assessment area would generally produce more favorable climate conditions for plant growth. However, warmer temperatures may offset this. Accordingly, we examined projected climatic water deficit (CWD), which represents the amount by which potential evapotranspiration (PET) exceeds actual evapotranspiration (AET) and is a key indicator of drought stress (Stephenson 1998). CWD was calculated as an annual value, averaged by elevation bands (fig. 2.16). CWD is projected to increase markedly, with the largest percentage change above 1500 m where a 100 to 300 percent increase may occur. This would make end-of-century water stress at tree line (~1800 m) comparable to current levels between 300 and 600 m. Moreover, at elevations above 2400 m, which currently average near zero CWD, water stress would increase.

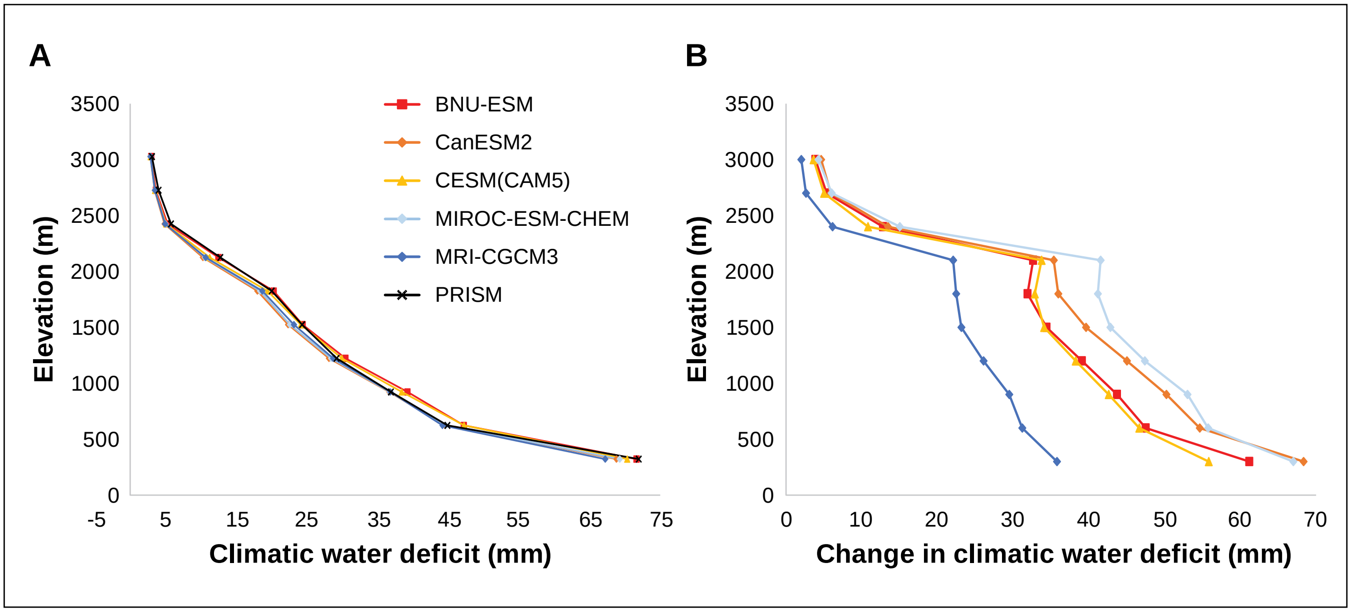


Figure 2.16—(A) climatic water deficit (CWD) for 1970–1999 and (B) projected change in CWD based on the five selected global climate models for the Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest assessment area. Data for the historical period were calculated from PRISM (Daly et al. 2008) and from the MC2 dynamic global vegetation model output for 1970–1999. Future projections (B) are under the Representative Concentration Pathway 8.5 emission scenario (van Vuuren et al. 2013) for 2070–2099.

Chapter Summary and Conclusions

Average annual temperature has increased by nearly 1.5 °C since 1895 within the CMWAP assessment area. Under the RCP 8.5 scenario, the GCMs analyzed suggest that temperature will continue to increase throughout the 21st century, with the rate of warming accelerating in the latter half of the century. Overall, the model ensemble average suggests a 4.5 °C annual temperature increase, with individual models ranging from a 2.6 to 6.0 °C increase by the end of the century (2070–2099). However, there is considerable variability among the GCMs in both the magnitude of temperature increase and precipitation changes. All GCMs project an increase in annual mean temperature, with the most warming in summer and least in winter. In general, the models project either a minimal increase in precipitation or no significant change. However, seasonal amplification of precipitation is a common theme in the GCMs; most models simulate slightly wetter conditions during mid-winter and drier summers.

With rising temperatures, the growing season length is expected to increase markedly. Below 1800 m, the growing season could become year-round, with freeze events rare to nonexistent. Even at the highest elevations within the CMWAP assessment area, the growing season could extend to nearly 9 months in areas where snow cover and alpine tundra currently exist. In addition, warmer temperatures will result in more precipitation falling as rain at high elevations, a substantial decline in mountain snowpack, earlier snowmelt, and a decrease in summer streamflow (see chapter 3). Higher temperatures more favorable for plant growth may be offset by a doubling of CWD expected with climate change. In each season, projected climate changes would transform the CMWAP area climate to one with no modern-period analog.

Literature Cited

Abatzoglou, J.T.; Rupp, D.E.; Mote, P.W. 2014. Seasonal climate variability and change in the Pacific Northwest of the United States. Journal of Climate. 27: 2125–2142.

Bumbaco, K.A.; Dello, K.D.; Bond, N.A. 2013. History of Pacific Northwest heat waves: synoptic pattern and trends. Journal of Applied Meteorology and Climatology. 52: 1618–1631.

Cobb, K.M.; Charles, C.D.; Edwards, R.L. [et al.]. 2003. El Nino/Southern Oscillation and the tropical Pacific climate during the last millennium. Nature. 424: 271–276.

Cook, E.R.; Woodhouse, C.A.; Eakin, C.M. [et al.]. 2004. Long-term aridity changes in the western United States. Science. 306: 1015–1018.

Daly, C.; Conklin, D.R.; Unsworth, M.H. 2009. Local atmospheric decoupling in complex topography alters climate change impacts. International Journal of Climatology. 30. 1857–1864.

Daly, C.; Halbleib, M.; Smith, J.I. [et al.]. 2008. Physiographically sensitive mapping of climatological temperature and precipitation across the conterminous United States. International Journal of Climatology. 28: 2031–2064.

Diaz, H.F.; Eischeid, J.K. 2007. Disappearing "alpine tundra" Köppen climatic type in the Western United States. Geophysical Research Letters. 34: L18707.

Durack, P.J.; Wijffels, S.E.; Matear, R.J. 2012. Ocean salinities reveal strong global water cycle intensification during 1950 to 2000. Science. 336: 455–458.

Figueres, C.; Le Quéré, C.; Mahindra, A.; Bäte, O. 2018. Emissions are still rising: ramp up the cuts. Nature. 564: 27–30.

Gergel, D.R.; Nijssen, B.; Abatzoglou, J.T. [et al.]. 2017. Effects of climate change on snowpack and fire potential in the Western USA. Climatic Change. 141: 287–299.

Gutman, N.B.; Quayle, R.G. 1996. A historical perspective of U.S. climate divisions. Bulletin of the American Meteorological Society. 77: 293–304.

International Panel on Climate Change [IPCC]. 2014. Summary for policymakers. In: Field, C.B.; Barros, V.R.; Dokken, D.J. [et al.], eds. Climate change 2014: impacts, adaptation, and vulnerability. Part A: Global and sectoral aspects. Contribution of working group II to the fifth assessment report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY: Cambridge University Press: 1–32.

Lehner, F.; Coats, S.; Stocker, T.F. [et al.]. 2017. Projected drought risk in 1.5 °C and 2 °C warmer climates. Geophysical Research Letters. 44: 7419–7428.

Li, D.; Wrzesien, M.L.; Durand, M. [et al.]. 2017. How much runoff originates as snow in the western United States, and how will that change in the future. Geophysical Research Letters. 44: 6163–6172.

Luce, C.H.; Abatzoglou, J.T.; Holden, Z.A. 2013. The missing mountain water: slower westerlies decrease orographic enhancement in the Pacific Northwest USA. Science. 342: 1360–1364.

McCabe, G.J.; Dettinger, M.D. 1999. Decadal variations in the strength of ENSO teleconnections with precipitation in the western United States. International Journal of Climatology. 19: 1399–1410.

McCabe, G.J.; Legates, D.R. 1995. Relationships between 700 hPa height anomalies and 1 April snowpack accumulations in the western United States. International Journal of Climatology. 15: 517–530.

McMaster, G.S.; Wilhelm, W.W. 1997. Growing degree-days: one equation, two interpretations. Agricultural and Forest Meteorology. 87: 291–300.

McPhaden, M.J.; Busalacchi, A.J.; Cheney, R. [et al.]. 1998. The tropical ocean-global atmosphere observing system: a decade of progress. Journal of Geophysical Research: Oceans. 103: 14169–14240.

Miller, J.A.; Goodrich, G.B. 2007. Regionalization and trends in winter precipitation in the northwestern USA. Climate Research. 33: 215–227.

Moss, R.H.; Edmonds, J.A.; Hibbard, K.A. [et al.]. 2010. The next generation of scenarios for climate change research and assessment. Nature. 463: 747–756.

Mote, P.W. 2003. Trends in snow water equivalent in the Pacific Northwest and their climatic causes. Geophysical Research Letters. 30: 1601.

Mote, P.W.; Hamlet, A.F.; Clark, M.P.; Lettenmaier, D.P. 2005. Declining mountain snowpack in western North America. Bulletin of the American Meteorological Society. 86: 39–49.

Mote, P.W.; Li, S.; Lettenmaier, D.P. [et al.]. 2018. Dramatic declines in snowpack in the Western U.S. npj Climate and Atmospheric Science. 2: 1–6.

Mote, P.W.; Parson, E.A.; Hamlet, A.F. [et al.]. 2003. Preparing for climatic change: the water, salmon, and forests of the Pacific Northwest. Climatic Change. 61: 45–88.

Newman, M.; Alexander, M.A.; Ault, T.R. [et al.]. 2016. The Pacific Decadal Oscillation, revisited. Journal of Climate. 29: 4399–4427.

Oyler, J.W.; Dobrowski, S.Z.; Ballantyne, A.P. [et al.]. 2015. Artificial amplification of warming trends across the mountains of the western United States. Geophysical Research Letters. 42: 153–161.

Pepin, N.C.; Bradley, R.S.; Diaz, H.F. [et al.]. 2015. Elevation-dependent warming in mountain regions of the world. Nature Climate Change. 5: 424–430.

Pepin, N.C.; Lundquist, J. 2008. Temperature trends at high elevations: patterns across the globe. Geophysical Research Letters. 35: L14701.

Rangwala, I.; Miller, J.R. 2012. Climate change in mountains: a review of elevation-dependent warming and its possible causes. Climatic Change. 114: 527–547.

Rangwala, I.; Sinsky, E.; Miller, J.R. 2013. Amplified warming projections for high altitude regions of the northern hemisphere mid-latitudes from CMIP5 models. Environmental Research Letters. 8: 1–9.

Redmond, K.T.; Koch, R.W. 1991. Surface climate and streamflow variability in the western United States and their relationship to large-scale circulation indices. Water Resources Research. 27: 2381–2399.

Ritchie, J.; Dowlatabadi, H. 2017. Why do climate change scenarios return to coal? Energy. 140: 1276–1291.

Rupp, D.E.; Abatzoglou, J.T.; Hegewisch, K.C.; Mote, P.W. 2013. Evaluation of CMIP5 20th century climate simulations for the Pacific Northwest USA. Journal of Geophysical Research: Atmospheres. 118: 10884–10906.

Seager, R.; Kushnir, Y.; Herweijer, C. [et al.]. 2005. Modeling of tropical forcing of persistent droughts and pluvials over western North America: 1856–2000. Journal of Climate. 18: 4065–4088.

Siler, N.; Proistosescu, C.; Po-Chedley, S. 2018. Natural variability has slowed the decline in Western U.S. snowpack since the 1980s. Geophysical Research Letters. 46: 346–355.

Sproles, E.A.; Roth, T.R.; Nolin, A.W. 2017. Future snow? A spatial-probabilistic assessment of the extraordinarily low snowpacks of 2014 and 2015 in the Oregon Cascades. The Cryosphere. 11: 331–341.

Stahle, D.W.; Fye, F.K.; Cook, E.R.; Griffin, R.D. 2007. Tree-ring reconstructed megadroughts over North America since A.D. 1300. Climatic Change. 83: 133–149.

Stephenson, N. 1998. Actual evapotranspiration and deficit: biologically meaningful correlates of vegetation distribution across spatial scales. Journal of Biogeography. 25: 855–870.

Stewart, I.T.; Cayan, D.R.; Dettinger, M.D. 2005. Changes toward earlier streamflow timing across western North America. Journal of Climate. 18: 1136–1155.

Stoelinga, M.T.; Albright, M.D.; Mass, C.F. 2010. A new look at snowpack trends in the Cascade Mountains. Journal of Climate. 23: 2473–2491.

Strachan, S.; Daly, C. 2017. Testing the daily PRISM air temperature model on semiarid mountain slopes. Journal of Geophysical Research-Atmospheres. 122: 5697–5715.

Taylor, K.E.; Stouffer, R.J.; Meehl, G.A. 2012. An overview of CMIP5 and the experiment design. Bulletin of the American Meteorological Society. 93: 485–498.

Thrasher, B.; Xiong, J.; Wang, W. [et al.]. 2013. Downscaled climate projections suitable for resource management. Eos, Transactions, American Geophysical Union. 94: 321–323.

van Vuuren, D.P.; Edmonds, J.; Kainuma, M. [et al.]. 2011. The Representative Concentration Pathways: an overview. Climatic Change. 109: 5–31.

Vose, R.S.; Easterling, D.R.; Gleason, B. 2005. Maximum and minimum temperature trends for the globe: an update through 2004. Geophysical Research Letters. 31: L23822.

Vuille, M.; Bradley, R.S. 2000. Mean annual temperature trends and their vertical structure in the tropical Andes. Geophysical Research Letters. 27: 3885–3888.

Wang, J.; Feng, L.; Tang, X.; Bentley, Y. 2017. The implications of fossil fuel supply constraints on climate change projections: a supply-side analysis. Futures. 86: 58–72.

Westerling, A.L.; Hidalgo, H.G.; Cayan, D.R.; Swetnam, T.W. 2006. Warming and earlier spring increase Western U.S. forest wildfire activity. Science. 313: 940–943.

Western Regional Climate Center [WRCC]. 2019. Oregon cooperative climatological data summaries. https://wrcc.dri.edu/summary/Climsmor.html. (11 February 2019).

Yan, H.; Sun, N.; Wigmosta, M. [et al.]. 2019. Observed spatiotemporal changes in the mechanisms of extreme water available for runoff in the Western United States. Geophysical Research Letters. 46: 767–775.

Zachariassen, J.; Zeller, K.; Nikolov, N.; McClelland, T. 2003. A review of the Forest Service remote automated weather station (RAWS) network. Gen. Tech. Rep. RMRS-GTR-119. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 153 p. + CD.

Chapter 3: Climate Change Effects on Water Resources and Infrastructure

Caty F. Clifton, Charles H. Luce, Robert W. Hoyer, Johan Hogervorst, Diane Hopster, Todd Reinwald, Jessica E. Halofsky, Brian P. Staab, Joy Archuleta, Helmut Kreidler, and Jamie Alonso Sheahan[1]

Overview of Climate Change Effects on Hydrologic Processes

Climate change will affect physical hydrological processes and resource values that are influenced by hydrology, including water available for human uses, water quality, roads, and developed infrastructure. Climate change is likely to alter the amount, timing, and type of precipitation, resulting in less snow, receding glaciers, more winter precipitation as rain, earlier snowmelt, and less summer precipitation (Dalton et al. 2017, Holden et al. 2018, Luce et al. 2013, Mote et al. 2018) (chapter 2). Anticipated streamflow changes include higher winter peak-flow events associated with increased rain and rain-on-snow in middle to higher elevations. Higher peak flows will also mean overall declines in summer baseflows, with consequences for stream channels and physical aquatic habitat. Hydrologic effects will vary across watersheds as topographic and geologic variability mediate some expected changes. Slower groundwater recession in areas with younger, more permeable volcanic rocks may dampen peak flow increases and summer low-flow declines. Increasing temperature and changes in the amount and timing of precipitation and runoff will also affect water quality, water availability, soils, and vegetation, with broad implications for water resource management.

This chapter summarizes hydrologic processes, historical trends in snowpack, peak and low streamflow, and the projected effects of climate change on hydrologic parameters in the Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest Adaptation Partnership (CMWAP) assessment area. It also outlines the effects of altered hydrology on water resources (water uses, water quality), roads, and infrastructure.

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[1] **Caty F. Clifton** is a hydrologist (retired), **Brian P. Staab** is the regional hydrologist, and **Joy Archuleta** is the water quality and water rights program manager, Pacific Northwest Region, 1220 SW 3rd Avenue, Portland, OR 97204; **Charles H. Luce** is a research hydrologist, Rocky Mountain Research Station, 322 East Front Street, Suite 401, Boise, ID 83702; **Robert W. Hoyer** is a climate change program associate, Pacific Northwest Region and Pacific Northwest Research Station, Forestry Sciences Laboratory, 1220 SW 3rd Avenue, Portland, OR 97204; **Johan Hogervorst** is the forest hydrologist and **Helmut Kreidler** is the assistant forest engineer, Willamette National Forest, 3106 Pierce Parkway Suite D, Springfield, OR 97477; **Diane Hopster** is a hydrologist, Columbia River Gorge National Scenic Area, 902 Wasco Avenue, Suite 200, Hood River, OR 97031; **Todd Reinwald** is the watershed program manager, Mount Hood National Forest, 16400 Champion Way, Sandy, OR 97055; **Jessica E. Halofsky** is the director, Western Wildland Environmental Threat Assessment Center and Northwest Climate Hub, Pacific Northwest Research Station, 3625 93rd Avenue SW, Olympia, WA 98512; **Jamie Alonso Sheahan** is a hydrologist, Willamette National Forest, Detroit Ranger District, 44125 North Santiam Highway SE, Detroit, OR 97342.

Landscape Setting

The Columbia River Gorge and Oregon Cascade Range are rugged, complex, and dynamic landscapes extending from the deeply carved canyon sides of the Columbia River, where it bisects the Cascade Range, south along the crest of the young High Cascades from Mount Hood to Diamond Peak, and westward to the forested ridges and valleys underlain by older western Cascade volcanics bounding the Willamette Valley. Elevations range from sea level on the Columbia River (tidal influenced to Bonneville Dam) to 3419 m on Mount Hood. The area includes the section of the Lower Columbia River between the lower Klickitat River and Wind River in Washington, the Lower Deschutes River and Sandy River in Oregon, and major tributaries to the Willamette River, including the Clackamas River, Santiam River, McKenzie River, and Middle Fork Willamette River.

Columbia Gorge landforms include late Miocene basalt lava flows of the Columbia River Basalt Group from vents in eastern Oregon and Washington. These are overlain by Miocene to Quaternary river gravels, younger volcanic deposits from the Cascade Range, and more recent landslides and landslide complexes. Uplift and deformation further altered the river corridor, and landslides and landslide complexes are common (O’Conner and Burns 2009). The Cascade Range is composed almost entirely of volcanic and volcaniclastic rocks with two major subdivisions, the Western and High Cascades, and is stratigraphically complex, having formed in a subduction zone environment. The resulting volcanic and sedimentary units represent different depositional environments, including lava flows, ash flows, and large-volume debris flows. The oldest rocks are in the southern and western portion of the Cascade Range, and the youngest rocks are in the High Cascades (Sherrod and Smith 2000).

Pleistocene glaciation and massive glacial outburst floods shaped the region, from the sculpted peaks and ridges in the High Cascades to the Missoula flood features in the Columbia Gorge and Willamette River basin. Tectonic and volcanic activity continue to modify landforms, including recent landslides in the Columbia Gorge and young lava flows in the High Cascades. Geologic history, bedrock properties, and geomorphic context influence hydrology and groundwater dynamics and geomorphic processes. Characteristics of the High Cascades and Western Cascades strongly influence the hydrology of the CMWAP assessment area. In the High Cascades, with several peaks over 3000 m, deep snowpacks last into spring and early summer. Areas with highly permeable bedrock provide greater storage volume and longer recession during spring and winter high-flow periods, as well as higher baseflows. Young lava flows lack stream dissection, and many channels are formed by spring systems sustained from groundwater aquifers. The middle elevations of the Western Cascades have shallow and brief snowpacks, and the lower elevations see only rain with occasional, short-lived snowfall. Older dissected and less permeable bedrock generally has shallower flow paths, less storage, and shorter recession, with lower baseflows.

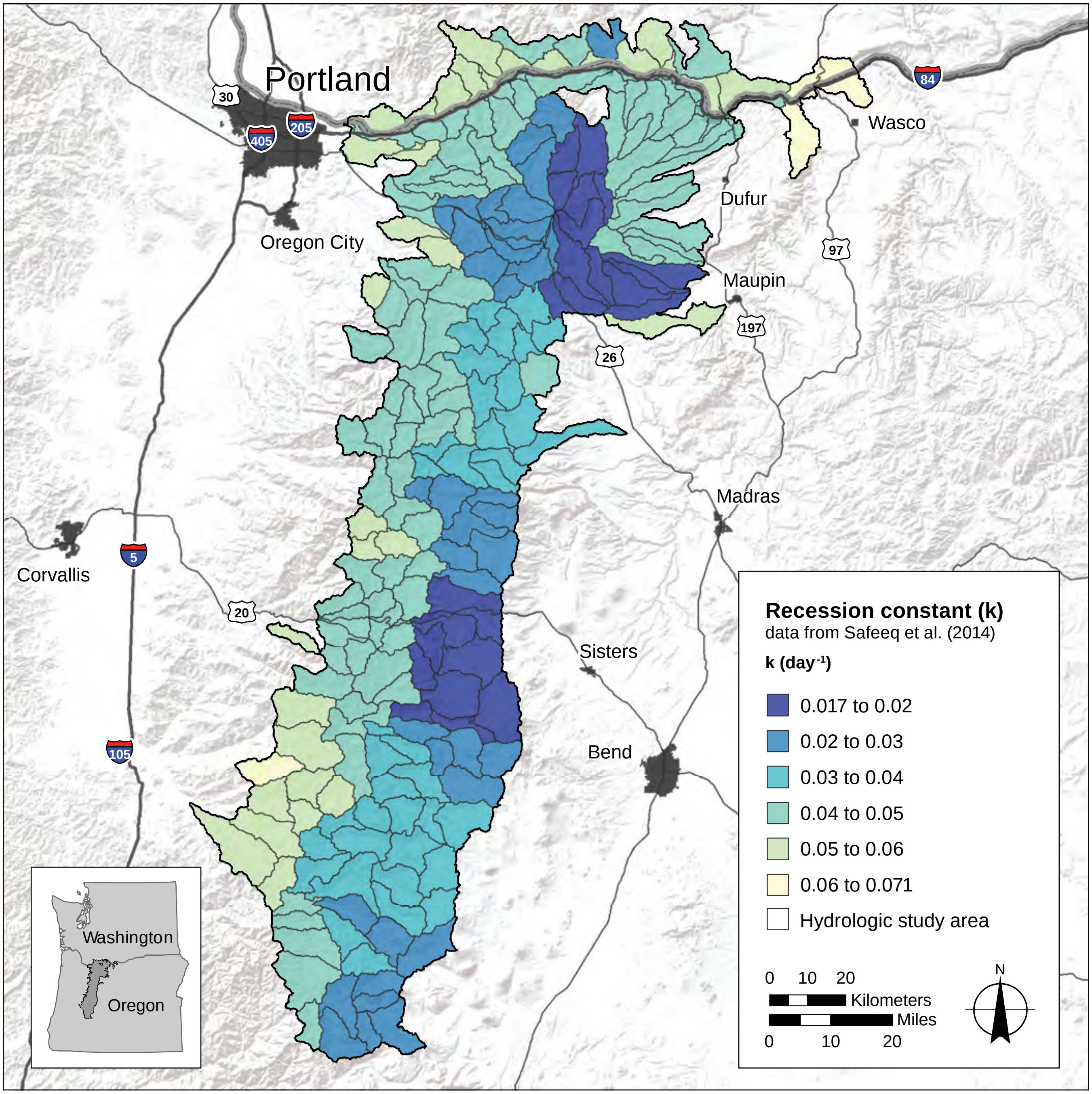

Figure 3.1—Recession constant (k) across the Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest assessment area. The inverse of k, or 1/k, is the number of days for the flow rate to fall to 1/e from an initial flow rate (e is Euler's number used in natural logarithms and has a value of 2.71828). Small k values have longer recession, in this case about 6 weeks, whereas higher k values reflect about a 2-week recession to 1/e times original flow. The longest recessions are mapped in the younger volcanics of the High Cascades subprovince in the vicinity of Mount Hood and the Upper McKenzie River.

Differences in geology and hydrogeology are reflected spatially in the recession constant "k," derived by Safeeq et al. (2013, 2014) and used in streamflow calculations described below (fig. 3.1). The k constant has units of fraction per day and shows places with faster recession (higher values of k) that drain more rapidly relative to total storage, and places with slower recession (lower values of k) that drain more slowly relative to total storage. Much of the assessment area (Western Cascades) has moderate groundwater storage that is more sensitive to shifts in the timing of water inflow (Stewart et al. 2005). The deeper aquifers of the High Cascades, with low k values (slower recession, greater storage relative to outflow rates), are less sensitive in terms of percentage changes to a shift in timing of inflow but can be sensitive in terms of absolute flow. Some of the locally deepest aquifers and springs have long enough storage times that shifts in snowmelt timing have almost no effect on late-season baseflows. However, these areas are sensitive to longer term trends in annual precipitation amounts (e.g., Luce et al. 2013).

Streamflow Response Calculations

We estimated climate-induced changes in streamflow for the CMWAP assessment area using the variable infiltration capacity (VIC) model (Liang et al. 1994), modified to account for deeper storage. The VIC model calculates snow accumulation and melt, runoff generation, and evaporation on large grid cells (1/16th degree) using elevation bands and discretization (converting continuous data into a finite set of intervals) across vegetation types to describe the heterogeneity within cells. The data used in this assessment are derived from VIC projections developed by the Climate Impacts Group at the University of Washington (https://cig.uw.edu/datasets/wus) (Littell et al. 2014). The runoff generated within VIC cells was apportioned to streams based on fractional contributions in each catchment following Wenger et al. (2010).

The VIC model was calibrated to large watersheds. Although the groundwater parameters are some of the most important to VIC calibration (Mattheusen et al. 2000), the large calibration units do little to inform local watershed groundwater behavior. Given the importance of groundwater to low flows in portions of the assessment area, we modified the catchment-scale routing process used by Wenger et al. (2010) to account for local information on groundwater storage and discharge based on k values (fig. 3.1). Specifically, we applied the k values to generate a unit hydrograph routing kernel by each unit for which k was calibrated. The groundwater recession properties explained in Tague and Grant (2009) and Safeeq et al. (2013, 2014) are fully consistent with the unit hydrograph approach, so the k estimates from the long summer recessions are appropriate for direct application. Each day's runoff from VIC was apportioned outflow timing based on each basin's k value, and the flow apportionments from each preceding day were summed to obtain the current day's streamflow.

Estimates of peak flows were obtained from VIC outputs without incorporating groundwater recession properties (k factor), because geologically mediated flow paths are less direct and not easily characterized or calibrated for high flows. Unmodified VIC outputs are also more informative as a measure of the degree to which rain-on-snow events are increasing midwinter flooding. Peak flow estimates in areas of low k recession in the High Cascades (fig. 3.1) may be dampened by groundwater storage, with lower peaks than projected. The version of VIC that we used does not simulate the effects of glaciers, which contribute to runoff in areas around Mount Hood, Mount Jefferson, and the Three Sisters, further complicating peak flow and baseflow estimates from those locations.

Snowpack and Glacier Changes

One of the principal changes expected in the hydrology of Western U.S. mountains is altered snowpacks with less snow accumulation and earlier snowmelt (Barnett et al. 2008). Snowpack declines have already been observed across the Western United States (Mote et al. 2018). Snow storage can be viewed as the amount of water stored in the snowpack and how long the snow lasts. The amount of water in the snowpack is represented as snow water equivalent (SWE) on April 1st, and duration is represented as snow residence time (SRT) (Luce et al. 2014). The SWE on April 1st is a widely used indicator of water availability for the coming spring runoff and irrigation season. The SRT is the amount of time that any new snow will last. Snow residence time in the range of a few weeks is generally associated with rapid accumulation and melt cycles, indicating transient snowpacks often associated with rain-on-snow events (e.g., Nolin and Daly 2006).

Changes in snowpack are expected across the CMWAP assessment area, ranging from a complete loss in the lower and middle elevations to significant declines in SWE and SRT at higher elevations (figs. 3.2, 3.3A, and 3.3B). Snow is already mostly absent or ephemeral in the western areas at lower elevations, and in these locations, warming temperatures will not change SWE or SRT in absolute terms, because there is little snow to lose. Middle-elevation ridges and peaks may maintain snowpack despite the “no-snow” display because of temperature averaging within the 4-km grid cells. For the upper elevations along the crest and peaks of the Cascades, average SRT is expected to decline by 8 to 10 weeks (>50 percent) relative to current SRT by 2080.

Receding mountain glaciers are an early indicator of warming climate documented in ground-based and aerial repeat photography. Recent work in the Pacific Northwest describes glacier loss and changes in runoff contributions to streamflow (Frans et al. 2018). In the Oregon Cascades, there are three concentrations of remnant glaciers around peaks over 3000 m (Mount Hood, Mount Jefferson, and Three Sisters) (Fountain et al. 2017, Ohlschlager 2012). Increasing rates of glacier recession in these areas may influence streamflow volume and variability (Fountain and Tangborn 1985), and glacier melt may buffer some effects of seasonal snowpack loss on decreasing summer flows. On Mount Hood, declines in glacier areal extent from 1907 to 2016 ranged from 15 percent (Coe Glacier) to

61 percent (White River Glacier) (table 3.1, figs. 3.4 and 3.5). Shrinking glaciers also leave unconsolidated glacial outwash debris and oversteepened slopes more susceptible to outburst floods, landslides, and debris flows (Moore et al. 2009, Walder and Dreidger 1995).

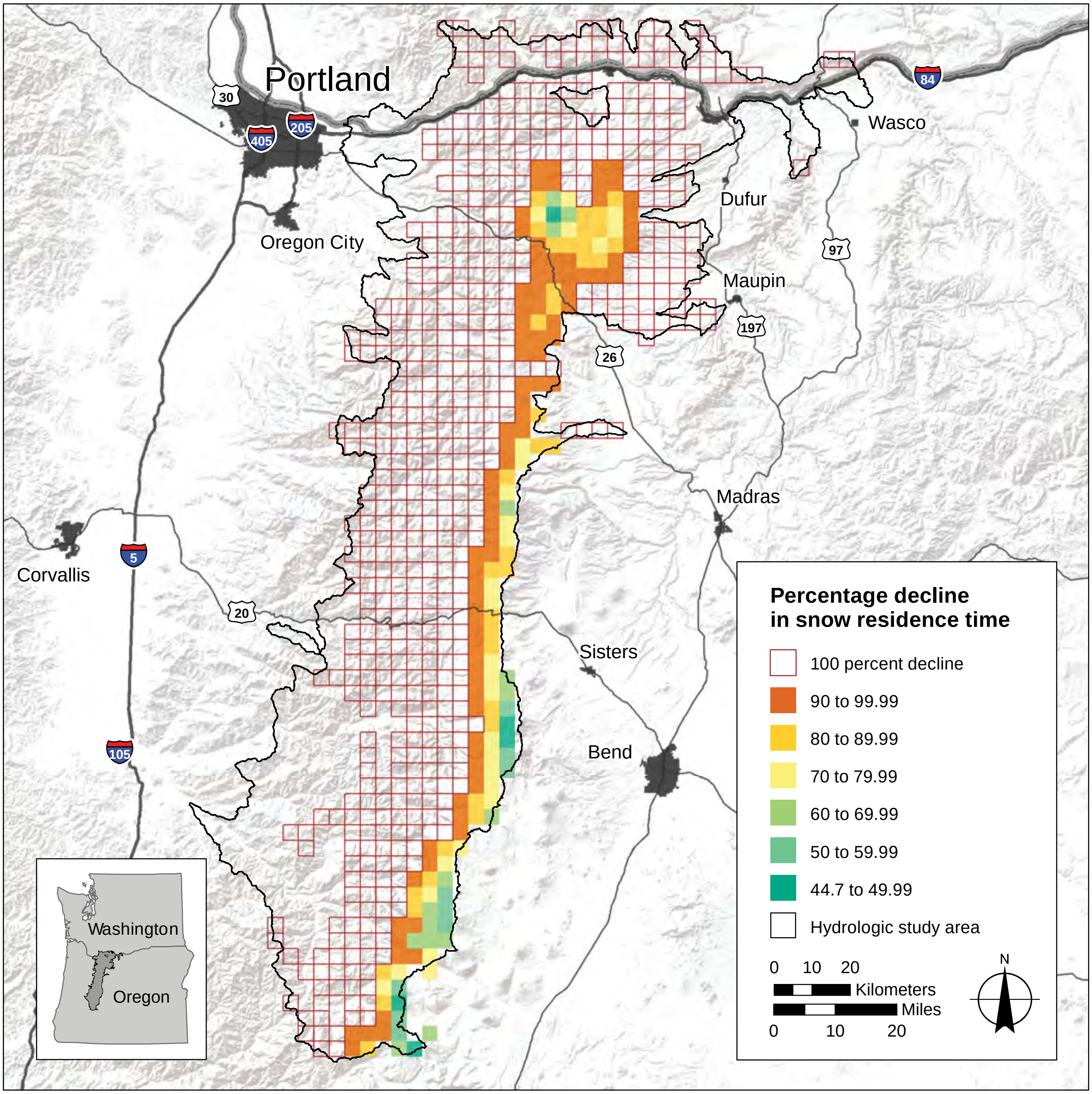

Figure 3.2—Projected percentage change in April 1 snow water equivalent between a historical period (1975–2005) and the 2080s (2071–2090) under Representative Concentration Pathway 8.5. From National Forest Climate Change Maps (https://www.fs.fed.us/rm/boise/AWAE/projects/national-forest-climate-change-maps.html).

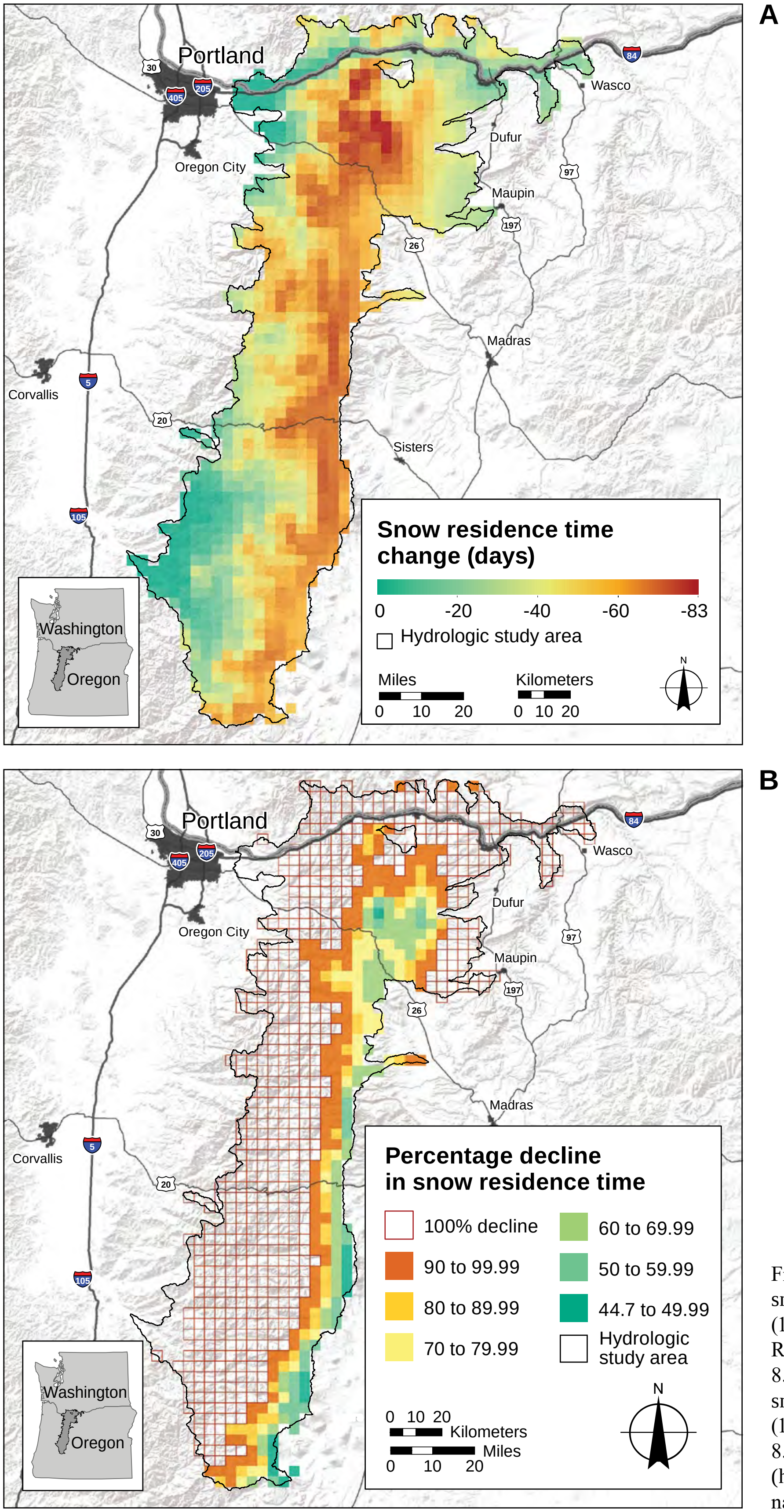

Figure 3.3—(A) Projected absolute change in snow residence time between a historical period (1975–2005) and the 2080s (2071–2090) under Representative Concentration Pathway (RCP) 8.5; and (B) projected percentage change in snow residence time between a historical period (1975–2005) and the 2080s (2071–2090) under RCP 8.5. From National Forest Climate Change Maps (https://www.fs.fed.us/rm/boise/AWAE/projects/national-forest-climate-change-maps.html).

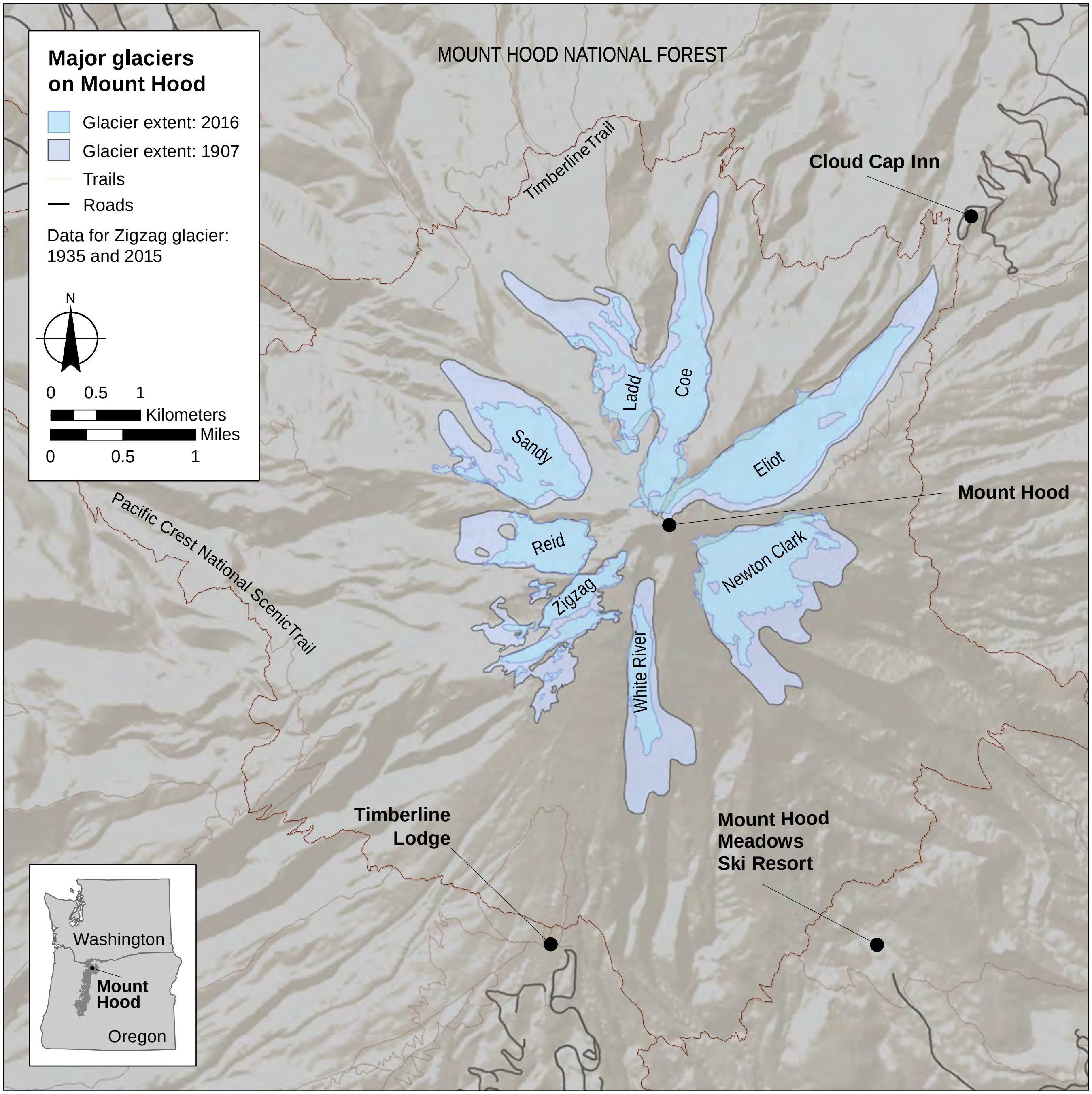

Figure 3.4—Glacier recession on Mount Hood between 1907 and 2016, based on mapping of aerial extent from historical photos and field mapping. Source: https://glaciers.us/glaciers.research.pdx.edu/index.html.

Figure 3.5—Documentation from the Glacier RePhoto Project (http://rephoto.glaciers.us) on retreating Eliot Glacier on Mount Hood. Photo taken at station #999 by Harry F. Reid, National Snow and Ice Data Center (23 July 1901), and by Hassan Basagic, Glacier RePhoto Project (4 October 2014).

Table 3.1—Estimated change in glacier area during the 20th century (1907–2016)

Mountain(s)	Glacier	Estimated areal percentage of change[a]
Mount Hood	Eliot	-18
	Coe	-15
	Ladd	-37
	Newton Clark	-32
	Reid	-36
	Sandy	-40
	White River	-61
	Zigzag	-52
Three Sisters	Collier	-55
	Renfrew	-31
	Irving	-50
	Skinner	-57
	Eugene	-79
	Lost Creek	-25
	Clark	-60
	Linn (Deschutes NF)	-50
	Thayer (Deschutes NF)	-81
	Villard (Deschutes NF)	-62
	Hayden (Deschutes NF)	-31
	Diller (Deschutes NF)	-49
	Carver (Deschutes NF)	-86
	Prouty (Deschutes NF)	-41
	Lewis (Deschutes NF)	-46

Note: Data for Mount Jefferson are currently unavailable.

[a] Estimated areal percentage of change was calculated for the period 1907–2004 for Newton Clark, 1935–2015 for Zigzag, and 1900–2003 for Collier.

Source: Andrew Fountain lab, Portland State University (https://glaciers.us/glaciers.research.pdx.edu/index.html).

Changes in Low Flows

Pacific Northwest winters have warmed over the past 50 years (see chapter 2), and mountain precipitation has declined over the same period (Luce et al. 2013), resulting in smaller snowpacks that melt out earlier in the year with less recharge to aquifers. In response, a higher fraction of the total annual flow occurs earlier in the year, and summer flows have been decreasing (Kormos et al. 2016, Luce and Holden 2009, Safeeq et al. 2013, Stewart et al. 2005). Luce and Holden (2009) showed declines in some Pacific Northwest annual streamflow quantiles, including decreases in the 25th percentile flow (drought year flows) between 1948 and 2006. This means the driest 25 percent of years are getting drier. Summer precipitation has also declined in much of the West (Holden et al. 2018). Although not a substantial contribution to water supply in most of the Cascades, summer rains may

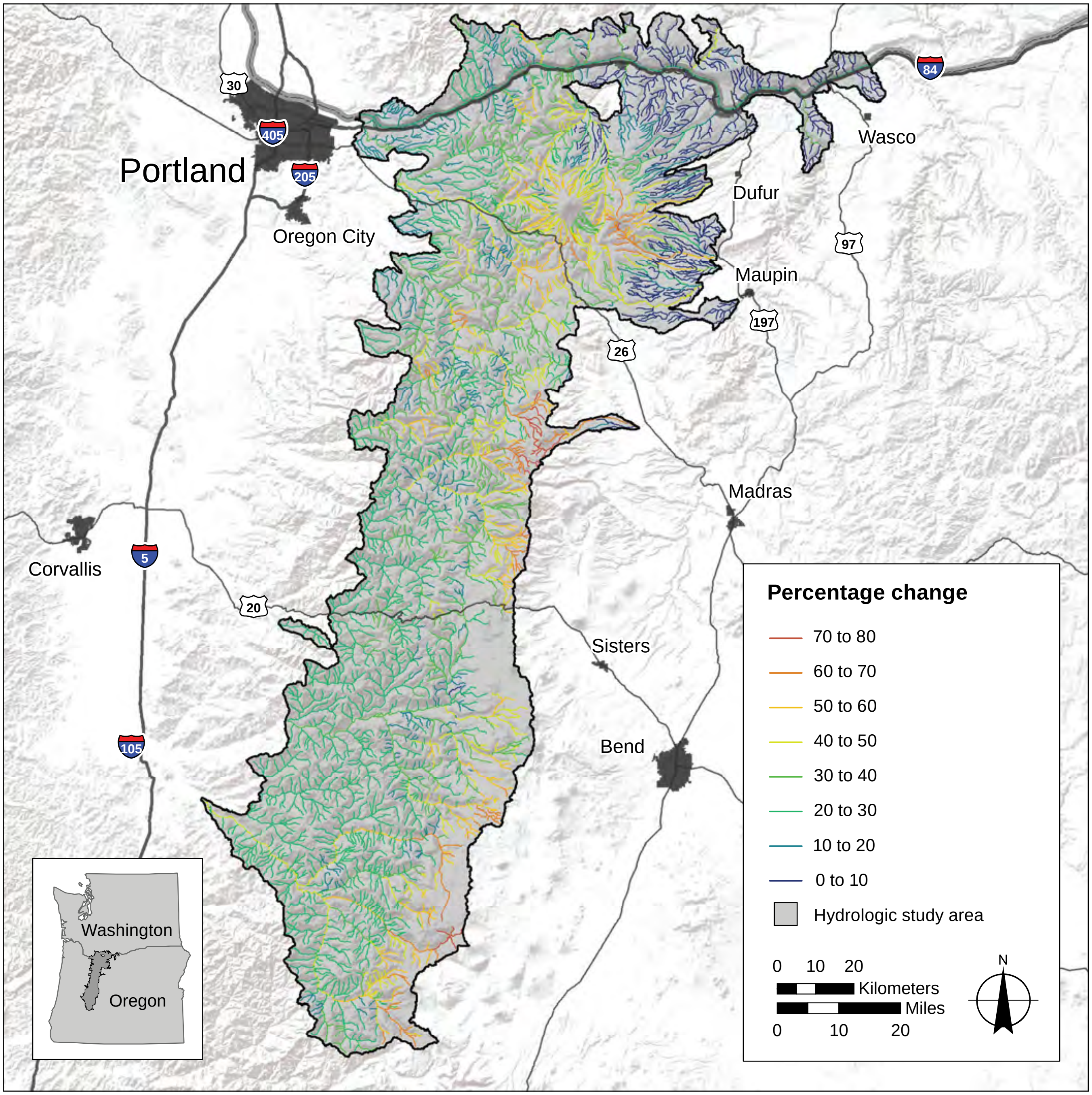

Figure 3.6—Projected percentage decrease in low flows between a historical period (1970–1999) and the 2080s under the A1B emission scenario. Projections are based on Variable Infiltration Capacity (VIC) model projections of surface water input changes filtered by a geologically based unit hydrograph. This modified version of VIC (with recession constant k) dampens low-flow decreases in areas of low k.

support late-season baseflows in low-elevation tributaries where snowmelt timing is less of a control (Chang et al. 2012).

Across much of the CMWAP assessment area where snow is not a large contributor to streamflow, small decreases in low flows are expected (fig. 3.6). Declines are greatest in higher elevations where the change in snowpack is greatest (figs. 3.2, 3.3A, and 3.3B). The biggest declines in low flows occur in High Cascade streams and some of the larger tributary rivers (Sandy River, Hood River, White River, Santiam River, Middle Fork Willamette River). The extent of large absolute change in SRT in the High Cascades (fig. 3.3A) indicates greater changes in low flows across these areas. Glacier recession is another factor influencing low flows in some areas, though not accounted for in the VIC modeling described here. Frans et al. (2018) indicated both positive and negative historical trends in summer streamflow in glacially influenced areas in the Pacific Northwest. Glacier mass balance, and therefore the area over which melt is generated, depends on a relatively long history of both precipitation and temperature variations (McCabe and Fountain 1995, Menounos et al. 2019, Stahl et al. 2008, Stahl and Moore 2006).

The drivers of summer low-flow declines include less winter snowpack and earlier melt, as mediated by landscape drainage efficiency, or how quickly landscapes convert recharge (precipitation) into discharge (Grant and Tague 2009, Safeeq et al. 2013). In essence, climatic conditions control the form of precipitation (snow versus rain), the amount converted to recharge, and the timing of this process. Geology and topography control when recharge is converted into streamflow. This analysis of low-flow sensitivity to climatic warming accounts for both major drivers.

In rain-dominated areas with minimal groundwater storage (higher k), streamflows recede quickly, resulting in prolonged periods of low flows in the region's dry summer and early fall. In transitional and snow-dominated areas that rely on snowmelt, groundwater storage (lower k) may continue to slow recession time, but overall, less snow and earlier melt will have a greater effect on the magnitude, timing, and duration of low flows.

Other factors influencing low flows include decreasing summer precipitation and extended dry periods. Although not a significant contributor to groundwater recharge, summer rain plays a part in supporting late-season flows in many lower elevation streams and rivers (Chang et al. 2012). Holden et al. (2018) showed that summer precipitation exerted a strong influence on wildfire area burned. Future expectations of even longer periods of consecutive dry days with little or no precipitation may further decrease summer streamflows and increase drought and fire risk (Luce et al. 2016, Walsh et al. 2014) (fig. 3.7). Changes in vegetation cover and water demand after wildfire or insect disturbance may temporarily increase water yield and low flows (e.g., Adams et al. 2012, Luce et al. 2012, Troendle et al. 2010, Vose et al. 2016), although the effects are generally localized and short term (e.g., Perry and Jones 2017). The overall picture for future summer water availability indicates less streamflow for extended periods. However, the picture is complicated by complex flow paths, interactions with disturbances, vegetation dynamics, and variable storage in soils and groundwater.

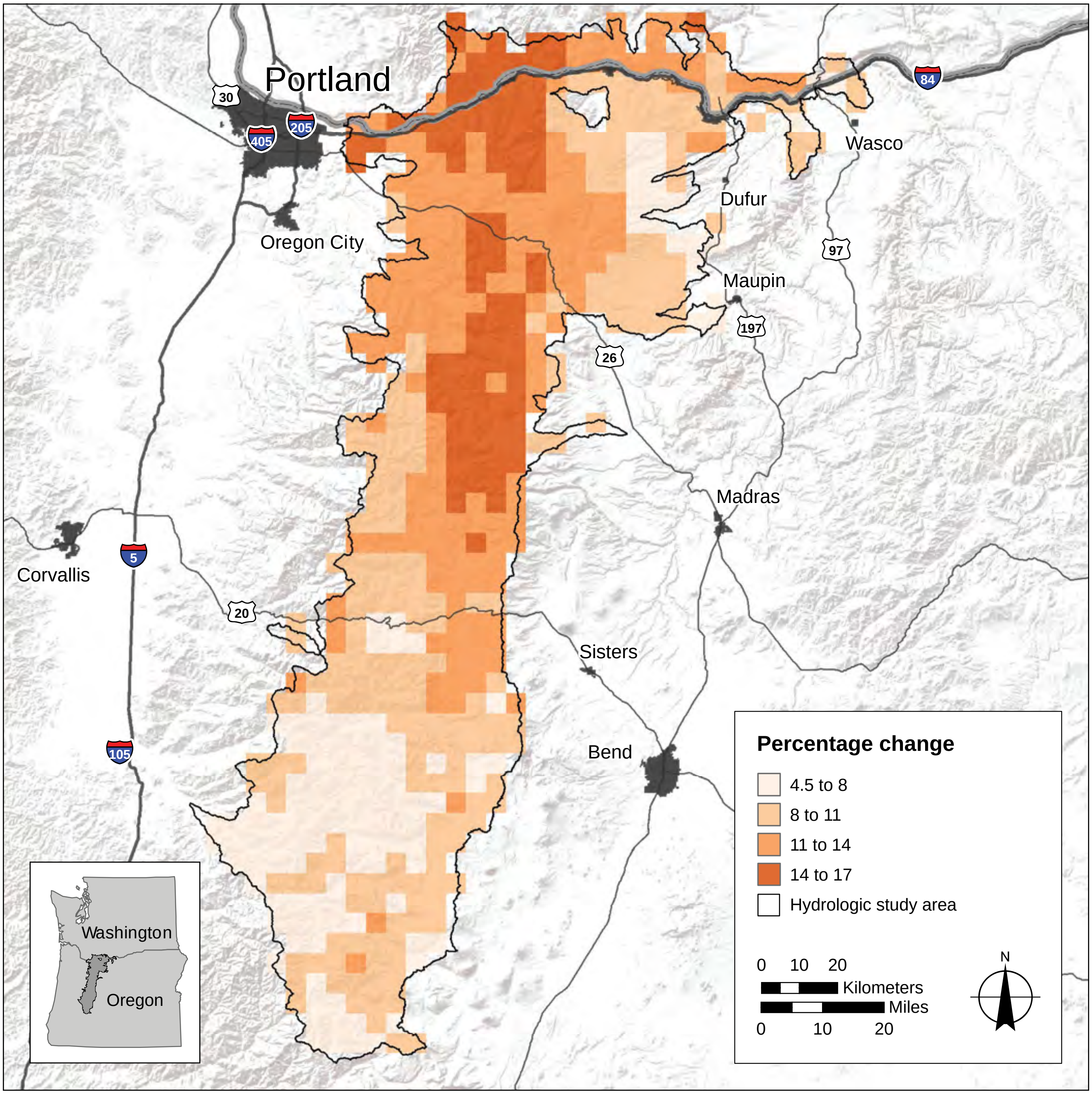

Figure 3.7—Projected changes in 90th percentile consecutive dry days (May–September). These changes were calculated by finding the greatest number of consecutive nonwetting rain days (>2.5 mm precipitation) for the historical period (1985–2004) compared to a future period centered on 2080s (2071–2090). The consecutive dry-day dataset was produced by the U.S. Forest Service Office of Sustainability and Climate using the mean output of 20 global climate models from MACAv2-METDATA downscaled data, under Representative Concentration Pathway 8.5 (https://climate.northwestknowledge.net/MACA/index.php).

Changes in Peak Flows

Flood regimes in the Pacific Northwest are sensitive to precipitation intensity, temperature effects on freezing elevation (whether precipitation falls as rain or snow), and the effects of precipitation and temperature on seasonal snow dynamics

(Hamlet and Lettenmaier 2007, Tohver et al. 2014). In general, flood regimes in the Columbia Gorge and Western Cascades are rain dominated in the lower to middle elevations, mixed rain and snow in the middle to higher elevations, and snow dominant at the highest elevations. Topography, basin size, geology, and land cover exert strong controls on the flood hydrology of individual rivers and streams (Safeeq et al. 2015).

Floods in the streams of the Columbia Gorge and Oregon Cascades occur in fall and winter following heavy rains or rain mixed with melting snow, and in spring during snowmelt. Summer thunderstorms can also produce local flooding. Rain-on-snow events, in which runoff from rainfall is mixed with melting snow, generate the most severe floods. Rain-on-snow flooding is partly caused by enhanced melt as moist air blows across the snow surface (Harr 1986, Marks et al. 1998, Tonina et al. 2008). More recently, it has been noted that rainfall contributions to such events are a primary driver (Wayand et al. 2015), with significant lateral routing occurring in the snowpack (Eiriksson et al. 2013, Rössler et al. 2014). Because most of the precipitation in the region occurs during winter months, increasing elevation of the snow-rain transition zone causes higher rainfall in landscapes where snowmelt has historically dominated. Rain-on-snow events tend to be much greater in magnitude, though briefer, than radiation-driven melt flooding (Goode et al. 2013). The seasonality shift of floods in these streams from spring to winter is critically important to fish species that spawn in fall months (e.g., bull trout [*Salvelinus confluentus* Suckley], Chinook salmon [*Oncorhynchus tshawytscha* Walbaum in Artedi]) because their eggs are still in the gravel where flood scour can affect them (Goode et al. 2013; Tonina et al. 2008; Wenger et al. 2011a, 2011b; chapter 4).

Under warmer conditions, lower elevation catchments, where rain is already the dominant flood-generating process, will be less affected than those at higher elevations, where the change from snowmelt-generated runoff to rainfall-generated runoff will promote higher flows. Some intermediate elevation basins, where rain-on-snow events are now relatively frequent, may also see little change in flooding, because there will be a transition to rain events without snow present to augment melt and routing speeds. Some lower elevation rivers draining higher elevation catchments will be affected by higher rain-on-snow contributions from upstream. Because loss of canopy can exacerbate melt enhancement and lateral routing distances during rain-on-snow events, a shift from winter snowfall to rainfall at higher elevation raises the elevation band where wildfire effects on flooding are most likely.

Peak-flow increases are notable across the CMWAP assessment area in middle to higher elevations and in main tributaries with the expansion of winter rain-on-snow events and greater contribution of winter rain to floods (fig. 3.8). Smaller streams in lower elevations in the western areas and east of Mount Hood do not show major

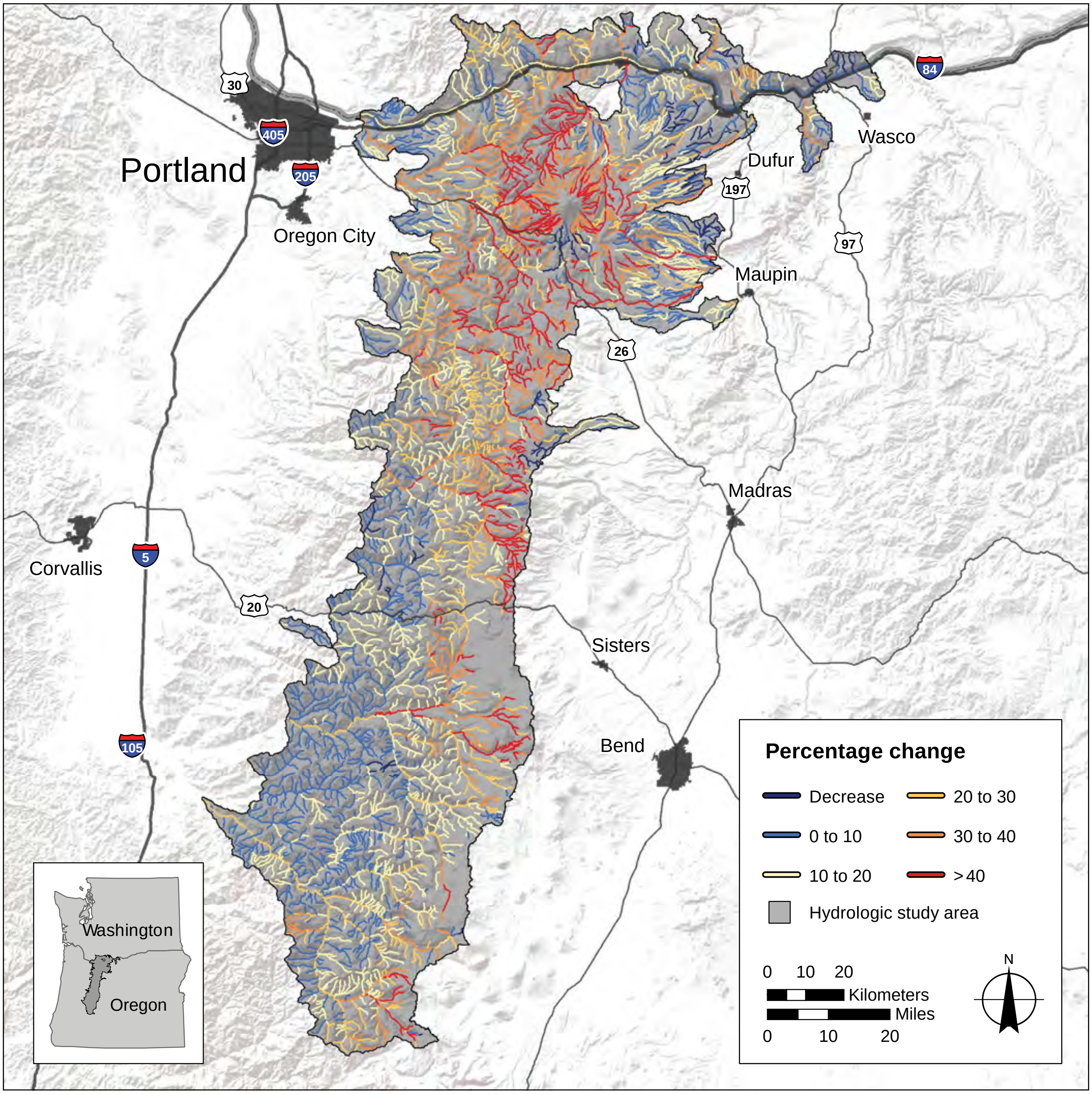

Figure 3.8—Projected percentage increase in peak flows between a historical period (1970–1999) and the 2080s under the A1B emission scenario, based on unmodified Variable Infiltration Capacity hydrologic modeling. Areas of low k recession may be overestimated (see fig. 3.1).

peak flow increases, because these areas remain rain dominated. There is some uncertainty in the absolute magnitude of peak-flow increases in the areas around Mount Hood and along the Cascade crest, where deep and permeable bedrock reduces the impacts of snowmelt changes on peak flows (Safeeq et al. 2015).

Changes in Hydrology, Water Resources, Roads, Infrastructure, and Access

Overview

Hydrologic effects of a warming climate include diminishing high-elevation snowpacks, receding glaciers, expansion of rain-dominated regions, an increase in elevation of rain-on-snow zones, declining summer low flows, extended summer dry periods, and changes in the timing and magnitude of peak flows. Climatic effects on streamflows are strongly influenced by topography and geology, with complex interactions at multiple scales. Groundwater storage in highly permeable bedrock mediates runoff extremes but will experience less snowmelt contribution over time, and areas adjoining melting glaciers may temporarily gain runoff with local flooding and sediment inputs. Places of greatest change for peak and low flows are in the middle to higher elevations and major low-elevation tributary rivers and streams. Effects to higher elevation areas will extend downstream into some larger rivers, including the Hood, Clackamas, Santiam, and McKenzie Rivers, and the Middle Fork of the Willamette River.

One of the key findings in the Fourth National Climate Assessment was that there is a high likelihood of chronic long-duration hydrologic drought as a result of reductions in snowpack and earlier melt (see chapter 8, key finding 5 in USGCRP 2017). Recent warm, low-snowpack years, such as 2015 in the Pacific Northwest, provide a glimpse into warmer futures and help to “daylight” the effects of future climate changes on hydrology and other resources (May et al. 2018). For example, the 2015 “snow drought” shortened the winter recreation season and reduced water allocation, with curtailed water use in many basins. Exacerbating the effects of decreased snowpack, longer summer dry spells without rain will amplify the level of drought experienced by forests and low-elevation streams, reducing streamflows and increasing wildfire risks and vulnerability to insects (Holden et al. 2018, Kolb et al. 2016, Littell et al. 2016, Luce et al. 2016).

Changes in hydrology with climate change affect multiple resources. Water scarcity, increased wildfire activity, and forest cover changes affect streamflow and water quality during critical times for fish. These factors also affect reservoir storage and operations, and recreation activities. Flooding in winter and spring affects vulnerable roads and infrastructure, and an extended snow-free season has increased access and impacts to roads and trails. The Willamette Water 2100 project, initiated to address climate change effects and socioeconomic pressures on future water supply and demand, addressed policy issues, such as instream flow protection and reservoir operations, linking biophysical and economic components modeled across the basin (Jaeger et al. 2017).

For the CMWAP assessment area, effects on water resources are described as potential changes to water uses and quality, roads, infrastructure, and access. Water resource vulnerabilities (risk and sensitivity) vary both spatially and temporally and depend on how the expected hydrologic changes interact with existing conditions and uses, and where they intersect with land management objectives and social and economic values (see chapter 8). The Columbia River Gorge National Scenic Area features major regional transportation corridors, high recreation values and uses, and complex land ownerships, with low road density, high trail density, and water resource vulnerabilities that range from aquatic organism passage to public safety. Mount Hood and Willamette National Forests also share an emphasis on recreation, fisheries, and aquatic resources, and Mount Hood National Forest contains the water supply for Portland (box 3.1), a major metropolitan area. The national forests have extensive road systems (initially developed for timber management) with emphasis on active management of forest vegetation.

Sixteen rivers in the CMWAP assessment area have been designated as wild and scenic rivers, recognizing their "outstandingly remarkable" water quality and fisheries, among other values. Uses of surface water and groundwater include agriculture, drinking water for municipal and smaller water systems, fish and recreation, and hydropower, serving large populations and supporting significant economic activity. Four of the 13 federal dams in the Willamette Basin are within Willamette National Forest. While constructed and operated primarily for flood protection, these facilities also provide hydropower, storage, and recreation uses.

Water Uses and Water Quality

Most of the CMWAP assessment area is designated as sourcewater protection for surface and groundwater public water systems (fig. 3.10). Municipal water systems that rely on water supplied from the CMWAP assessment area have several challenges and climate change vulnerabilities (see box 3.1). In general, water systems that rely on source areas with greater expected change in snowpack and runoff may be more vulnerable, depending on many factors, including water treatment type and secondary water supply.

Water rights and uses within the CMWAP assessment area include numerous small surface diversions, wells, and storage facilities that provide domestic drinking water to recreation residences, campgrounds, commercial developments, and facilities managed by the U.S. Department of Agriculture, Forest Service (Forest Service). Other water rights and uses include irrigation diversions on the east side of Mount Hood supplying water to orchards in the Hood River Valley, and water for livestock, fish propagation, wildlife, commercial uses, flood-control storage projects, hydropower, and instream flows for aquatic habitat and recreation (fig. 3.11).

Box 3.1

Bull Run Municipal Watershed

Bull Run Watershed on Mount Hood National Forest is the primary water supply for the city of Portland, providing drinking water to almost 1 million Oregonians (fig. 3.9). Bull Run is a temperate rainforest, receiving an average of 3.3 m of precipitation annually. Snowpack in the watershed acts as a store of cold water and helps keep water temperatures cool for threatened salmon. The Bull Run River below the reservoirs once exhibited high summertime water temperatures. The city of Portland installed a multiple-elevation intake tower to help manage water temperatures in the lower Bull Run River. The tower in reservoir 2 allows selective withdrawal from different elevations in the reservoir, which stratifies in the summer season. The tower was constructed as part of a habitat conservation plan for Endangered Species Act-listed salmonids.

The Bull Run water system depends on seasonal rainfall to fill and refill reservoirs each year. Climate change is expected to alter the hydrology of Bull Run, leading to heavier storms; higher peak runoff and lower snowpack in winter; earlier snowmelt during spring; and lower streamflow in summer and fall. Warmer water temperatures will also pose challenges, as cold water is critical for drinking water quality and protecting salmon in the watershed. The water system experienced a preview of a warmer future during the Northwest's 2015 snow drought and long summer dry season. This event stressed many water supplies across the region and led to the earliest and longest duration reservoir drawdown in Bull Run's history. The city was able to use its secondary source of water supply, groundwater aquifers at the Columbia South Shore Well Field, to supplement the Bull Run and meet customer needs. The groundwater supply will continue to be an important form of climate resilience for Portland's water system.

Figure 3.9—View of the Bull Run Watershed, Bull Run Lake, and Mount Hood, located on Mount Hood National Forest. The Bull Run Watershed is the primary drinking water source for the city of Portland, Oregon. Photo credit: Portland Water Bureau.

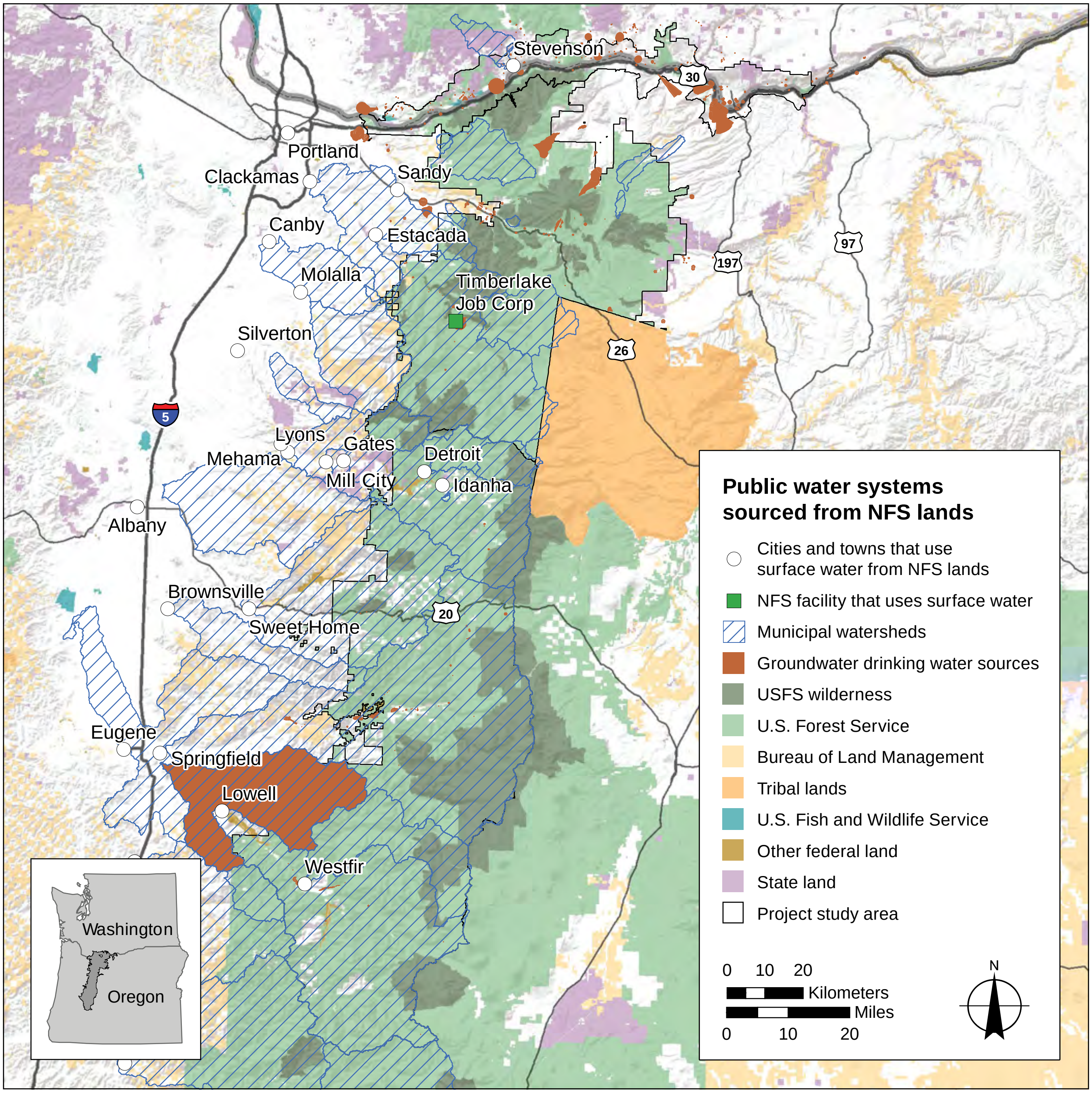

Figure 3.10—Surface and groundwater source-water protection areas and public water systems on and adjacent to National Forest System (NFS) lands in the assessment area.

Declining snowpack and altered hydrology will affect water supplies by changing the amount, timing, and availability of surface water and groundwater necessary to meet human uses and to support ecosystem functions.

Dams and stream diversions affect local hydrology and availability of water for different uses. Although dams increase water storage during low flow, they also increase water extraction and evaporation. Aging and inefficient diversion infrastructure can increase water loss. Engaging users in areas where water shortages can occur is critical for addressing climate change effects on water and resolving water distribution issues. Water quality will also be affected by climate change, including potential increases in summer stream temperatures (e.g., Isaak et al. 2017, chapter 4), particularly in areas of projected low-flow declines. Greater channel erosion and higher sediment loads will likely occur in places affected by

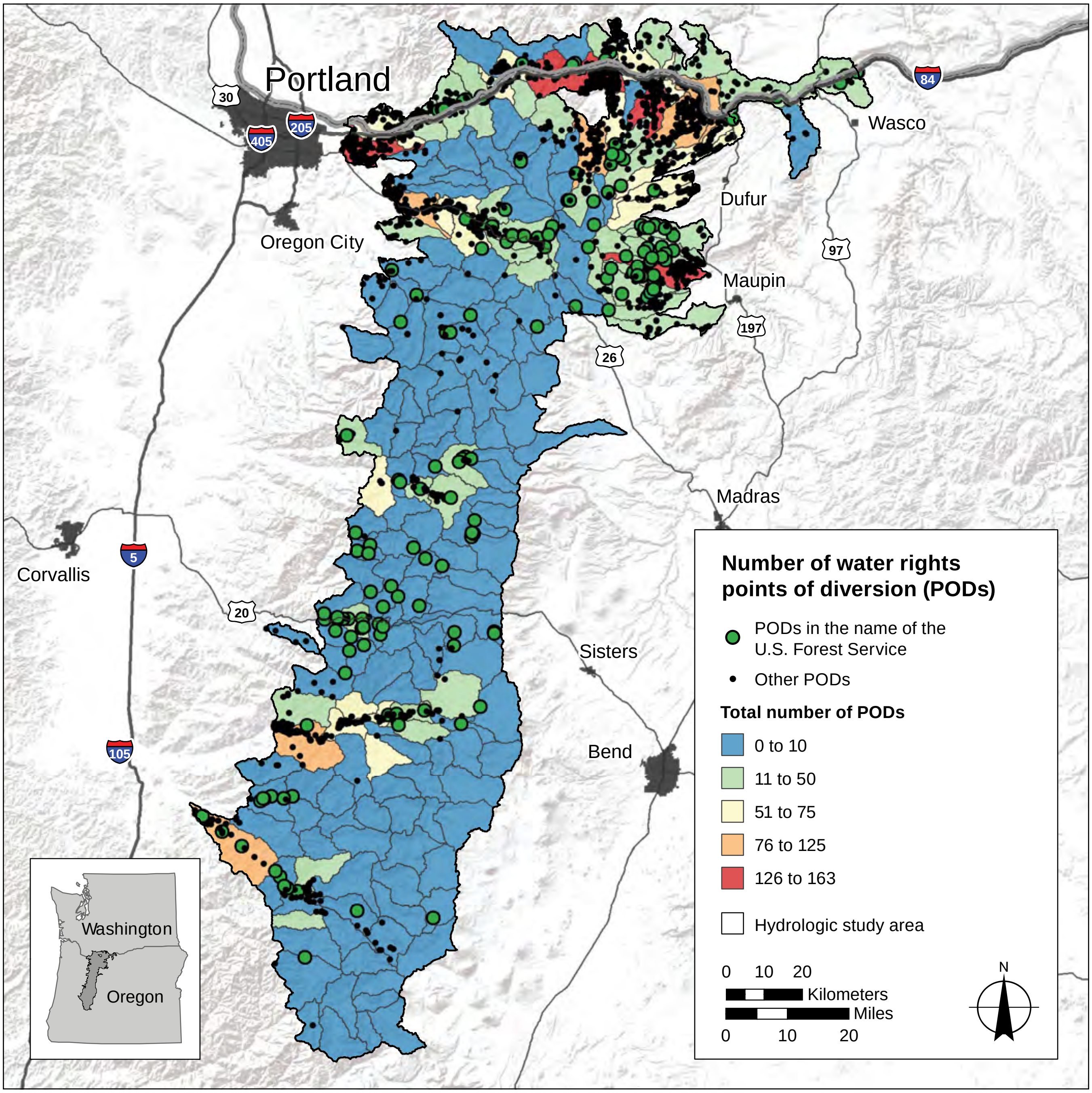

Figure 3.11—Appropriated water rights (points of diversion) on National Forest System land, including rights in the name of the U.S. Forest Service and rights in the name of others.

snow loss, peak flow increases, glacier melt, and increased wildfires (e.g., Goode et al. 2012). Many rivers and streams currently do not meet state water quality temperature criteria (e.g., total maximum daily load [TMDL]), and approved plans to meet water quality goals do not account for future climate effects to stream temperature. Figure 3.12 and table 3.2 show streamflow projections for rivers and streams already designated as water-quality impaired. These streams

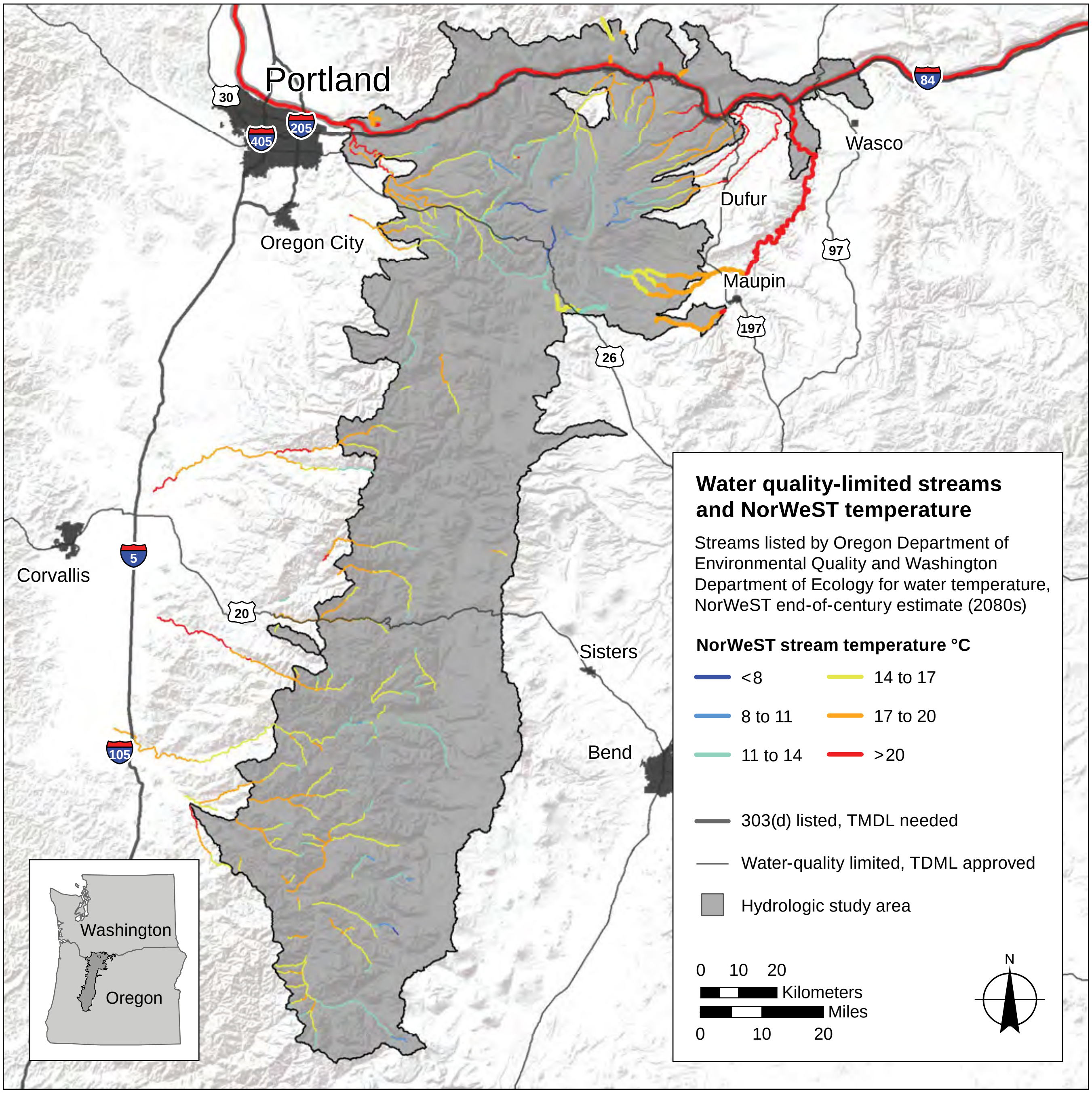

Figure 3.12—Projected increases in stream temperature in the 2080s on currently impaired waters. Category 303(d)-impaired streams needing total maximum daily load [TMDL]) are mapped with greater line width, Category 4A with TMDL approved are mapped with narrower line width). Stream temperature projections are from NorWeST (Isaak et al. 2017) under the A1B emission scenario.

present a challenge for regulators and managers in considering TMDL targets and management plans. See chapter 4 for more discussion about climate change effects on stream temperature and associated impacts to fisheries and aquatic resources. Increases in water temperature, low flows, and related effects (e.g., drought and wildfire occurrence) are also linked to increased occurrence of harmful algal blooms in vulnerable lakes and reservoirs, where exposure can pose risks to human health (May et al. 2018). Harmful algal blooms occur frequently in Detroit, Blue River, and Hills Creek Reservoirs on the Willamette National Forest.

Roads, Infrastructure, and Access

Roads, trails, bridges, and other infrastructure have been developed over the past century to provide access to public lands for logging, hunting, fishing, and

Table 3.2—Kilometers of stream for different winter peak-flow change categories (in the 2080s), and kilometers of current water quality-impaired streams listed by the Department of Environmental Quality (DEQ) for temperature and sediment, by management unit and subbasin (8-digit hydrologic unit code)

Unit	Subbasin	Area	>10 percent increase in peak flow	>20 percent increase in peak flow	>30 percent increase in peak flow	DEQ-listed streams for temperature	DEQ-listed streams for sediment
		km^2	*Kilometers*				
Columbia River Gorge National Scenic Area	Klickitat	23	16	3	3	2	0
	Lower Columbia—Sandy	335	132	23	18	49	0
	Lower Deschutes	8	1	1	1	1	0
	Middle Columbia—Hood	800	336	179	91	131	1
	Total	1166	485	206	113	183	1
Mount Hood National Forest	Clackamas	1664	1144	914	611	59	0
	Lower Columbia—Sandy	951	696	606	493	153	0
	Lower Deschutes	660	401	285	219	48	16
	Middle Columbia—Hood	802	649	540	483	111	48
	North Santiam	9	6	6	6	0	0
	Total	4086	2896	2351	1812	371	64
Willamette National Forest	Clackamas	13	7	7	7	0	0
	McKenzie	2210	931	523	301	94	0
	Middle Fork Willamette	2794	1056	444	172	329	2
	North Santiam	1186	759	531	315	23	15
	South Santiam	592	178	22	2	68	0
	Upper Willamette	24	0	0	0	6	0
	Total	6819	2931	1527	797	520	17

tourism. Today there are about 15 000 km of Forest Service-managed roads within the Columbia River Gorge National Scenic Area and Mount Hood and Willamette National Forests (table 3.3). Road design and condition differ widely across the landscape, with much of the road system originally designed for timber hauling. Recreation use has increased with population growth in recent years, and further growth and demand for access is expected (see chapter 7).

Although some roads are paved and designed to provide a high degree of comfort for passenger car use, most roads are "low standard" and surfaced with aggregate (maintenance level 1 and 2 in table 3.3). Because of the rugged topography in much of this area, roads and trails cross many waterways. Most road-water crossings use culverts installed decades ago, and most roads were developed when engineering standards for road-stream crossings were required to withstand a 25-year flood event (pre-1990), rather than a 100-year event (the construction standard today). Some crossings are being replaced, but many have not been inventoried, and conditions are unknown.

The effects of roads on hydrologic processes include changes to precipitation interception and infiltration; increased peak flows, erosion, and stream sedimentation; and altered late-season flows (Furniss et al. 1991, Luce and Black 1999, Wemple et al. 2001 Roads near rivers and streams (tables 3.4 and 3.5) generally have a greater direct effect on the fluvial system. However, roads in the uplands also affect these processes and can decrease slope stability in some locations (Trombulak and Frissell 2000).

Table 3.3—Kilometers of Forest Service-administered roads by maintenance level within the Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest assessment area

Operation maintenance level		Columbia River Gorge National Scenic Area	Mount Hood National Forest	Willamette National Forest	Total
Code	Description				
			Kilometers		
ML 1	Basic custodial care (closed)	18	670	1746	2434
ML 2	High clearance cars/trucks	125	3296	7443	10864
ML 3	Suitable for passenger cars	4	349	740	1093
ML 4	Passenger car (moderate comfort)	6	141	130	277
ML 5	Passenger car (high comfort)	0	88	234	322
	Total	153	4544	10,293	14,990

Table 3.4—Kilometers of road within 90 m of rivers and streams by peak-flow percent change category (in the 2080s) for the Columbia River Gorge National Scenic Area, Mount Hood, and Willamette National Forest assessment area

Operation maintenance level							
Code	Description	<0	0–10	10–20	20–30	>30	Total
		Kilometers					
ML 1	Basic custodial care (closed)	4	76	66	41	7	194
ML 2	High clearance cars/trucks	43	462	333	200	43	1081
ML 3	Suitable for passenger cars	7	56	57	49	20	189
ML 4	Passenger car (moderate comfort)	1	17	20	10	5	53
ML 5	Passenger car (high comfort)	1	36	28	27	1	93
	Total	56	647	504	327	76	1610

National forests develop prioritized annual road maintenance plans based on operational maintenance level and category. Forest roads subject to Highway Safety Act standards receive priority for appropriated capital maintenance, road maintenance, or improvement funds over roads maintained for high-clearance vehicles. Activities that are critical to health and safety generally receive priority, but these investment decisions are balanced with demands for access and protection of aquatic habitat. Federal agencies balance benefits of access with costs of maintaining a sustainable transportation system that is safe, affordable, responsive to public needs, and causes minimal environmental impact. Management actions that promote sustainability include storm-proofing roads, upgrading drainage structures and stream crossings, reconstructing and upgrading roads, decommissioning roads, converting roads to alternative travel routes (e.g., trails), and developing comprehensive access and travel management plans.

Climate change effects on transportation systems—

Climate-driven changes in snowpack, glaciers, runoff, low flows, and peak flows are expected to affect roads, infrastructure, and access in different ways, depending on location, timing, and conditions (box 3.2). Roads and infrastructure adjacent to and crossing rivers and streams, or located on steep slopes and unstable terrain, are more vulnerable to changes in precipitation, snowmelt, and peak flows (tables 3.4 and 3.5). The level of road use and condition (e.g., surface type) also affect hydrologic processes. Heavy traffic on native surface roads saturated after snowmelt or rainfall increases runoff, road erosion, and sediment delivery to streams.

Table 3.5—Summary of the number of road-stream crossings and length of road near streams for different peak-flow risk categories (by management unit and subbasin [8-digit hydrologic unit code])[a]

Unit	Subbasin	Area	Crossings	Total stream-adjacent roads	Stream-adjacent roads with >10 percent increase in peak flows	Stream-adjacent roads with >20 percent increase in peak flows	Stream-adjacent roads with >30 percent increase in peak flows
		km²	*Number*	*Kilometers*			
Columbia River Gorge National Scenic Area	Lower Columbia—Sandy	335	12	6	4	0	0
	Middle Columbia—Hood	800	13	6	5	2	2
	Total	1135	25	12	9	2	2
Mount Hood National Forest	Clackamas	1664	466	218	210	166	118
	Lower Columbia—Sandy	951	104	74	65	57	50
	Lower Deschutes	660	242	123	83	53	41
	Middle Columbia—Hood	802	192	116	105	88	74
	North Santiam	9	7	3	1	1	1
	Total	4086	1,011	534	464	365	284
Willamette National Forest	Clackamas	13	2	1	1	1	1
	McKenzie	2210	456	226	164	76	41
	Middle Fork Willamette	2794	1,198	528	304	107	28
	North Santiam	1186	288	175	162	120	58
	South Santiam	592	133	118	58	5	1
	Upper Willamette	24	9	14	1	0	0
	Total	6819	2,086	1062	690	535	129

[a] Stream-adjacent roads are defined as roads that cross or are within 90 m of rivers and streams using the medium-resolution (1:100,000) National Hydrography Dataset. Values are approximate, and not all road-stream crossings and roads near streams are accounted for because of stream mapping limitations.

Roads within 90 m of major rivers and streams with projected peak-flow increases show areas of potential vulnerabilities (tables 3.4 and 3.5, fig. 3.14). About 10 percent (1600 km) of roads in the CMWAP assessment area are within 90 m of streams and rivers. Most of these are maintenance level 2 roads and located in middle and upper elevations. A small number of roads (415 km, about 3 percent of all roads) are in the highest (>30 percent) peak-flow increase category. These segments may be most vulnerable to increased flooding impacts (table 3.5).

Box 3.2

Mount Jefferson Glaciers and infrastructure: a case of shrinking glaciers

Glacial retreat leads to a variety of geomorphic hazards that can threaten downslope and downstream resources and infrastructure (Moore et al. 2009, Walder and Dreidger 1995). Receding glaciers leave deposits of unconsolidated rock debris, and oversteepened valley walls no longer buttressed by ice experience regular rockfalls, landslides, and slope sagging. An abundance of sediment, ice, and water can trigger debris flows by a variety of mechanisms. Sudden mobilizations of debris can damage or destroy forest assets and endanger forest visitors. The remnant glaciers on the western slopes of Mount Jefferson have experienced these types of events in recent years.

Mount Jefferson is a stratovolcano in the Cascade Volcanic Arc and is the second highest peak in the state of Oregon. It is situated in the northern portion of Willamette National Forest, where the surrounding area provides a variety of recreation opportunities to the public. The Pacific Crest National Scenic Trail (PCT) traverses its western flank, and Pamelia Lake to the southwest of the peak is a popular hiking and backpacking destination. Two stream systems provide conduits for debris flows.

The Pamelia Lake and Milk Creek drainage was subject to a series of debris flows in the 2000s fed by deposits from Milk Creek Glacier (though it no longer functions as a glacier and is now a persistent ice feature.) The PCT bridge crossing over Milk Creek was destroyed by debris flows in 2006, and the Pamelia Lake Trailhead received substantial damage. The Whitewater Creek and Russell Creek drainages contain the Russell Glacier, Jefferson Park Glacier, and part of the Whitewater Glacier. There is also a history of glacial outwash here with substantial glacial mass still upslope, and the trail system is also vulnerable to debris flows.

Glacier retreat and loss in the Pacific Northwest is well documented and expected to continue in the future with increased warming (Granshaw and Fountain 2006, Ohlschlager 2015, Riedel et al. 2015, Sitz et al. 2007). The pattern of decline on Mount Jefferson likely tracks with Mount Hood and the Three Sisters (table 3.1). Unconsolidated debris on steep mountain slopes already poses a challenge to resource managers tasked with maintaining infrastructure and ensuring safe recreational opportunities. A landslide-risk model developed by the joint Forest Service and Bureau of Land Management Aquatic and Riparian Effectiveness Monitoring Program (Miller et al. 2017), which incorporates the main drivers of landslides in the region, shows high risk for landslides over much of the western face of Mount Jefferson (fig. 3.13A). The effects of warming on peak flows and rain-on-snow events could exacerbate vulnerability in areas downstream of glaciers and permanent ice by entraining more water in debris deposits and increasing potential for mobilization or remobilization. Several trail and road segments within the Russell Creek and Whitewater Creek watersheds are adjacent to streams expected to experience higher peak flows (fig. 3.13B). Those segments directly in the path of glacial outburst flow are already vulnerable to scouring and debris torrents from upslope glacial deposits. Projected increased peak flows will exacerbate this vulnerability. Erosional processes, including mass wasting, are important throughout the landscape.

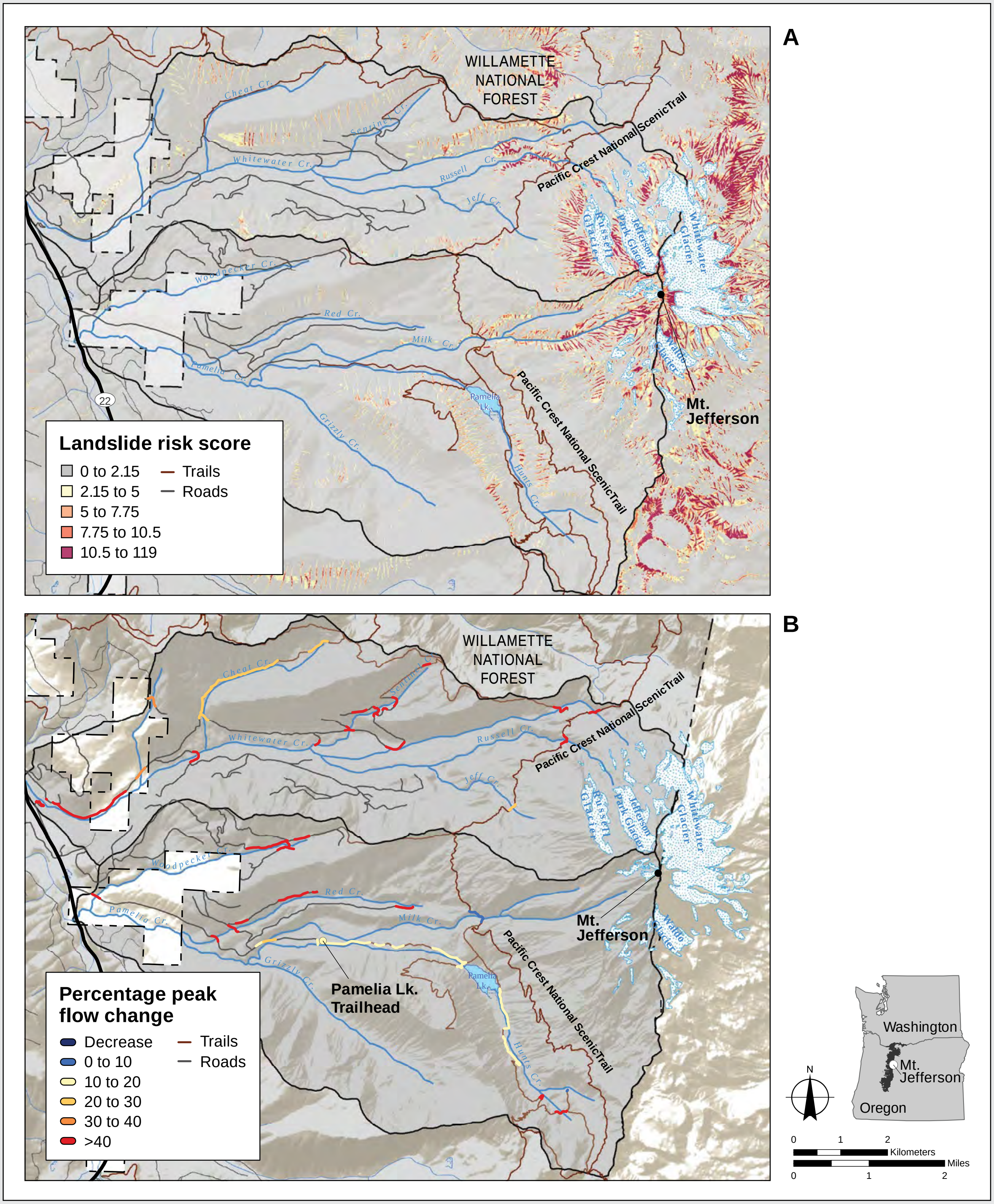

Figure 3.13—(A) Whitewater Creek and Russell Creek landslide risk, based on Miller et al. (2017), and (B) Whitewater Creek and Russell Creek infrastructure, based on Miller et al. (2017). Streamflow projections are based on Variable Infiltration Capacity model output (under the A1B emission scenario) for surface-water input changes filtered by geologically based unit hydrograph.

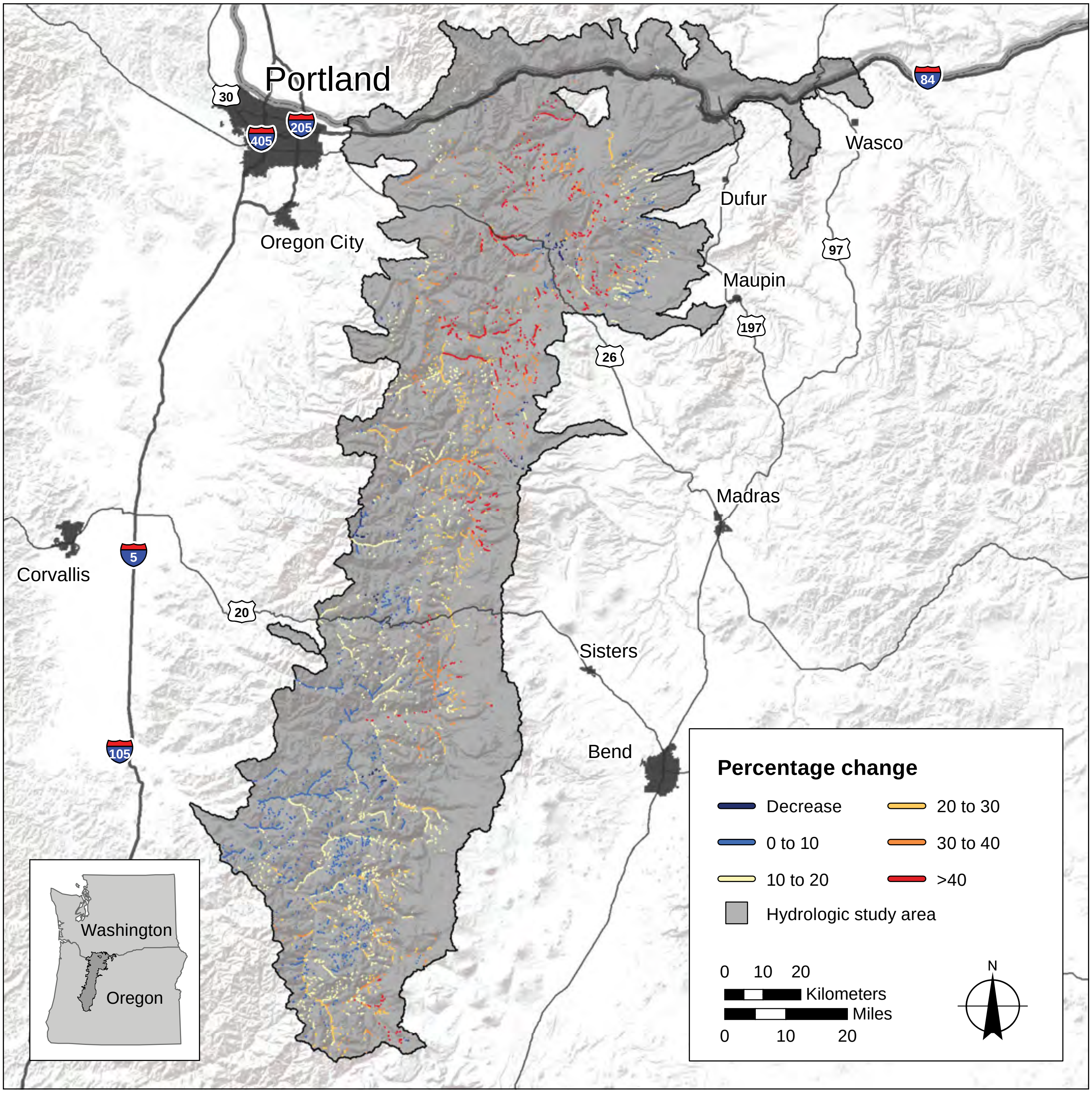

Figure 3.14—Projected change (between historical data [1970–1999] and the 2080s) in bankfull flow for road segments within 90 m of streams and rivers. Not all vulnerable roads are represented, and some roads intersect intermittent streams. Streamflow projections are based on Variable Infiltration Capacity model output (under the A1B emission scenario) for surface-water input changes filtered by geologically based unit hydrograph.

Antecedent moisture conditions, geology, and terrain are good predictors of mass wasting (including landslides and debris flows) (Kim et al. 1991), and elevated soil moisture and rapid changes in soil moisture are important triggers (Crozier 1986). Therefore, portions of the CMWAP assessment area with projected increases in antecedent soil moisture, coupled with more intense winter storms (Buma and Johnson 2015), will have a higher probability of mass wasting. These effects will vary with elevation, because higher elevation areas typically have steeper slopes and more precipitation during storms. Furthermore, reduced snowpack, particularly in middle elevations, is expected to increase antecedent soil moisture conditions in winter (Hamlet et al. 2013). Increasing trends in April 1st soil moisture have been observed in modeling studies as a result of climatic warming, indicating that soil moisture recharge is occurring earlier in spring and is now higher on April 1st than it was before 1947 (Hamlet et al. 2007). Transportation system infrastructure and access will be at greater risk in areas increasingly predisposed to landslide activity.

Climate change effects on roads are also expected to affect public access and safety. A longer snow-free season will likely extend visitor use in spring and fall, increase road use, and expose visitors to more hazards (chapter 7). For example, increased use in spring and fall increases the opportunity for the public to be physically present during the time of year when soil moisture conditions and storm events are most likely to cause landslides and flood events. In the CMWAP assessment area, projected snow-free areas, which allow for increasing access and exposure to impacts, occur in middle and upper elevations in the same general areas with potential flooding effects on roads (fig. 3.15, table 3.6).

Roads and trails built decades ago have high sensitivity to climate change because of age and declining condition. Many infrastructure components are at or near the end of their design lifespan. Culverts, by far the most common infrastructure component of the transportation system, are typically designed to last 25 to 75 years, depending on structure and material. Culverts remaining in place beyond their design life are less resilient to high flows and bedload movement and have a higher likelihood of structural failure. As roads and trails age, their surface and subsurface structure deteriorates, leaving them increasingly vulnerable to less severe storm events. In the face of higher severity storms, aging infrastructure and outdated design standards can lead to increased incidents of road failure.

New or replaced infrastructure will have increased resilience to climate change, if projected runoff characteristics for later in the 21st century are considered in design and materials. New culverts and bridges are typically wider than the original structures to meet agency regulations and current design standards. Over the past 15 years, many culverts under federal roads in the CMWAP assessment area have been replaced to improve fish passage and stream function using open-bottomed arch structures or bridges that are less constraining during high flows and support aquatic organism passage at a full range of flows. Natural channel design techniques that mimic the natural stream channel condition upstream and downstream of the crossings are being used at these crossings on fish-bearing streams. Culverts on non-fish-bearing streams are also being upgraded.

The location of roads and trails can affect vulnerability to climate change. Roads and trails in rugged topography were often built on steep slopes. Large cutslopes and fill material were sometimes required, creating oversteepened hill slopes and increased risk of landslides. Increased soil moisture can further exacerbate slope instability in disturbed areas (e.g., wildfire can reduce root cohesion). Higher

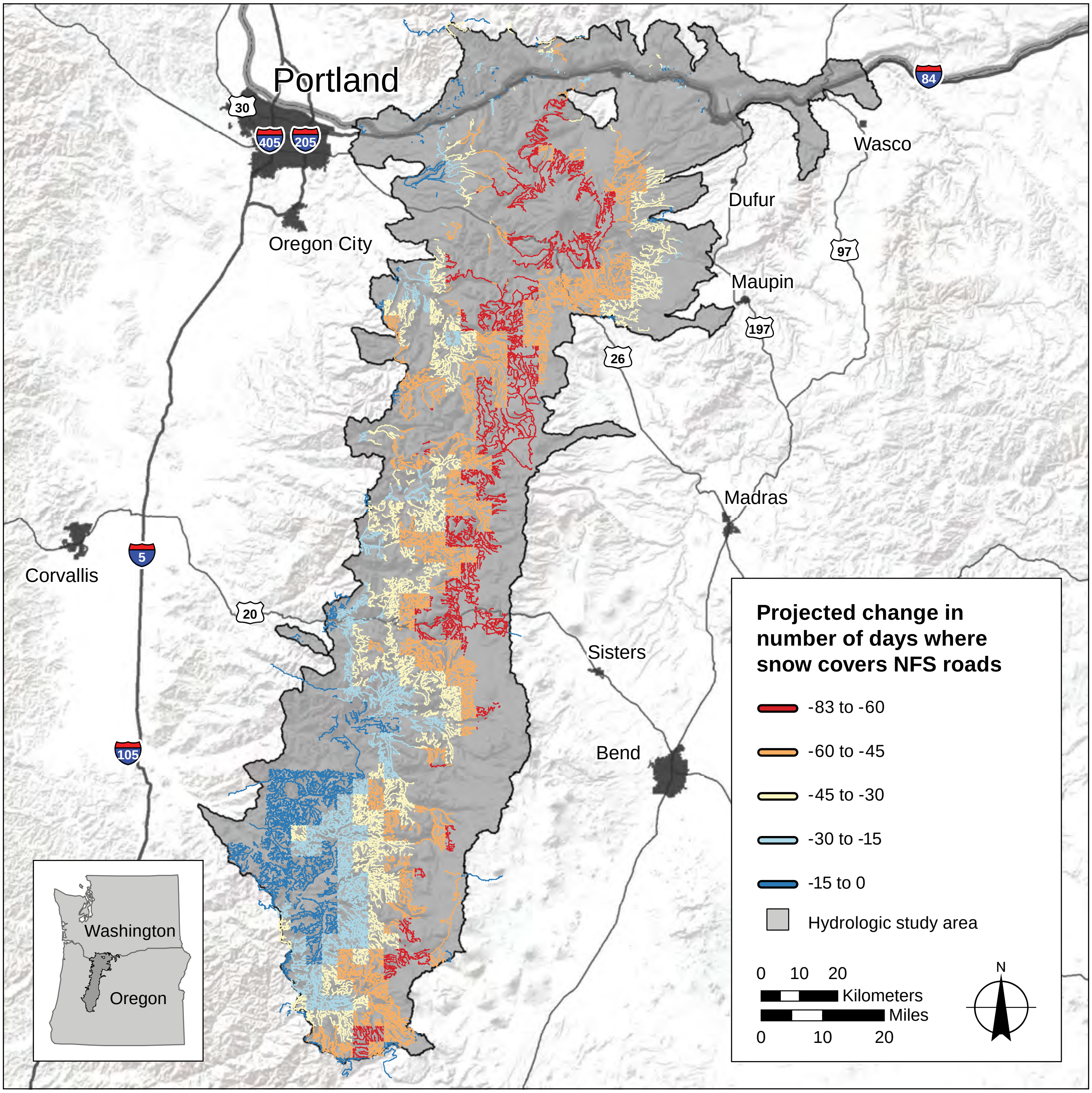

Figure 3.15—Projected (2080s) decline in snow residence time on National Forest System (NFS) roads (in days) under Representative Concentration Pathway 8.5. Fewer days of snow cover make roads accessible for a longer period. Snow residence time is from National Forest Climate Change Maps (https://www.fs.fed.us/rm/boise/AWAE/projects/national-forest-climate-change-maps.html).

runoff and peak flows from disturbed areas can also damage road-stream crossing infrastructure (Croke and Hairsine 2006, Schmidt et al. 2001, Swanston 1971). Roads and trails that were built in valley bottoms near streams are also at greater risk to flooding, channel migration, bank erosion, landslide deposition, and shifts in alluvial fans and debris cones.

Management of roads and trails (planning, funding, maintenance, response) will determine how sensitive current and future transportation systems are to climate change effects. Although not immune to these potential effects, highways in the CMWAP assessment area that were built to a higher design standard and are regularly maintained will be less sensitive to climate change than unpaved roads on federal lands that were built to a lower standard. Insufficient funding for road and trail management activities often constrains options for responding to infrastructure repair and improvement, thus contributing to the vulnerability of roads and trails.

Current and near-term climate change effects—

Changes in climate have already altered hydrologic regimes in the Pacific Northwest, resulting in decreased snowpack, higher winter streamflow, earlier spring snowmelt, earlier peak spring streamflow, and lower streamflow in summer (Hamlet et al. 2007). Ongoing changes in climate and hydrologic response in the short term (the next 10 years) are likely to be a mix of natural variability combined with ongoing trends related to climate change. High variability of short-term trends is an expected part of the response of the evolving climate system. Natural climatic variability, in the short term, may exacerbate, compensate for, or even temporarily reverse expected trends in some hydroclimatic variables. This is particularly true for strong El Niño years (high El Niño Southern Oscillation index) and during warm phases of the Pacific Decadal Oscillation (high Pacific Decadal Oscillation index), which may provide a preview of future climatic conditions under climate change.

Table 3.6—Projected decline in days with snow cover (in the 2080s) for roads (length in kilometers) in the Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest

Projected decline in snow cover	Columbia River Gorge National Scenic Area	Mount Hood National Forest	Willamette National Forest	Total
Days	*Kilometers*			
0 to 15	57	121	1971	2149
15 to 30	57	212	2100	2369
30 to 45	17	1040	2548	3605
45 to 60	19	1685	2578	4282
60 to 83	0	1481	1100	2581
Total	150	4539	10 297	14 987

Higher streamflow in winter (October through March) and higher peak flows, in comparison to historical conditions, increase the risk of flooding and impacts to structures, roads, and trails (MacArthur et al. 2012, Walker et al. 2011). Floods also transport logs and sediment that block culverts or are deposited on bridge abutments. Isolated intense storms can overwhelm the capacity of vegetation and soil to retain water, concentrating high-velocity flows that erode soils and remove vegetation. During floods, roads and trails can become preferential paths for floodwaters, reducing operational function and potentially damaging infrastructure not designed to withstand inundation.

In the short term, flooding of roads and trails will likely increase in late fall and winter, threatening the structural stability of stream-crossing infrastructure and subgrade material. Roads near perennial and other major streams are especially vulnerable (fig. 3.14). Increased high flows and winter soil moisture may also increase the amount of large woody debris delivered to streams, further increasing damage to culverts and bridges, and in some cases, making roads impassable or requiring road and facility closures. Unpaved roads with few drainage structures or minimal maintenance are likely to experience increased surface erosion, requiring additional repairs or grading.

Increasing incidence of intense precipitation and higher soil moisture in winter could increase the risk of landslides in some areas. In addition, increased frequency and extent of fire, coupled with increased rain-on-snow events in winter, could trigger instability of slopes in landslide-prone areas. Landslides contribute to flooding by diverting water, blocking drainage, and filling channels with debris (Chatwin et al. 1994, Crozier 1986, Schuster and Highland 2003), often elevating flood risk through aggradation of streambeds. Culverts filled with debris can cause flooding, damage, or complete destruction of roads and trails (Halofsky et al. 2011). Landslides that connect with waterways or converging drainages can transform into more destructive flows (Baum et al. 2007). Roads themselves also increase landslide risk, especially if they are built on steep slopes and through erosion-prone drainages (Chatwin et al. 1994, Montgomery 1994, Swanson and Dyrness 1975, Swanston 1971). In the Western United States, the presence of roads has increased the rate of debris avalanche erosion by 25 to 340 times the rate found in forested areas without roads (Swanston 1976). Consequently, areas with high road or trail density in landscapes that already experience frequent landslides will be especially vulnerable to increased landslide risks in a warmer climate.

Short-term exposures to climatic extremes may affect safety and access in the CMWAP assessment area. Damaged or closed roads also reduce agency capacity to respond to or provide detours during emergencies (e.g., wildfires). Increased flood risk could make conditions more hazardous for river recreation and camping.

Increased frequency and extent of wildfires (chapter 5) could reduce safe operation of some roads and require additional emergency response to protect recreationists and communities (Strauch et al. 2014).

Emerging and intensifying exposure in the medium and long term—
Many of the observed exposures to climate change in the short term are likely to increase in the medium (10 to 30 years) and long term (greater than 30 years). In the medium term, natural climatic variability may continue to affect outcomes in any given decade, whereas in the long term, the cumulative effects of climate change may become a dominant factor. Conditions thought to be extreme today may be averages in the future, particularly for temperature-related changes (MacArthur et al. 2012).

Flooding in fall and early winter is projected to continue to intensify in the medium and long term, particularly in mixed-rain-and-snow basins, but direct rain-on-snow events may diminish in importance as a cause of flooding (McCabe et al. 2007). At middle to higher elevations, more precipitation falling as rain rather than snow will continue to increase winter streamflow. By the 2080s, peak flows are anticipated to increase in magnitude and frequency (figs. 3.8 and 3.14). In the long term, higher and more frequent peak flows will likely continue to increase sediment and debris transport within waterways. These elevated peak flows could affect stream-crossing structures downstream as well as adjacent structures because of elevated stream channels. Even as crossing structures are replaced with wider and taller structures, shifting channel dynamics caused by changes in flow and sediment may affect lower elevation segments adjacent to crossings, such as bridge approaches.

Projected increases in flooding in fall and early winter will shift the timing of peak flows and affect the timing of maintenance and repair of roads and trails. More repairs may be necessary during the cool, wet, and dark time of year in response to damage from fall flooding and landslides, challenging crews to complete necessary repairs before snowfall. If increased demand for repairs cannot be met, access may be restricted until conditions are more suitable for construction and repairs.

In the long term, declining streamflow in summer may require increased use of more expensive culverts designed to balance the management of peak flows with providing low-flow channels in fish-bearing streams. Road design regulations for aquatic habitat will become more difficult to meet as warming temperatures hinder recovery of coldwater fish populations, although some streams may be buffered by inputs from snowmelt or groundwater (chapter 4).

Over the long term, landslide risk is expected to increase more in areas with tree mortality caused by wildfire and insect outbreaks, because tree mortality reduces soil root cohesion and soil water uptake (Martin 2006, Montgomery et al. 2000, Neary et al. 2005, Schmidt et al. 2001). Thus, soils will likely become more saturated and vulnerable to slippage on steep slopes during the wet season. Although floods and landslides will continue to occur near known hazard areas (e.g., because of high road density), they may also occur in new areas (e.g., those areas which are currently covered by deep snowpack in mid-winter) (MacArthur et al. 2012). Thus, more landslides at increasingly higher elevations may be a long-term effect of climate change.

A longer snow-free season may extend visitor use in early spring and late autumn at higher elevations (chapter 7). Lower snowpack may lead to fewer snow-related road closures for a longer portion of the year, allowing visitors to reach trails and campsites earlier in the season. As noted earlier, roads that were historically frozen during winter months will be subject to more flowing water and increased exposure to erosion.

Warmer temperatures and earlier snowmelt may encourage use of roads and trails before they are cleared. Trailheads, which are located at lower elevations, may be snowfree earlier, but hazards associated with melting snow bridges, avalanche chutes, or frozen snowfields in shaded areas may persist at higher elevations. Early-season visitors may be exposed to more extreme weather than they have encountered historically (Hamlet and Lettenmaier 2007), creating potential risks to visitors. Whitewater rafters may encounter unfavorable conditions from lower streamflows in late summer (chapter 7) and hazards associated with sediment deposition and woody debris from high winter flows. Warmer winters may shift river recreation to times of year when risks of extreme weather and flooding are higher.

Climate change may also benefit access and some aspects of transportation operations over the long term. Lower snow cover will reduce the need for and cost of snow removal, and earlier snow-free dates projected for the 2040s suggest that low- and middle-elevation areas will be accessible earlier. For example, temporary trail bridges on rivers may be installed earlier in spring as spring flows decline. A longer snow-free season and warmer temperatures may allow for a longer construction season at higher elevations. Although less snow may increase access for summer recreation, it may reduce opportunities for winter recreation at low and moderate elevations (chapter 7).

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Literature Cited

Adams, H.D.; Luce, C.H.; Breshears, D.D. [et al.]. 2012. Ecohydrological consequences of drought- and infestation-triggered tree die-off: insights and hypotheses. Ecohydrology. 5: 145–159.

Barnett, T.P.; Pierce, D.W.; Hidalgo, H.G. [et al.]. 2008. Human-induced changes in the hydrology of the Western United States. Science. 319: 1080–1083.

Baum, R.; Harp, E.; Highland, L. 2007. Landslide hazards in the Seattle, Washington area. Fact Sheet 2007-3005. Denver, CO: U.S. Department of the Interior, Geological Survey. 4 p. http://pubs.usgs.gov/fs/2007/3005/pdf/FS07-3005_508.pdf. (3 September 2019).

Buma, B.; Johnson, A.C. 2015. The role of windstorm exposure and yellow cedar decline on landslide susceptibility in southeast Alaskan temperate rainforests. Geomorphology. 228: 504–511.

Chang, H.; Jung, I.W.; Steele, M.; Gannett, M. 2012. Spatial patterns of March and September streamflow trends in Pacific Northwest streams, 1958–2008. Geographical Analysis. 44: 177–201.

Chatwin, S.C.; Howes, D.E.; Schwab, J.W.; Swantson, D.N. 1994. A guide for management of landslide-prone terrain in the Pacific Northwest. Land Management Handbook No. 18. 2nd ed. Victoria, BC: Ministry of Forests, Research Program. 10 p.

Croke, J.; Hairsine, P. 2006. Sediment delivery in managed forest: a review. Environmental Reviews. 14: 59–87.

Crozier, M.J. 1986. Landslides: causes, consequences, and environment. Dover, NH: Croom Helm, Ltd. 252 p.

Dalton, M.M.; Dello, K.D.; Hawkins, L. [et al.]. 2017. The third Oregon climate assessment report. Corvallis, OR: Oregon Climate Change Research Institute, College of Earth, Ocean and Atmospheric Sciences, Oregon State University.

Eiriksson, D.; Whitson, M.; Luce, C.H. [et al.]. 2013. An evaluation of the hydrologic relevance of lateral flow in snow at hillslope and catchment scales. Hydrologic Processes. 27: 640–654.

Fountain, A.G.; Glenn, B.; Basagic, H.J. 2017. The geography of glaciers and perennial snowfields in the American West. Arctic, Antarctic, and Alpine Research. 49: 391–410.

Fountain, A.G.; Tangborn, W.V. 1985. The effect of glaciers on streamflow variations. Water Resources Research. 21: 579–586.

Frans, C.; Istanbulluoglu, E.; Lettenmaier, D.P.; Fountain, A.G. 2018. Glacier recession and the response of summer streamflow in the Pacific Northwest United States, 1960–2099. Water Resources Research. 54: 6202–6225.

Furniss, M.J.; Roelofs, T.D.; Yee, C.S. 1991. Road construction and maintenance. In: Meehan, W.R., ed. Influences of forest and rangeland management on salmonid fishes and their habitats. American Fisheries Society Special Publication. Bethesda, MD: American Fisheries Society: 297–323.

Goode, J.R.; Buffington, J.M.; Tonina, D. [et al.]. 2013. Potential effects of climate change on streambed scour and risks to salmonid survival in snow-dominated mountain basins. Hydrologic Processes. 27: 750–765.

Goode, J.R.; Luce, C.H.; Buffington, J.M. 2012. Enhanced sediment delivery in a changing climate in semi-arid mountain basins: implications for water resource management and aquatic habitat in the northern Rocky Mountains. Geomorphology. 139–140: 1–15.

Halofsky, J.E.; Shelmerdine, W.S.; Stoddard, R. [et al.]. 2011. Climate change, hydrology, and road management at Olympic National Forest and Olympic National Park. In: Halofsky, J.E.; Peterson, D.L.; O’Halloran, K.A.; Hoffman, C.H., eds. Adapting to climate change at Olympic National Forest and Olympic National Park. Gen. Tech. Rep. PNW-GTR-844. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 21–42.

Hamlet, A.F.; Elsner, M.M.; Mauger, G.S. [et al.]. 2013. An overview of the Columbia Basin climate change scenarios project: approach, methods, and summary of key results. Atmosphere-Ocean. 51: 392–415.

Hamlet, A.F.; Lettenmaier, D.P. 2007. Effects of 20th century warming and climate variability on flood risk in the Western U.S. Water Resources Research. 43: W06427.

Hamlet, A.F.; Mote, P.W.; Clark, M.P.; Lettenmaier, D.P. 2007. 20th century trends in runoff, evapotranspiration, and soil moisture in the Western U.S. Journal of Climate. 20: 1468–1486.

Harr, R.D. 1986. Effects of clearcutting on rain-on-snow runoff in western Oregon: a new look at old studies. Water Resources Research. 22: 1095–1100.

Holden, Z.A.; Swanson, A.; Luce, C.H. [et al.]. 2018. Decreasing fire season precipitation increased recent Western U.S. forest wildfire activity. Proceedings of the National Academy of Sciences, USA. 115: E8349–E8357. https://doi.org/10.1073/pnas.1802316115.

Isaak, D.J.; Wenger, S.J.; Peterson, E.E. [et al.]. 2017. The NorWeST summer stream temperature model and scenarios for the Western U.S.: a crowd-sourced database and new geospatial tools foster a user community and predict broad climate warming of rivers and streams. Water Resources Research. 53: 9181–9205.

Jaeger, W.K.; Plantinga, A.J.; Langpap, C. [et al.]. 2017. Water, economics, and climate change in the Willamette Basin, Oregon. Corvallis, OR: Oregon State University Extension Service. https://catalog.extension.oregonstate.edu/em9157/html. (10 July 2019).

Kim, S.K.; Hong, W.P.; Kim, Y.M. 1991. Prediction of rainfall-triggered landslides in Korea. In: Bell, D.H., ed. Landslides. Proceedings of the 6th international symposium on landslides, Christchurch, New Zealand; Rotterdam, The Netherlands: A.A. Balkema: 989–994.

Kolb, T.E.; Fettig, C.J.; Ayres, M.P. [et al.]. 2016. Observed and anticipated impacts of drought on forest insects and diseases in the United States. Forest Ecology and Management. 380: 321–334.

Kormos, P.; Luce, C.; Wenger, S.J.; Berghuijs, W.R. 2016. Trends and sensitivities of low streamflow extremes to discharge timing and magnitude in Pacific Northwest mountain streams. Water Resources Research. 52: 4990–5007.

Liang, X.; Lettenmaier, D.P.; Wood, E.F.; Burges, S.J. 1994. A simple hydrologically based model of land surface water and energy fluxes for general circulation models. Journal of Geophysical Research. 99: 14415–14428.

Littell, J.; Mauger, G.S.; Salathé, E.P. [et al.]. 2014. Uncertainty and extreme events in future climate and hydrologic projections for the Pacific Northwest: providing a basis for vulnerability and core/corridor assessments. Final report to the Northwest Climate Science Center. Seattle, WA: University of Washington, Climate Impacts Group. 19 p. https://cig.uw.edu/wp-content/uploads/sites/2/2021/02/Litteletal2014_CSCFinalReport717.pdf. (7 November 2019).

Littell, J.S.; Peterson, D.L.; Riley, K.L. [et al.]. 2016. A review of the relationships between drought and forest fire in the United States. Global Change Biology. 22: 2353–2369.

Luce, C.H.; Abatzoglou, J.T.; Holden, Z.A. 2013. The missing mountain water: slower westerlies decrease orographic enhancement in the Pacific Northwest USA. Science. 342: 1360–1364.

Luce, C.H.; Black, T.A. 1999. Sediment production from forest roads in western Oregon. Water Resources Research. 35: 2561–2570.

Luce, C.H.; Holden, Z.A. 2009. Declining annual streamflow distributions in the Pacific Northwest United States, 1948–2006. Geophysical Research Letters. 36: L16401.

Luce, C.H.; Lopez-Burgos, V.; Holden, Z. 2014. Sensitivity of snowpack storage to precipitation and temperature using spatial and temporal analog models. Water Resources Research. 50: 9447–9462.

Luce, C.H.; Morgan, P.; Dwire, K. [et al.]. 2012. Climate change, forests, fire, water, and fish: building resilient landscapes, streams, and managers. Gen. Tech. Rep. RMRS-GTR-290. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 207 p.

Luce, C.H.; Vose, J.M.; Pederson, N. [et al.]. 2016. Contributing factors for drought in United States forest ecosystems under projected future climates and their uncertainty. Forest Ecology and Management. 380: 299–308.

MacArthur, J.; Mote, P.; Ideker, J. [et al.]. 2012. Climate change impact assessment for surface transportation in the Pacific Northwest and Alaska. Res. Rep. WA-RD 772.1. Olympia, WA: State of Washington, Department of Transportation, Office of Research and Library Services. 272 p. http://www.wsdot.wa.gov/research/reports/fullreports/772.1.pdf. (1 August 2016).

Marks, D.; Kimball, J.; Tingey, D.; Link, T. 1998. The sensitivity of snowmelt processes to climate conditions and forest cover during rain-on-snow: a case study of the 1996 Pacific Northwest flood. Hydrological Processes. 12: 1569–1587.

Martin, Y.E. 2006. Wildfire disturbance and shallow landsliding in coastal British Columbia over millennial time scales: a numerical modeling study. Catena. 69: 206–219.

Matheussen, B.; Kirschbaum, R.L.; Goodman, I.A. [et al.]. 2000. Effects of land cover change on streamflow in the interior Columbia River Basin (USA and Canada). Hydrological Processes. 14: 867–885.

May, C.; Luce, C.; Casola, J. [et al.]. 2018. Northwest. In: Reidmiller, D.R.; Avery, C.W.; Easterling, D.R. [et al.], eds. Impacts, risks, and adaptation in the United States: fourth national climate assessment. Volume II. Washington, DC: U.S. Global Change Research Program: 1036–1100. Chapter 24.

McCabe, G.J.; Clark, M.P.; Hay, L.E. 2007. Rain-on-snow events in the western United States. Bulletin of the American Meteorological Society. 88: 319–328.

McCabe, G.J.; Fountain, A.G. 1995. Relations between atmospheric circulation and mass balance of South Cascade Glacier, Washington, USA. Arctic and Alpine Research. 27: 226–233.

Menounos, B.; Hugonnet, R.; Shean, D. [et al.]. 2019. Heterogeneous changes in western North American glaciers linked to decadal variability in zonal wind strength. Geophysical Research Letters. 46: 200–209.

Miller, S.A.; Gordon, S.N.; Eldred, P. [et al.]. 2017. Northwest Forest Plan—the first 20 years (1994–2013): watershed condition status and trend. Gen. Tech. Rep. PNW-GTR-932. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 74 p.

Montgomery, D.R. 1994. Road surface drainage, channel initiation, and slope instability. Water Resources Research. 30: 1925–1932.

Montgomery, D.R.; Schmidt, K.M.; Greenberg, H.M.; Dietrich, W.E. 2000. Forest clearing and regional landsliding. Geology. 28: 311–314.

Moore, R.D.; Fleming, S.W.; Menounos, B. [et al.]. 2009. Glacier change in western North America: influences on hydrology, geomorphic hazards and water quality. Hydrological Processes. 23: 42–61.

Mote, P.W.; Li, S.; Lettenmaier, D. [et al.]. 2018. Dramatic declines in snowpack in the western U.S. npj Climate and Atmospheric Science. 1: 2.

Neary, D.G.; Ryan, K.C.; DeBano, L.F., eds. 2005. Wildland fire in ecosystems: effects of fire on soils and water. Gen. Tech. Rep. RMRS-GTR-42-vol.4. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 250 p.

Nolin, A.W.; Daly, C. 2006. Mapping "at risk" snow in the Pacific Northwest. Journal of Hydrometeorology. 7: 1164–1171.

O'Conner, J.E.; Burns, S.F. 2009. Cataclysms and controversy—aspects of the geomorphology of the Columbia River Gorge. In: O'Conner, J.E.; Dorsey, R.J.; Madin, I.P., eds. Volcanoes to vineyards: geologic field trips through dynamic landscapes of the Pacific Northwest. Geological Society of America Field Guide 15. Boulder, CO: Geological Society of America: 237–251.

Ohlschlager, J. 2015. Glacier change on the Three Sisters volcanoes, Oregon: 1900–2010. Portland, OR: Portland State University. 144 p. M.S. thesis.

Perry, T.D.; Jones, J.A. 2017. Summer streamflow deficits from regenerating Douglas-fir forest in the Pacific Northwest, USA. Ecohydrology. 10: e1790.

Rössler, O.; Froidevaux, P.; Börst, U. [et al.]. 2014. Retrospective analysis of a nonforecasted rain-on-snow flood in the Alps—a matter of model limitations or unpredictable nature. Hydrology and Earth System Sciences. 18: 2265–2285.

Safeeq, M.; Grant, G.; Lewis, S. [et al.]. 2014. A hydrogeologic framework for characterizing summer streamflow sensitivity to climate warming in the Pacific Northwest, USA. Hydrology and Earth System Sciences. 18: 3693–3710.

Safeeq, M.; Grant, G.E.; Lewis, S.L.; Staab, B. 2015. Predicting landscape sensitivity to present and future floods in the Pacific Northwest, USA. Hydrological Processes. 29: 5337–5353.

Safeeq, M.; Grant, G.E.; Lewis, S.L.; Tague, C. 2013. Coupling snowpack and groundwater dynamics to interpret historical streamflow trends in the western United States. Hydrological Processes. 27: 655–668.

Schmidt, K.; Roering, J.J.; Stock, J.D. [et al.]. 2001. The variability of root cohesion as an influence on shallow landslide susceptibility in the Oregon Coast Range. Canadian Geotechnical Journal. 38: 995–1024.

Schuster, R.L.; Highland, L.M. 2003. Impact of landslides and innovative landslide-mitigation measures on the natural environment. In: Lee, C.F.; Tham, L.G., eds. Proceedings of the international conference on slope engineering. Hong Kong, China: University of Hong Kong: 64–74.

Sherrod, D.R.; Smith, J.G. 2000. Geologic map of upper Eocene to Holocene volcanic and related rocks of the Cascade Range, Oregon. Geologic Investigations Series I-2569, version 1.0. Denver, CO: U.S. Department of the Interior, Geological Survey. https://pubs.usgs.gov/imap/i-2569. (10 July 2019).

Stahl, K.; Moore, R. 2006. Influence of watershed glacier coverage on summer streamflow in British Columbia, Canada. Water Resources Research. 42: W06201.

Stahl, K.; Moore, R.; Shea, J. [et al.]. 2008. Coupled modelling of glacier and streamflow response to future climate scenarios. Water Resources Research. 44: W02422.

Stewart, I.T.; Cayan, D.R.; Dettinger, M.D. 2005. Changes toward earlier streamflow timing across western North America. Journal of Climate. 18: 1136–1155.

Strauch, R.L.; Raymond, C.L.; Hamlet, A.F. 2014. Climate change, hydrology, and access in the North Cascade Range. In: Raymond, C.L.; Peterson, D.L.; Rochefort, R.M., eds. Climate change vulnerability and adaptation in the North Cascades region. Gen. Tech. Rep. PNW-GTR-892. Portland OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 45–112.

Swanson, F.J.; Dyrness, C.T. 1975. Impact of clear-cutting and road construction on soil erosion by landslides in the western Cascade Range, Oregon. Geology. 3: 393–396.

Swanston, D.N. 1971. Principal mass movement processes influenced by logging, road building, and fire. In: Krygier, J.T.; Hall, J.D., eds. Forest land uses and stream environment: proceedings of a symposium. Corvallis, OR: Oregon State University: 29–40.

Swanston, D.N. 1976. Erosion processes and control methods in North America. In: XVI International Union of Forest Research Organizations World Congress proceedings. Aas, Norway: Norwegian IUFRO Congress Committee: 251–275. http://andrewsforest.oregonstate.edu/pubs/pdf/pub505.pdf. (1 August 2016).

Tague, C.; Grant, G.E. 2009. Groundwater dynamics mediate low-flow response to global warming in snow-dominated alpine regions. Water Resources Research. 45: W07421.

Tohver, I.M.; Hamlet, A.F.; Lee, S.Y. 2014. Impacts of 21st-century climate change on hydrologic extremes in the Pacific Northwest Region of North America. Journal of the American Water Resources Association. 50: 1461–1476.

Tonina, D.; Luce, C.H.; Rieman, B. [et al.]. 2008. Hydrological response to timber harvest in northern Idaho: implications for channel scour and persistence of salmonids. Hydrological Processes. 22: 3223–3235.

Troendle, C.A.; MacDonald, L.H.; Luce, C.H.; Larsen, I. 2010. Fuel management and water yield. In: Elliot, W.J.; Miller, I.S.; Audin, L., eds. Cumulative watershed effects of fuel management in the Western United States. Gen. Tech. Rep. RMRS-GTR-231. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 124–148.

Trombulak, S.C.; Frissell, C.A. 2000. Review of ecological effects of roads on terrestrial and aquatic communities. Conservation Biology. 14: 18–30.

U.S. Global Change Research Program [USGCRP]. 2017. Climate science special report. In: Wuebbles, D.J.; Fahey, D.W.; Hibbard, K.A. [et al.], eds. Fourth national climate assessment. Volume I. Washington, DC: U.S. Global Change Research Program.

Vose, J.M.; Miniat, C.F.; Luce, C.H. [et al.]. 2016. Ecohydrological implications of drought for forests in the United States. Forest Ecology and Management. 380: 335–345.

Walder, J.S.; Driedger, C.L. 1995. Frequent outburst floods from South Tahoma Glacier, Mount Rainier, U.S.A.: relation to debris flows, meteorological origin and implications for subglacial hydrology. Journal of Glaciology. 41: 1–10.

Walker, L.; Figliozzi, M.; Haire, A.; MacArthur, J. 2011. Identifying surface transportation vulnerabilities and risk assessment opportunities under climate change: case study in Portland, Oregon. Transportation Research Record: Journal of the Transportation Research Board. 2244: 41–49.

Walsh, J.; Wuebbles, D.; Hayhoe, K. [et al.]. 2014. Appendix 3: Climate science supplement. In: Melillo, J.M.; Richmond, T.C.; Yohe, G.W., eds. Climate change impacts in the United States: the third national climate assessment. Washington, DC: U.S. Global Change Research Program: 735–789.

Wayand, N.E.; Lundquist, J.D.; Clark, M.P. 2015. Modeling the influence of hypsometry, vegetation, and storm energy on snowmelt contributions to basins during rain-on-snow floods. Water Resources Research. 51: 8551–8569.

Wemple, B.C.; Swanson, F.J.; Jones, J.A. 2001. Forest roads and geomorphic process interactions, Cascade Range, Oregon. Earth Surface Processes and Landforms: 26: 191–204.

Wenger, S.J.; Isaak, D.J.; Dunham, J.B. [et al.]. 2011a. Role of climate and invasive species in structuring trout distributions in the interior Columbia River Basin, USA. Canadian Journal of Fisheries and Aquatic Sciences. 68: 988–1008.

Wenger, S.J.; Isaak, D.J.; Luce, C.H. [et al.]. 2011b. Flow regime, temperature, and biotic interactions drive differential declines of trout species under climate change. Proceedings of the National Academy of Sciences, USA. 108: 14175–14180.

Wenger, S.J.; Luce, C.H.; Hamlet, A.F. [et al.]. 2010. Macroscale hydrologic modeling of ecologically relevant flow metrics. Water Resources Research. 46: W09513.

Chapter 4: Climate Change Effects on Fishes of Concern

Brooke E. Penaluna, Dona Horan, Gordon H. Reeves, Daniel J. Isaak, and John C. Chatel[1]

Introduction

The U.S. Department of Agriculture, Forest Service (Forest Service) and other federal land managers are responsible for maintaining the productivity of aquatic and riparian ecosystems, the associated native biota, and the ecosystem services they provide. Public lands are important sources of water, recreation opportunities, and habitat for animals and plants, including many that are protected under the U.S. Endangered Species Act. However, there has been increasing global consumption of natural resources, introduction of invasive species, increasing effects of climate change, and an overall decline in ecosystem services (Millennium Ecosystem Assessment 2005). The effects of climate change on streams, in conjunction with other stressors, have become apparent in recent years (Sabater et al. 2018).

Under climate change, stream habitats will continue to warm, have more variable temperature and flow regimes, and experience more extreme events, such as wildfires, floods, and drought (Jentsch et al. 2007). There is growing evidence for reductions in summer streamflow (Luce and Holden 2009, Papadaki et al. 2016, Safeeq et al. 2013) and increases in stream temperature (Arismendi et al. 2012, Isaak et al. 2012). However, actual and projected responses differ across space and time. For example, variability in stream temperature is attributed to groundwater influences and shading by riparian forests (Arismendi et al. 2012). Because solar radiation is the dominant driver of stream temperature in most forested headwater and mid-order stream systems (Johnson 2004, Sinokrot and Stefan 1993), shading by riparian forests can decrease water temperatures (Arismendi et al. 2012, Johnson 2004, Wondzell et al. 2018). Changes in habitat conditions have direct or indirect effects on fish survival, abundance, distribution, fecundity, and reproductive success, which in turn influence species interactions; timing of key life events; and distribution, abundance, and dynamics of invasive species.

Coldwater fishes are especially vulnerable to the thermal effects of climate change. Fishes are ectothermic, so thermal conditions dictate their metabolic rates and most aspects of their life cycles—how fast they grow and mature, whether and when they migrate, when and how often they reproduce, and when they die

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[1] **Brooke E. Penaluna** is a research fisheries biologist and **Gordon H. Reeves** is a research fish ecologist (emeritus), Pacific Northwest Research Station, Forestry Sciences Laboratory, 3200 SW Jefferson Way, Corvallis, OR 97331; **Dona Horan** is a fish biologist and **Daniel J. Isaak** is a research fish biologist, Rocky Mountain Research Station, 322 East Front Street, Suite 401, Boise, ID 83702; **John C. Chatel** is the threatened and endangered species program manager, Pacific Northwest Region, 1220 SW 3rd Avenue, Portland, OR 97204.

(Brannon et al. 2004, Magnuson et al. 1979, Neuheimer and Taggart 2007). Climate change has been implicated in reductions in animal species distributions (Parmesan and Yohe 2003), changes in timing of key life events (Cohen et al. 2018, Parmesan and Yohe 2003, Thackeray et al 2016), and decreasing body sizes for fishes around the globe (Daufresne et al. 2009). Climate change affects fishes, especially coldwater species, through altered distribution (Wenger et al. 2011), phenology (Crozier et al 2011, Kovach et al. 2013), demography (Al-Chokhachy et al. 2013), recruitment (Ward et al. 2015), and genetic diversity (Muhlfeld et al. 2014). Climate change simulations have shown changes in trout phenology and shrinking body sizes (Penaluna et al. 2015). Possible acceleration of climate change during the 21st century (chapter 2) is likely to have important implications for coldwater fishes, complicating conservation and management efforts.

Here, we present a climate change vulnerability assessment for fishes and their associated aquatic habitats for the Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest Adaptation Partnership (CMWAP) assessment area (fig. 4.1). We describe the status and potential climate vulnerabilities for fishes of concern in the assessment area, as identified in discussions with land managers, Forest Service regional staff, and biologists from several agencies. Here, we focus on three spring-spawning and four fall-spawning salmonids. Spring-spawning fishes include steelhead and redband trout (anadromous life form and subspecies of *Oncorhynchus mykiss* Walbaum), coastal cutthroat trout (*O. clarkii clarkii* Richardson), and Pacific lamprey (*Entosphenus tridentatus* Richardson). Fall-spawning fishes include bull trout (*Salvelinus confluentus* Suckley), coho salmon (*O. kisutch* Walbaum), spring and fall runs of Chinook salmon (*O. tshawytscha* Walbaum in Artedi), and chum salmon (*O. keta* Walbaum in Artedi) (table 4.1). For *O. mykiss*, resident rainbow trout were not analyzed here because their distribution in the Pacific Northwest region is unknown, but we discuss potential implications for them in the steelhead and redband trout section.

We incorporate results from two analyses: (1) temperature modeling using NorWeST (Isaak et al. 2017a) to understand climate influences on stream habitats for focal fishes in the assessment area at the scale of 1 km and (2) downscaled projections to 100-m reaches using NetMap (Benda et al. 2007) that allow for a finer scale understanding of climate influences on stream habitats. We characterize the vulnerability of the fishes in the assessment area based on Crozier at al. (2019) and USDI FWS (2017). We conclude with options for management opportunities that may potentially mitigate the future effects of climate change, with an emphasis on diverse life histories and habitats.

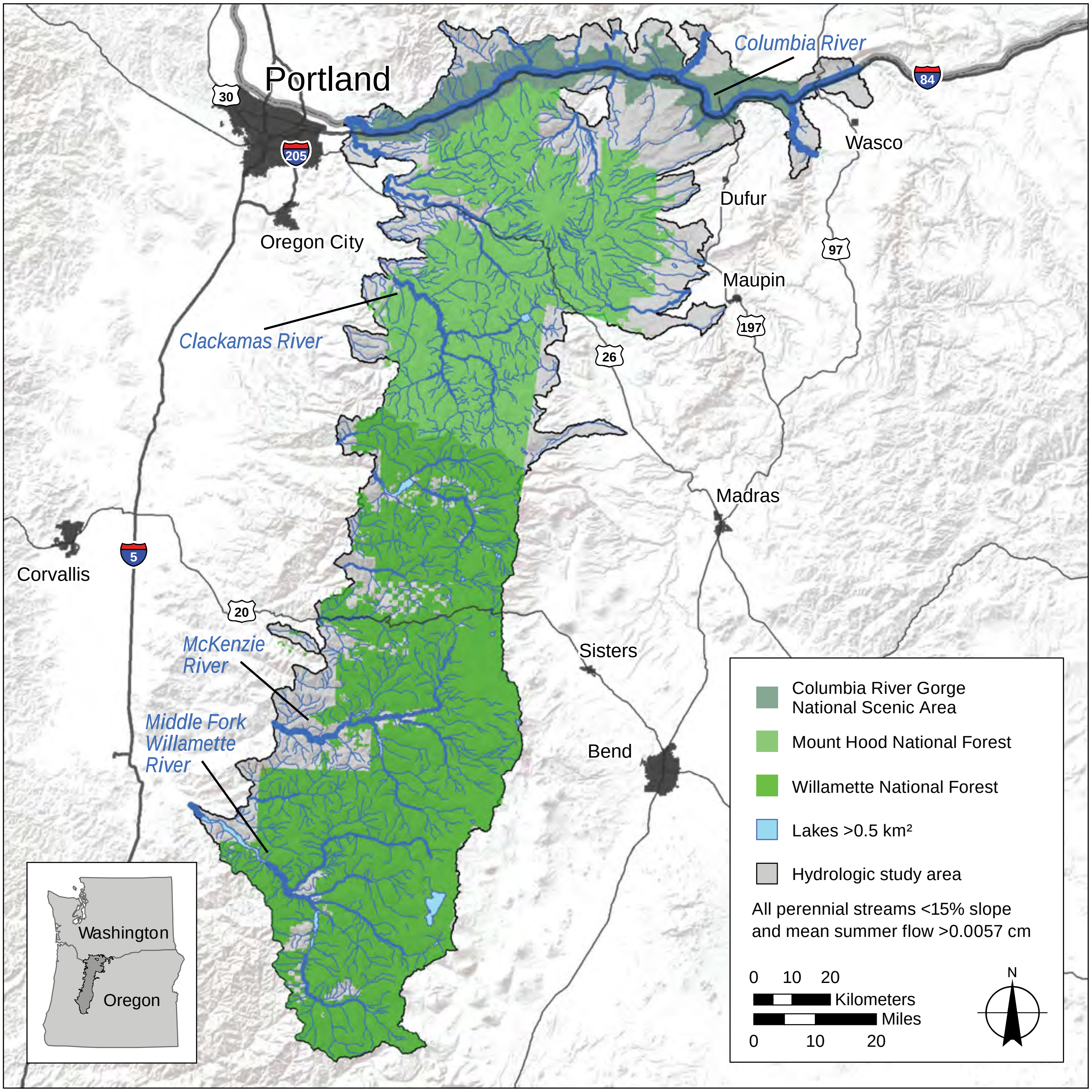

Figure 4.1—Network of 6969 stream kilometers in the Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest assessment area, with land ownership and major rivers.

Pacific Ocean Conditions

All fishes considered in this assessment except redband and adfluvial bull trout are sea-run (anadromous), relying on multiple habitats across the freshwater-marine interface in their lifetime. Many Pacific salmon spend more time in ocean than freshwater environments, making marine environments critical to population sustainability. Most of these sea-run fishes move into estuaries and the ocean as juveniles or smolts, and their timing and size at ocean entry are important for survival in their first year at sea (Van Doornik et al. 2007). In the Pacific Ocean, climate change will increase sea-surface temperature, El Niño Southern Oscillation (ENSO) strength (Fasullo et al. 2018), and the more recently created "blob" (a large mass of relatively warm water in the Pacific Ocean off the coast of North America), leading to changes in the Pacific Ocean's net primary production, and consequently the reliability of food sources for Pacific salmon and trout (Behrenfeld et al. 2006).

Assessment Area

The CMWAP assessment area encompasses streams and rivers in the Columbia River Gorge National Scenic Area (CRGNSA), Mount Hood National Forest (NF), and Willamette NF. The project area covers portions of major rivers and their tributaries, including the Columbia, McKenzie, Santiam, and Middle Fork Willamette Rivers (fig. 4.1). The Columbia River is a central focus for this assessment because it is the main swimming corridor for every fish considered here, including sea-run fishes, redband and adfluvial bull trout. Stream habitats throughout the assessment area have been altered by human actions, beginning with Euro-American colonization of North America. As Euro-American explorers and settlers began moving westward at the turn of the 19th century, so too did modifications to streams. Eradication of American beaver (*Castor canadensis* Kuhl) (Larson and Gunson 1983), grazing of rangelands (Platts 1991), logging of forests (Northcote and Hartman 2004), diking and draining of river floodplains (Brinson and Malvárez 2002), and widespread mining (e.g., Mount 1995) contributed to degraded stream conditions.

Throughout the 20th century, free-flowing rivers became fragmented by construction of barriers, including hydropower dams on major rivers and passage-constraining road crossings, dikes, and diversions. Such modifications in the connectivity among and within stream networks have isolated some fishes in headwater enclaves (fig. 4.2), while simultaneously impairing the ability of migratory fishes to move among estuary, mainstem, and headwater environments. Multiple channel-spanning dams impound reservoirs in the assessment area (fig. 4.2). Most of these dams have caused blockages for passage of sea-run fishes and rely on direct handling of fish to move them past the barrier (i.e., trap and haul). In addition, there are other major dams above and below the assessment area that also influence water conditions and fish passage. Collectively, these contemporary and historical legacies fundamentally transformed many streams and rivers (McIntosh et al. 2000). Current levels of fish populations are depressed for most species and are estimated to be 5 to 15 percent of their presettlement abundance (Meengs and Lackey 2005).

Table 4.1—Summary of fish species of concern and climate vulnerability[a] in the Columbia River Gorge National Scenic Area (CRGNSA), Mount Hood National Forest (MTH), and Willamette National Forest (WIL) assessment area

Species or run	ESU/DPS[b]	National Forest/Scenic Area	Population status/trend	Climate vulnerability
Spring spawning:				
Steelhead (rainbow trout)				
Summer run:	Lower Columbia River, Mid-Columbia River	CRGNSA, MTH, WIL	Depressed/stable	Moderate, high
Winter run:		CRGNSA, MTH, WIL	Depressed/stable	Moderate, high
Redband (rainbow trout)		CRGNSA, MTH	Depressed/stable	Moderate
Coastal cutthroat trout		CRGNSA, MTH, WIL	Depressed/stable	Moderate
Pacific lamprey		CRGNSA, MTH, WIL	Depressed/unknown	High
Fall spawning:				
Bull trout	Conterminous U.S. population	CRGNSA, MTH, WIL	Depressed/stable	Very high
Coho salmon	Lower Columbia	CRGNSA, MTH	Depressed/stable	High
Chinook salmon	Lower Columbia, Upper Willamette			
Spring run:		CRGNSA, MTH, WIL	Depressed/stable	Very high
Fall run:		CRGNSA, MTH	Depressed/stable	Moderate
Chum salmon	Columbia River	CRGNSA	Depressed/stable	Moderate

[a] Climate vulnerability is based on their biological risk summary from the National Oceanic and Atmospheric Administration (Crozier et al. 2019) or U.S. Fish and Wildlife Service (2017), which incorporates their sensitivity and exposure to potential changes.

[b] ESU = evolutionarily significant unit for Pacific salmon and trout and Pacific lamprey; DPS = distinct population segment for bull trout.

Sport fishing for trout and supporting activities of hatcheries, put-and-take stocking, and a wave of introductions of invasive trout have also affected fishes in the assessment area. Numerous hatcheries support fisheries in the Columbia River and its tributaries that affect Columbia River Gorge National Scenic Area and Mount Hood NF streams, chiefly the Bonneville, Sandy, and Clackamas fish hatcheries. The Upper Willamette watershed contains the South Santiam, McKenzie, Leaburg, and Fall River fish hatcheries which affect Willamette NF.

Methods

Modeled Stream Temperatures and Flows Using NorWeST

To project stream temperatures into the future and describe the extent of habitat available for species of concern, we delineated a CMWAP assessment area stream network using the 1:100,000-scale National Hydrography Dataset (NHD)–Plus Version 2 (McKay et al. 2012), downloaded from the Horizons Systems website (https://nhdplus.com/NHDPlus). We obtained summer flow values projected by the Variable Infiltration Capacity (VIC) hydrologic model (Wenger et al. 2010) from the

Western U.S. Flow Metrics website (https://www.fs.fed.us/rm/boise/AWAE/projects/modeled_stream_flow_metrics.shtml) and linked these to the NHDPlus stream reaches. We filtered the network to exclude reaches with summer flows of less than

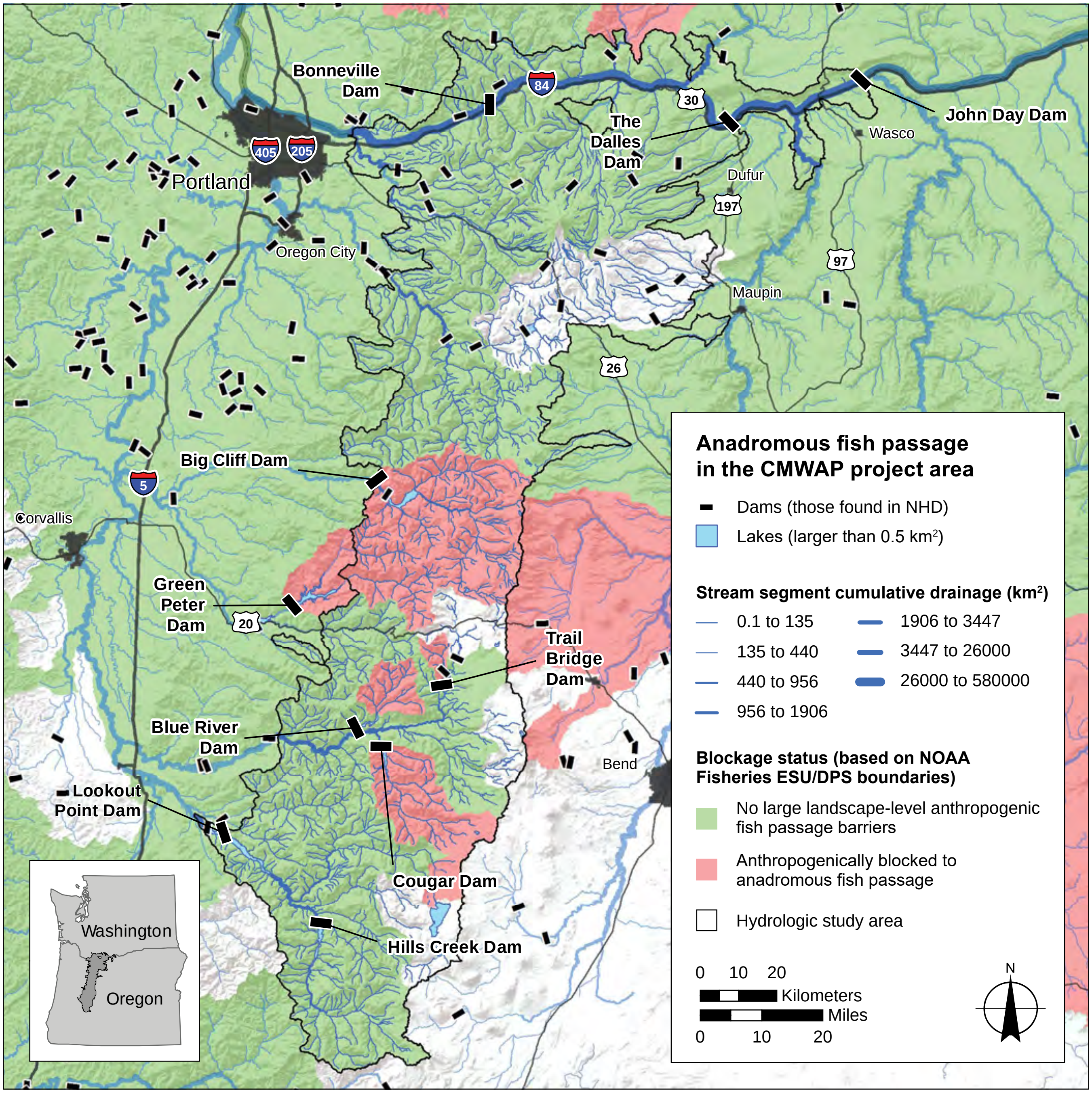

Figure 4.2—Locations of dams and resulting blockages preventing anadromous fish passage in the Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest (CMWAP) assessment area. Although additional areas may have some blockages, this blockage status is based on evolutionarily significant unit and distinct population segment (ESU/DPS) boundaries (as determined by National Oceanic and Atmospheric Administration [NOAA] Fisheries). NHD = National Hydrography Dataset.

$0.0057\ m^3\ s^{-1}$, which approximates a low-flow wetted width of 1 m (based on an empirical relationship developed in Peterson et al. [2013]), because fish occurrences are rare in these low-flow areas (Isaak et al. 2017b).

We filtered the network to exclude reaches with >15 percent slope. This reflects both physical barriers and disturbance events that make these environments less consistently accessible by fishes. Steep headwater reaches (>15 percent slope) often have natural waterfalls or high-gradient areas that can be barriers to fish movement. These areas may experience more frequent disturbances (e.g., postwildfire debris torrents) than areas lower in the stream network, leading to local fish mortality (May and Gresswell 2004, Miller et al. 2003). Application of the reach-slope and summer-flow criteria created the final 6969-km network that served as the basis for subsequent analyses and summaries. Proportionally, 73 percent of the network flows through Forest Service lands, 24 percent flows through private lands, and 3 percent flows through other lands (fig. 4.1).

We downloaded scenarios representing mean August stream temperature from the NorWeST website and linked them to reaches in the assessment area. NorWeST scenarios have a 1-km resolution and were developed by applying spatial stream-network models (Ver Hoef et al. 2006) to temperature records at 560 unique stream sites collected by resource agencies in the CMWAP assessment area (Isaak et al. 2017a). The predictive accuracy of the NorWeST model (cross-validated $r^2 = 0.91$; cross-validated root mean square prediction error = 1.0 °C), combined with substantial empirical support, provided a consistent and spatially balanced rendering of temperature patterns and thermal habitat for streams across the assessment area.

To depict temperatures during a baseline period, we used a scenario that represented average conditions for 1993–2011 (hereafter 2000s). The mean August stream temperature during this period was 12.0 °C, ranging from 3.9 to 27.4 °C throughout the network (table 4.2, fig. 4.3). We also downloaded future stream temperature scenarios from the NorWeST website for the same emission scenario (A1B) and climate periods (2030–2059, hereafter 2040s; 2070–2099, hereafter 2080s) as those used for the VIC streamflow analysis in the CMWAP water and infrastructure assessment (chapter 3). The future NorWeST scenarios we used, S30 (2040s) and S32 (2080s), account for differential sensitivity and slower warming rates of the coldest streams, which are often buffered by groundwater (Isaak et al. 2016, Luce et al. 2014). Projected August stream temperature increases relative to the baseline period (2000s) are 1.3 °C by the 2040s and 2.2 °C by the 2080s, which implies warming rates of ~0.3 °C per decade (table 4.2, fig. 4.4), similar to historical warming rates observed during several months at long-term monitoring sites within the CMWAP assessment area and throughout the region (fig. 4.4) (Isaak et al. 2018).

Table 4.2—Lengths of streams in the Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest assessment area categorized by mean August stream temperatures during a baseline period and two future periods associated with the A1B emission scenario

	Mean August stream temperatures					
	< 8 °C	8 to 11 °C	11 to 14 °C	14 to 17 °C	17 to 20 °C	>20 °C
	Stream kilometers					
All lands:						
1980s (1970–1999)	439	2335	2812	1089	148	145
2040s (2030–2059)	174	1336	3036	1881	321	208
2080s (2070–2099)	88	777	2809	2290	728	252
Forest Service lands:						
1980s (1970–1999)	434	2080	1976	528	59	15
2040s (2030–2059)	172	1249	2493	1006	116	45
2080s (2070–2099)	88	752	2433	1414	326	58

Downscaling Stream Climate Projections Using NetMap

We used geospatial tools developed by NetMap (Benda et al. 2007) to model the effects of climate change on stream temperature and streamflow. We also modeled the importance of riparian shading to mitigate climate change effects by considering distributions of fish in streams and local landscape features, such as topographic shading (based on digital elevation models, or DEMs) and roads. The delineated stream layer in these analyses is synthetic, with approximately 100-m reaches, and is based on 10-m DEMs. We used the NHD to guide channel locations where channel gradients were less than 4 percent; the NHD was applied where flow accumulation and direction are insufficient to accurately delineate the low-relief portions of river networks from 10-m DEMs.

All watersheds contain attributes of habitat intrinsic potential for coho salmon, Chinook salmon, coastal cutthroat trout, and steelhead (e.g., Burnett et al. 2007). The habitat intrinsic potential modeling requires channel gradient, valley confinement (valley width divided by channel width) and mean annual flow. To describe shade and its effects on thermal loading, analyses use the metric “SolDifMax,” which is the difference between the current shade thermal energy and estimated thermal energy under maximum shade. It provides an index of where increasing shade would have the greatest benefit, thus informing decisions about riparian management.

For climate change scenarios under NetMap, we included climate change projections developed by the Climate Impacts Group at the University of Washington (Littell et al. 2014). The approximate 7- by 7-km gridded climate change data (rasters) included air temperature, precipitation, snowmelt, snow-water

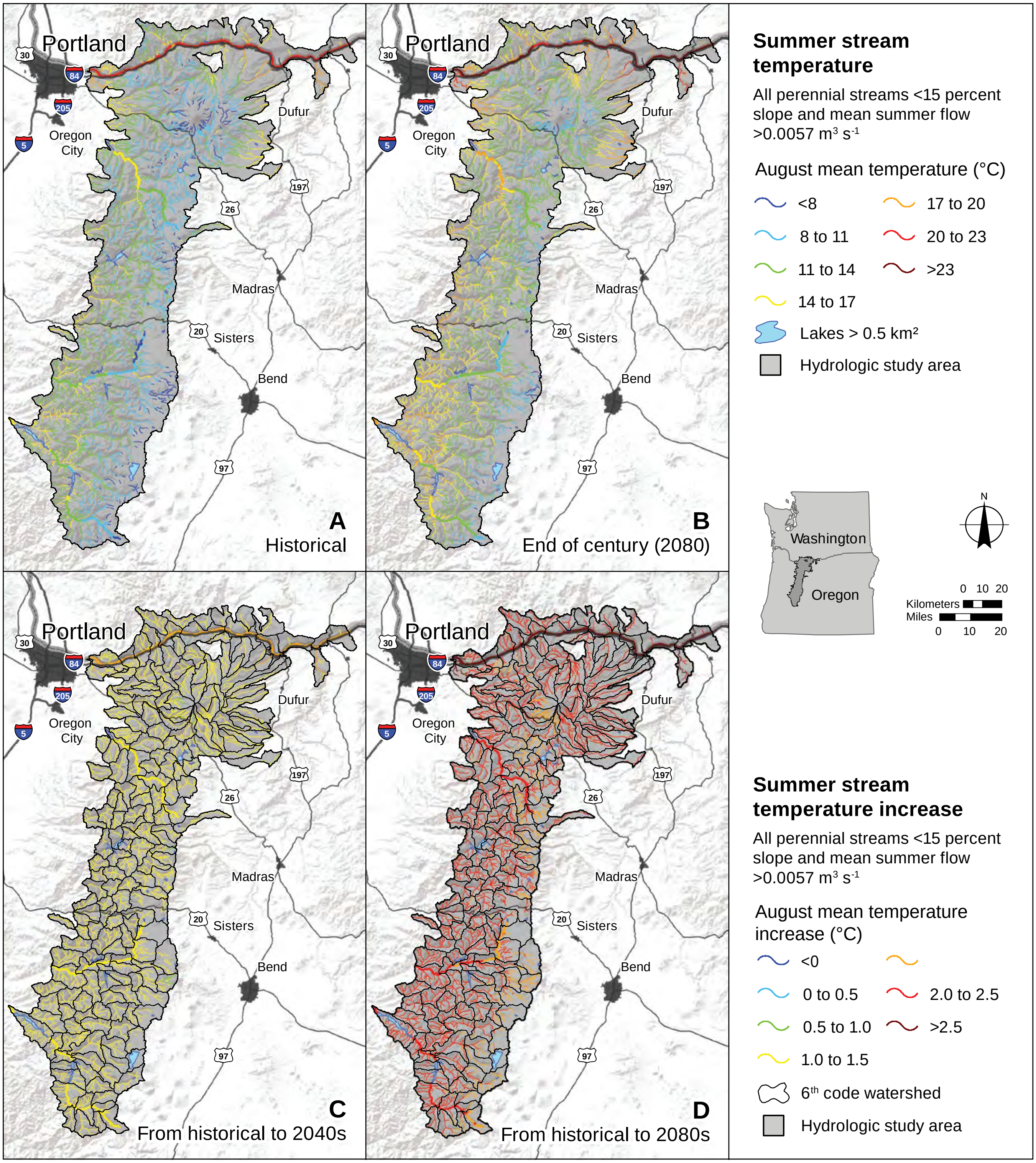

Figure 4.3—Scenarios depicting mean August stream temperatures across the 6969 km of streams in the Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest assessment area during (A) a baseline period (2000s) and (B) late 21st-century period (2080s). Panels C and D show future temperature increases relative to the baseline period (future increases are summarized in app. A by 6th-code hydrologic unit code boundaries that are shown as small black polygons). High-resolution images of these maps and ArcGIS shapefiles with reach-scale predictions are available at the NorWeST website (http://www.fs.fed.us/rm/boise/AWAE/projects/NorWeST.html).

equivalent, and summer and winter runoff (streamflows). The climate projections represent a composite average of 10 global climate models (GCMs) for the Western United States under one greenhouse gas scenario (A1B, a middle-of-the-road scenario for future emissions). We developed projected summer and winter runoff using the VIC model.

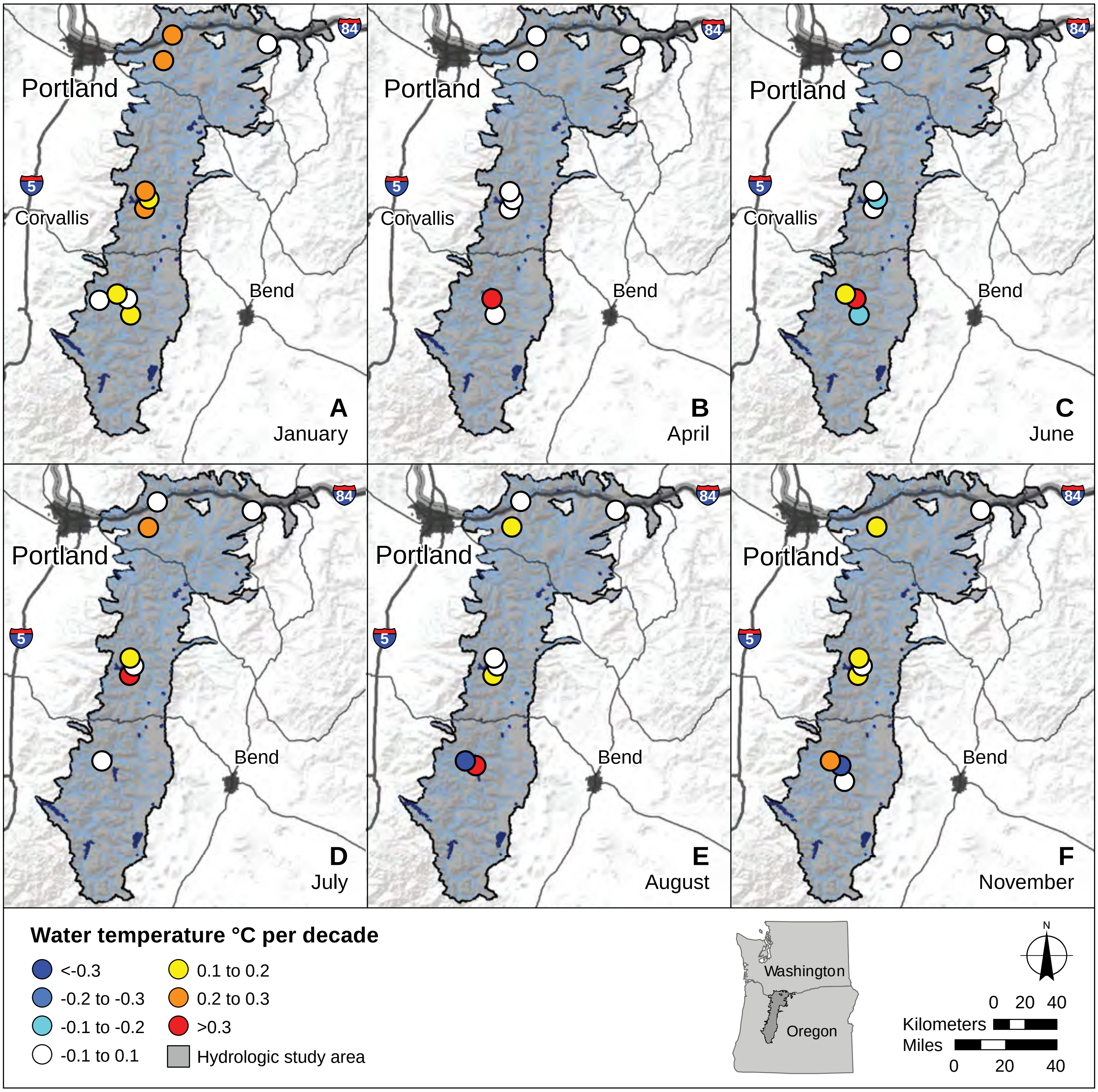

Figure 4.4—Decadal river temperature trends estimated from long-term monitoring records in the Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest assessment area for 1976–2015. Trend estimates are a subset of those reported for a regional river temperature trend analysis in Isaak et al. (2018).

Based on local contributing area on both sides of the stream (these local contributing areas are referred to as “drainage wings” in NetMap), we applied climate change projections to individual channel segments (entire network including headwaters). We also aggregated climate change projections of stream temperature and flow downstream. Projections in NetMap are reported as percentage of change from historical (1993–2011) to the 2040s (2030–2059) and 2080s (2070–2099); values can be positive or negative except for air temperature projections, which are absolute change in degrees Celsius). In addition to incorporating future projections of stream temperature based on climate change projections, we used stream temperature values for the fish-bearing network from the NorWeST regional database on modeled stream temperatures in August. Geospatial shapefiles of NetMap data are available on the Forest Service shared T drive in the CMWAP project directory.

Results

Stream Temperature and Flow Projections From NorWeST Analyses

We found that throughout the broader network outside of regulated reaches, temperature increases were relatively uniform, except for smaller increases in streams at the highest elevations along the eastern and southern portions of the CMWAP assessment area (figs. 4.3c and 4.3d). A few long-term temperature monitoring sites in the McKenzie River basin located downstream of large dams and reservoirs showed little evidence of warming trends, or even exhibited cooling trends, during late summer months compared to nearby free-flowing reaches (fig. 4.4). Releases of cold water from upstream reservoirs may account for these local anomalies, and although they are implemented to moderate current effects of dams and reservoirs, coldwater releases represent a climate adaptation strategy to improve thermally stressful conditions for some fishes.

Potential changes in flow characteristics are described in chapter 3. There is spatial variation in projections for summer flows and the frequency of high-flow events during winter (figs. 4.5 and 4.6). The frequency of high winter flows is projected to change slightly, except along the flanks of Mount Hood and the Cascade crest in the eastern portion of the CMWAP assessment area, where greater increases are expected (figs. 4.5c and 4.5d). Summer flows are projected to decline by 22 to 43 percent in the 2040s and 38 to 58 percent in the 2080s (table 4.3), which implies rates of change similar to those observed in past decades at unregulated gages with long-term records in this area and regionally (Isaak et al. 2018). Summer flow is anticipated to decline more in streams at the highest elevations along the Cascade crest where snowpack is also projected to decline (figs. 4.6c and 4.6d). For

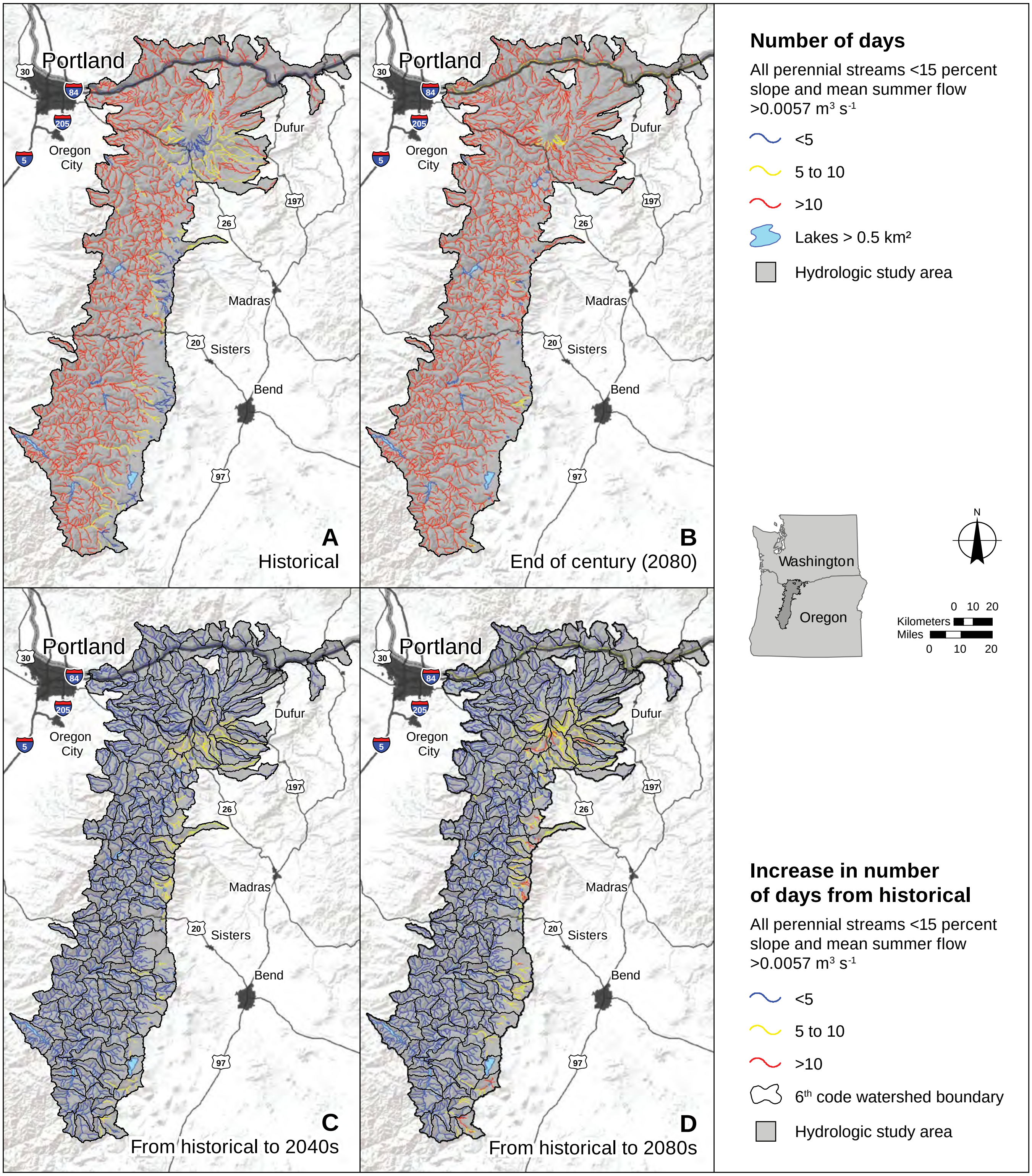

Figure 4.5—Scenarios depicting the number of days with high flows during winter across the 6969 km of streams in the Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest assessment area during (A) a baseline period (2000s) and (B) late 21st-century period (2080s). Panels C and D show future flow changes relative to the baseline period (future increases are summarized in app. A by 6th-field hydrologic unit code boundaries that are shown as small black polygons). ArcGIS shapefiles with reach-scale predictions of this flow information are available at the Western U.S. Stream Flow Metrics website (https://www.fs.fed.us/rm/boise/AWAE/projects/modeled_stream_flow_metrics.shtml).

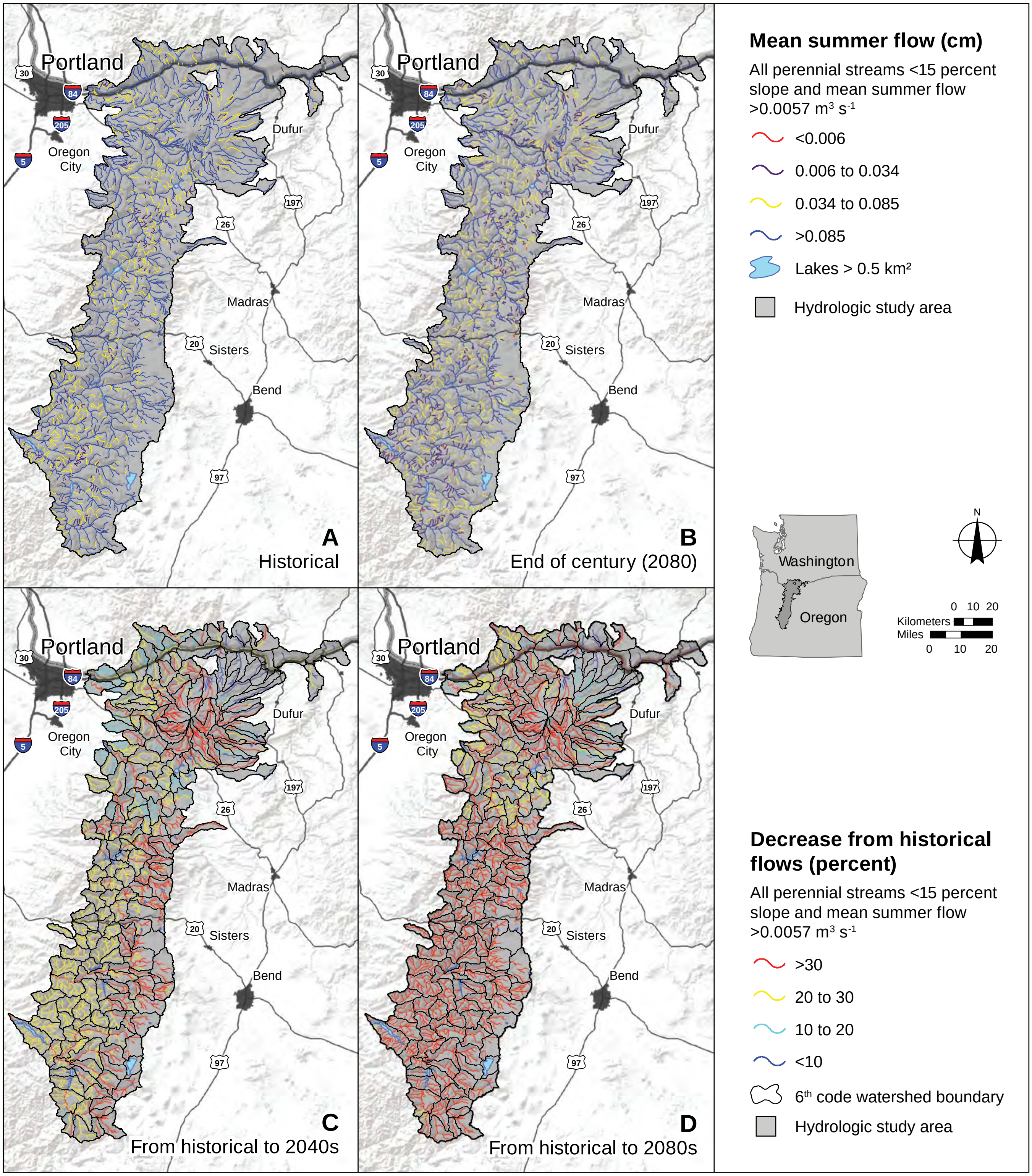

Figure 4.6—Scenarios depicting mean summer flows across the 6969 km of streams in the Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest assessment area during a baseline period (A: 2000s) and late 21st-century period (B: 2080s). Panels C and D show future flow changes as percentages relative to the baseline period (future increases are summarized in app. 4A.1 by 6th-field hydrologic unit code boundaries that are shown as small black polygons). ArcGIS shapefiles with reach-scale predictions of this flow information are available at the Western U.S. Stream Flow Metrics website (https://www.fs.fed.us/rm/boise/AWAE/projects/modeled_stream_flow_metrics.shtml).

Table 4.3—Summary of streamflow statistics relevant to fish populations in the Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest assessment area, based on changes associated with the A1B emission scenario (compared to the 1980s baseline)

		All lands		Forest Service lands	
Flow metric	Climate period	Day of year[a]	Days advance	Day of year	Days advance
Center of flow mass	1980s	149	—	151	—
	2040s	137	-12	137	-14
	2080s	131	-18	131	-20
		Number of days	Days increase	Number of days	Days increase
Winter 95-percentile flow	1980s	10.0	—	11.4	—
	2040s	11.6	1.6	13.3	1.9
	2080s	12.4	2.4	14.0	2.6
		Cubic meters per second	Percent change	Cubic meters per second	Percent change
Mean summer flow[b]	1980s	118.9	—	1.2	—
	2040s	92.4	-22.3	0.7	-43.3
	2080s	74.1	-37.7	0.5	-57.5
Mean annual flow	1980s	113.2	—	3.0	—
	2040s	120.0	6.0	3.0	1.0
	2080s	125.1	10.5	3.0	0.3

— = not applicable.

[a] Refers to day of water year starting October 1.

[b] Average flow across all reaches in the network.

additional spatial resolution, this chapter's appendix provides a tabular summary of conditions for flow and stream temperature characteristics over the historical and future climate periods by 6th-code hydrologic unit (basin).

Application and Discussion

Focal Species Status and Vulnerability

Interactions among climate change, other stressors, the physiological requirements and life history of the species, habitat availability, and shifts in aquatic community composition determine the vulnerability of different fish populations. We focus on spring-spawning and fall-spawning fishes, many of which are already in peril, because climate change may make them even more vulnerable (table 4.1). Some fishes are immediately affected by climate change, whereas others may temporarily benefit from projected changes in stream condition. We discuss vulnerabilities and contextualize them in this section using (1) species-specific distribution maps provided by the USDA Forest Service Pacific Northwest Region with NorWeST modeling of temperature and VIC modeling of flows; and (2) a fine-scale analysis using NetMap tools. Fish distribution data from Forest Service Pacific Northwest Region (acquired fall 2018) were the best available information at the time, but the database is currently being updated.

Spring-Spawning Fish

Climate change is already affecting fishes, although there is still much uncertainty about how those effects vary by life stage and season, as well as with watershed-scale and reach-scale stream characteristics. Although the timing of their upstream migration into river systems may vary, spring-spawning fishes lay their eggs in spring. Emerging fry and developing juveniles stay in the gravel during spring and early summer. Consequently, egg and early-emergent life stages of these fishes are vulnerable to freshwater and forest conditions during spring and early summer months. Changes in flow and temperature during this time can affect habitat, survival, and outmigration timing for spawning and rearing fishes. In addition, some fishes rear for an extended period in fresh water and are consequently affected by stream habitat conditions for a greater proportion of their life cycle.

Increasing flows in winter projected under climate change (fig. 4.5) may destabilize redds for fish that spawn early, but spring-spawning fish are generally less susceptible to high flows during winter than fall spawners because they are larger going into the winter months. If the higher winter flows persist into spring, then emerging smaller fish may be more susceptible to displacement by higher flows. Decreasing flows in summer, which are anticipated for most streams in the assessment area by 2080, especially along the Cascade crest (fig. 4.6), may dewater later-hatching redds, compromise critical rearing habitat, push juveniles into main channels where they face competition with and predation by adult conspecifics and other larger fish, and increase disease transmission and development. Changes in stream temperature and flow may effectively block the passage of adult fish that are moving through or holding in streams in transit to spawning sites, or may cause them to accelerate or delay the timing of their upstream or downstream movements.

Steelhead and redband trout—

Oncorhynchus mykiss has an extensive native distribution spanning the entire west coast of North America, and portions of Asia (Penaluna et al. 2016). The species expresses multiple life histories, including sea-run, estuarine, adfluvial, and resident. *O. mykiss* found west of the Cascade Range and Sierra Nevada along the Pacific coast are currently classified as coastal rainbow trout (*O. m. irideus* Gibbons), with the sea-run form known as steelhead. Inland rainbow trout groups occurring east of the Cascade Range and the Sierra Nevada along the Pacific coast are classified as redband trout (*O. mykiss* spp.) (Muhlfeld et al. 2015), which can be resident or adfluvial but not anadromous. The current hypothesis for the expression of anadromy or residency of *O. mykiss* is as a response to the combination of absolute water temperature and variation in water temperature, with colder thermal regimes fostering residency via earlier maturation (Kendall et al. 2014). Regardless of whether the *O. mykiss* lineage is steelhead, rainbow trout, or redband trout, they spawn in spring. The Columbia River redband trout reside in rivers and streams, and steelhead are found in the mainstem and tributaries all the way up the Columbia River.

***Steelhead*—**Steelhead are grouped into summer and winter runs, with the type of run determined by the season of the year that the fish enter fresh water. Although both summer and winter steelhead spawn in spring, they enter the river at different times and different stages of reproductive maturity, leading to different vulnerabilities to climate change. Summer steelhead return to fresh water in early summer months and hold in rivers and streams for several months before spawning. Winter steelhead migrate into rivers in late fall, early winter, and spring and often spawn shortly after entering fresh water, rendering them more vulnerable to ocean conditions than summer steelhead, which spend more time in fresh water. Juveniles of both winter- and summer-run fish rear for one or more years in relatively steep channels, where they may be vulnerable to more frequent or larger disturbances associated with wildfires and debris flows or floods and scour (Goode et al. 2012, Sloat et al. 2016).

Winter and summer steelhead co-occur, but rivers tend to be dominated by one type. For example, the Lower Columbia River has winter steelhead. However, near the Columbia River Gorge (in the assessment area), summer steelhead begin to predominate. Consequently, both winter and summer steelhead runs are important for rivers that connect to the Columbia River in the assessment area, including the Clackamas and Hood Rivers. However, the McKenzie and Middle Fork Willamette Rivers also currently have summer steelhead runs as a result of hatchery programs.

In the CMWAP assessment area, summer steelhead consist of populations from the Lower and Middle Columbia River populations, which are listed as threatened under the Endangered Species Act. Distributions of summer steelhead comprise 886 km of streams (fig. 4.7, table 4.4). Summer steelhead in the assessment area do not include resident forms (redband or rainbow trout), and they do not co-occur in the same streams with winter steelhead. Five major population groups have been identified for summer steelhead, including Lower Columbia–Hood, Lower Columbia–Wind, Middle Columbia–Deschutes (west of Cascade crest), Middle

Columbia-White Salmon, and Middle Columbia-Klickitat (fig. 4.7). The area inhabited by the Lower Columbia-Hood summer steelhead population group is projected to have more frequent winter peak flows, a decrease in summer low

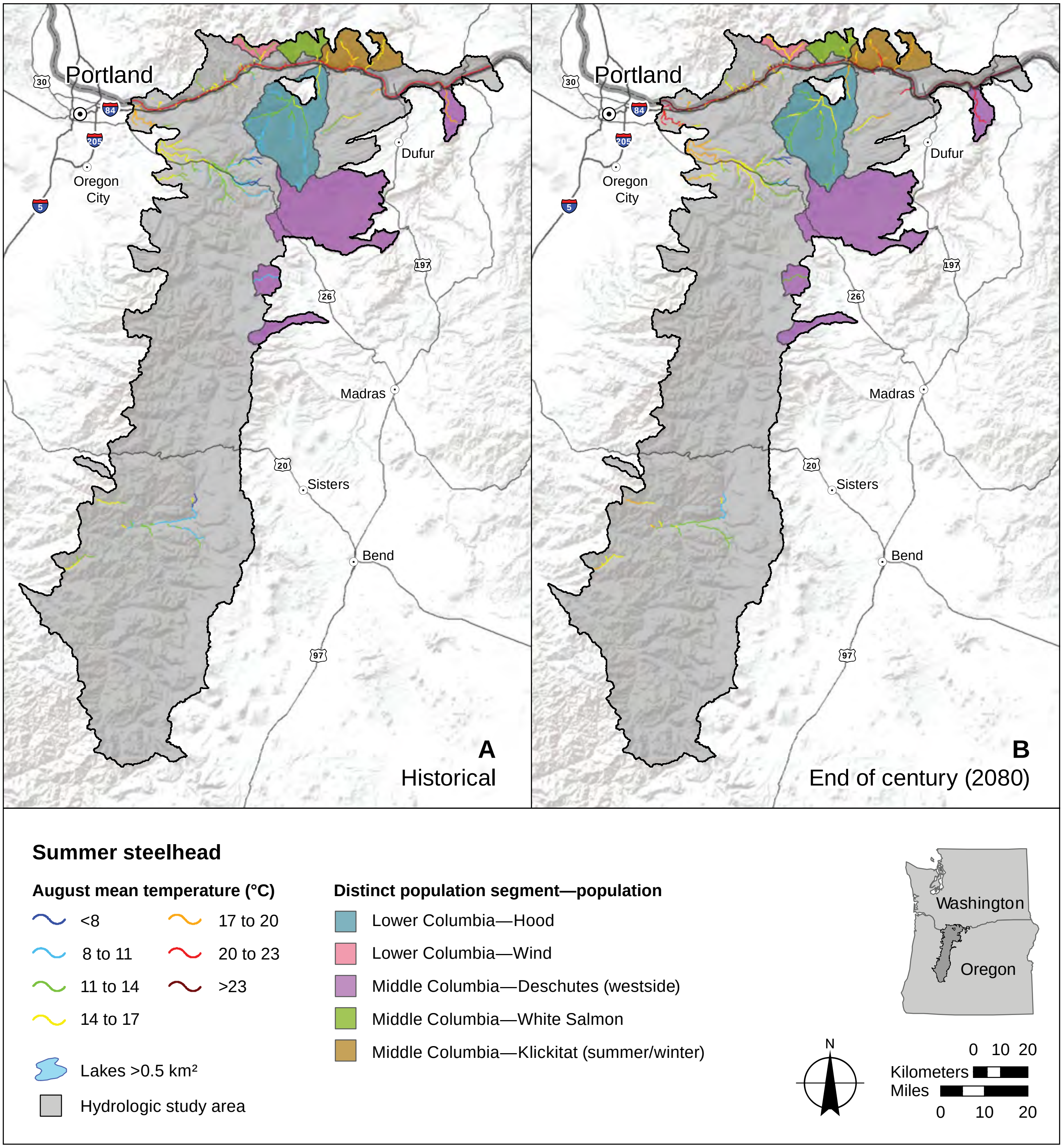

Figure 4.7—Summer stream temperatures in summer steelhead habitats during (A) the historical baseline period of the 2000s and (B) the 2080s based on NorWeST analyses and the A1B emission scenario.

Table 4.4—Streamflow and temperature characteristics for summer steelhead population groupings based on changes associated with the A1B emission scenario[a]

			Winter 95-percentile flow days			Summer flow m³ s⁻¹			August temperature °C						
Distinct population segment	**Population**	**Period**	**<5**	**5–10**	**>10**	**<0.034**	**0.034–0.085**	**>0.085**	**<8**	**8–11**	**11–14**	**14–17**	**17–20**	**20–23**	**>23**
Lower Columbia	Hood	1980s	8.0	30.3	105.6	0.5	3.0	140.4	0	64.6	61.3	18.1	0	0	0
		2040s	0	8.0	135.9	1.9	3.5	138.6	0	13.3	96.5	33.6	0.6	0	0
		2080s	0	2.1	141.8	1.9	10.0	132.0	0	2.2	89.3	40.5	11.9	0	0
Lower Columbia	Wind	1980s	0	0	26.2	0	2.7	23.5	0	0	20.3	5.9	0	0	0
		2040s	0	0	26.2	0	2.7	23.5	0	0	2.7	23.5	0	0	0
		2080s	0	0	26.2	0	2.7	23.5	0	0	1.0	22.9	2.2	0	0
Lower Columbia	None	1980s	80.8	46.0	280.0	6.8	20.2	379.8	23.5	50.4	129.7	104.0	42.0	56.4	0.9
		2040s	57.6	20.1	329.0	11.5	29.4	365.9	18.8	22.9	100.5	134.8	60.1	57.0	12.6
		2080s	3.0	56.1	347.7	16.2	28.5	362.0	17.0	11.5	79.0	121.8	86.2	44.1	47.1
Middle Columbia	Deschutes	1980s	0	0	29.4	1.3	0	28.1	0	12.6	0	0	16.8	0	0
	(west side)[b]	2040s	0	0	29.4	1.3	0.8	27.3	0	0	12.6	0	0	16.8	0
		2080s	0	0	29.4	1.3	2.0	26.1	0	0	12.6	0	0	16.8	0
Middle Columbia	White Salmon	1980s	0	0	9.8	0	0	9.8	0	0	8.4	1.4	0	0	0
		2040s	0	0	9.8	0	0	9.8	0	0	7.9	0.6	1.4	0	0
		2080s	0	0	9.8	0	0	9.8	0	0	2.5	5.9	1.4	0	0

			Winter 95-percentile flow days			Summer flow $m^3 s^{-1}$			August temperature °C						
Distinct population segment	**Population**	**Period**	**<5**	**5–10**	**>10**	**<0.034**	**0.034–0.085**	**>0.085**	**<8**	**8–11**	**11–14**	**14–17**	**17–20**	**20–23**	**>23**
Middle Columbia	Klickitat	1980s	0	0	37.4	0	6.8	30.6	0	0	1.0	28.6	7.8	0	0
	(summer/winter)	2040s	0	0	37.4	0	6.8	30.6	0	0	0	11.7	22.7	3.0	0
		2080s	0	0	37.4	0	9.3	28.1	0	0	0	4.6	26.8	6.0	0
Middle Columbia	None	1980s	76.0	0	32.2	0	2.2	107.3	0	1	7.5	8.1	10.0	78.4	0
		2040s	76.0	0	32.2	0	2.2	107.3	0	0	6.0	9.7	8.2	22.5	66.4
		2080s	0	76.0	32.2	0	2.2	107.3	0	0	3.0	11.5	8.0	9.7	77.3
Upper Willamette	None	1980s	0	0	12.1	0	0.4	11.7	0	0	1.2	10.1	0	0	0
		2040s	0	0	12.1	0.4	0	11.7	0	0	0	9.9	2.2	0	0
		2080s	0	0	12.1	0.4	0	11.7	0	0	0	4.4	7.7	0	0
None	None	1980s	0	3.1	86.0	0	5.3	83.8	6.3	36.5	35.3	11.0	0	0	0
		2040s	0	0	89.1	0	7.6	81.5	2.1	22.1	44.9	19.1	1.0	0	0
		2080s	0	0	89.1	1.0	6.7	81.5	0	13.4	50.6	20.9	4.3	0	0
Columbia	Segment shared by lower and middle	1980s	23.4	0	0	0	0	23.4	0	0	0	0	0	23.4	0
		2040s	23.4	0	0	0	0	23.4	0	0	0	0	0	1.3	22.1
	Columbia distinct population segment	2080s	0	23.4	0	0	0	23.4	0	0	0	0	0	10.1	13.3

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[a] Habitat extent matches the 886 km shown in figure 4.7 and is based on the Forest Service Pacific Northwest Region fish distribution database. Values are stream kilometers.

[b] Deschutes population includes portion of mainstem that splits Deschutes east-side and west-side populations.

flows, and warmer August stream temperatures. For example, streams inhabited by summer steelhead in the Lower Columbia-Hood population will see an increase in stream area with 10 or more days of 95th-percentile flows (from 106 stream kilometers historically to 142 stream kilometers by 2080) (table 4.4).

Because summer steelhead hold for extended periods in tributaries before spawning, lower flows and warmer temperatures place additional stress on these fish that may increase prespawn mortality rates or impair their spawning ability and the viability of eggs and embryos. Summer steelhead (particularly populations in the Middle Columbia) are projected to experience warmer temperatures and lower flows while in fresh water, and consequently, may find fewer coldwater refugia (table 4.4). Because summer steelhead make long upstream migrations to spawning grounds during warmer parts of the year, elevated stream temperatures will result in higher metabolic costs and mortality (Rand et al. 2006). Fish that do arrive at spawning grounds may be less capable of effective reproduction (Miller et al. 2011).

Winter steelhead inhabit 1177 km of stream in the assessment area (fig. 4.8, table 4.5). Winter steelhead do not include resident rainbow trout, summer steelhead, or redband that co-occur with them. Eleven major population groups have been identified as winter steelhead distinct population segments (fig. 4.8) for the Lower Columbia, Middle Columbia, and Upper Willamette Rivers. The Lower Columbia includes Clackamas, Hood, Sandy, Lower Gorge, and Upper Gorge River segments. The Middle Columbia includes Fifteenmile Creek and Klickitat River segments. The Upper Willamette includes Calapooia, Mollala, North Santiam, and South Santiam River segments. Like summer steelhead, the Lower Columbia-Hood winter steelhead population is projected to experience higher winter peak flows, decreases in summer low flows, and increases in August stream temperatures by 2080 (table 4.5, fig. 4.8). These changes are not expected in the area inhabited by the Lower Columbia-Wind population (table 4.4). These findings suggest that under climate change, winter steelhead will not experience uniform change across population segments; rather, each population will need to be evaluated independently. One potential management action to reduce stream temperatures is to increase riparian shading. For example, in the South Santiam River, water temperatures could potentially be reduced by effective riparian management along tributaries to the mainstem South Santiam River and Moose Creek (fig. 4.9).

In general, steelhead are vulnerable to warming temperatures under climate change, potentially leading to a change in life-history expression for *O. mykiss,* with a loss of steelhead life-history forms and an increase among inland rainbow trout forms of fluvial, adfluvial, and resident forms (Benjamin et al. 2013). Steelhead persist, at least in part, because there is a fitness advantage associated with migrating to the ocean to feed and returning to fresh water to spawn (Quinn and Myers 2004). If this advantage is reduced or lost, residency could increase in populations, assuming that changes in the freshwater environment are suitable for the persistence of the freshwater life-history variants of rainbow trout, including redband trout (Benjamin et al. 2013). Other Pacific coast populations of *O. mykiss* maintain primarily resident populations in locations where the stream temperatures

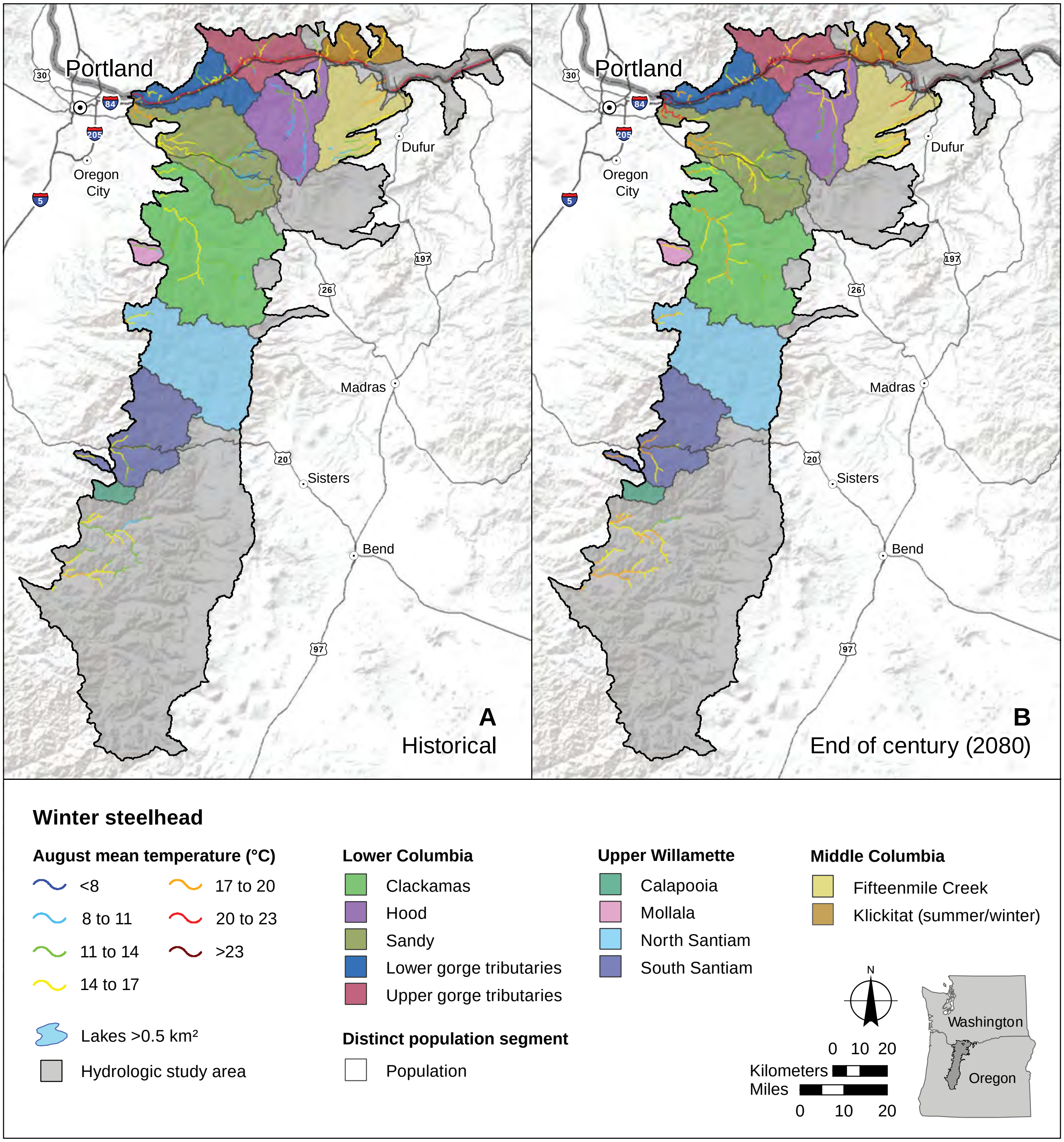

Figure 4.8—Summer stream temperatures in winter steelhead habitats during (A) the historical baseline period of the 2000s and (B) the 2080s based on NorWeST analyses and the A1B emission scenario.

Table 4.5—Streamflow and temperature characteristics for winter steelhead population groupings based on changes associated with the A1B emission scenario[a]

			Number of winter 95-percentile flow days			Summer flow $m^3 s^{-1}$			August temperature °C						
Distinct population segment	**Population**	**Period**	**<5**	**5–10**	**>10**	**<0.034**	**0.034–0.085**	**>0.085**	**<8**	**8–11**	**11–14**	**14–17**	**17–20**	**20–23**	**>23**
Lower Columbia	Clackamas	1980s	0	1.8	156.9	2.1	1.4	155.1	0	3.2	81.6	73.9	0	0	0
		2040s	0	0	158.7	2.1	6.8	149.8	0	0	51.8	101.8	5.1	0	0
		2080s	0	0	158.7	2.1	8.9	147.6	0	0	37.8	66.8	54.1	0	0
Lower Columbia	Hood	1980s	15.0	35.1	59.6	0.5	3.0	106.3	1.5	49.8	40.4	18.1	0	0	0
		2040s	0	15.0	94.8	1.9	1.7	106.3	0	15.7	61.0	32.5	0.6	0	0
		2080s	0	2.1	107.7	1.9	6.6	101.4	0	6.1	57.9	33.9	11.9	0	0
Lower Columbia	Lower Gorge	1980s	39.9	0	57.1	2.3	9.8	84.9	0	0	17.2	30.3	10.4	39.2	0
		2040s	39.9	0	57.1	6.6	6.5	84.0	0	0	4.0	29.6	23.5	30.9	8.9
		2080s	0	39.9	57.1	6.6	6.5	84.0	0	0	3.0	19.6	30.2	9.6	34.6
Lower Columbia	Sandy	1980s	31.4	51.4	204.4	3.6	9.2	274.5	27.3	56.8	106.4	68.2	28.6	0	0
		2040s	7.3	21.1	258.9	4.0	20.0	263.3	21.6	28.1	96.5	93.8	39.0	8.2	0
		2080s	3.5	5.3	278.5	7.7	21.6	257.9	19.8	13.5	82.6	93.1	53.9	24.3	0
Lower Columbia	Upper Gorge	1980s	38.1	0	39.1	1.0	12.0	26.2	0	1.8	15.6	11.7	4.4	4.9	0.0
		2040s	38.1	0	39.1	1.0	13.2	25.0	0	0	9.7	18.1	3.3	4.3	3.7
		2080s	0	38.1	39.1	2.0	12.8	24.4	0	0	3.6	19.4	7.0	4.6	4.6
Middle Columbia	Fifteenmile Creek	1980s	0	19.3	75.9	1.1	15.8	78.3	0	11.8	29.6	34.4	19.4	0	0
		2040s	0	0	95.2	1.1	19.8	74.3	0	4.8	21.9	33.6	16.8	18.1	0
		2080s	0	0	95.2	5.7	16.5	73.0	0	0.6	17.7	31.3	26.2	19.5	0

			Number of winter 95-percentile flow days			Summer flow $m^3 s^{-1}$			August temperature °C						
Distinct population segment	**Population**	**Period**	**<5**	**5–10**	**>10**	**<0.034**	**0.034–0.085**	**>0.085**	**<8**	**8–11**	**11–14**	**14–17**	**17–20**	**20–23**	**>23**
Middle Columbia	None	1980s	53.4	0	12.4	0	0	47.9	0	0	7.6	2.7	1.6	35.5	0
		2040s	53.4	0	12.4	0	0	47.9	0	0	7.6	0	2.7	4.8	32.5
		2080s	0	53.4	12.4	0	0	47.9	0	0	2.5	5.3	2.7	1.9	35.4
Middle Columbia	Klickitat (summer/winter)	1980s	0	0	39.2	0	6.8	32.4	0	0	1.0	30.4	7.8	0	0
		2040s	0	0	39.2	0	6.8	32.4	0	0	0	11.7	24.5	3.	0
		2080s	0	0	39.2	0	9.3	29.9	0	0	0	4.6	28.6	6.0	0
Upper Willamette	Mollala	1980s	0	0	11.5	0	0	11.5	0	2.0	9.5	0	0	0	0
		2040s	0	0	11.5	0	0	11.5	0	0	8.0	3.5	0	0	0
		2080s	0	0	11.5	0	0	11.5	0	0	4.0	7.51	0	0	0
Upper Willamette	North Santiam	1980s	0	0	18.7	0	0	18.7	0	0	3.6	13.8	1.2	0	0
		2040s	0	0	18.7	0	0	18.7	0	0	0	9.7	9.0	0	0
		2080s	0	0	18.7	0	0	18.7	0	0	0	5.9	12.8	0	0
Upper Willamette	South Santiam	1980s	0	0	56.9	0	0	56.9	0	0	13.7	43.3	0	0	0
		2040s	0	0	56.9	0	0	56.9	0	0	3.4	30.5	23.0	0	0
		2080s	0	0	56.9	0	0	56.9	0	0	0.4	20.9	35.6	0	0
None	None	1980s	0	0	160.6	0	8.2	152.4	0	10.5	59.6	84.0	6.6	0	0
		2040s	0	0	160.6	1.2	11.6	147.8	0	5.2	19.8	114.5	21.2	0	0
		2080s	0	0	160.6	3.4	9.5	147.7	0	1.5	15.7	80.4	63.0	0	0

Note: Calapooia population is not listed because there are no winter steelhead within the assessment area.

[a] Habitat extent matches the 1177 km shown in figure 4.8 and is based on the Forest Service Pacific Northwest Region fish distribution database. Values are stream kilometers.

are warming, such as in southern California (Penaluna et al. 2016). Overall, summer and winter steelhead in the CMWAP assessment area have a high climate vulnerability in the Middle Columbia River areas and moderate vulnerability in the Lower Columbia River areas owing to the extra time they spend in freshwater and their requirement for cold, connected habitats (table 4.1).

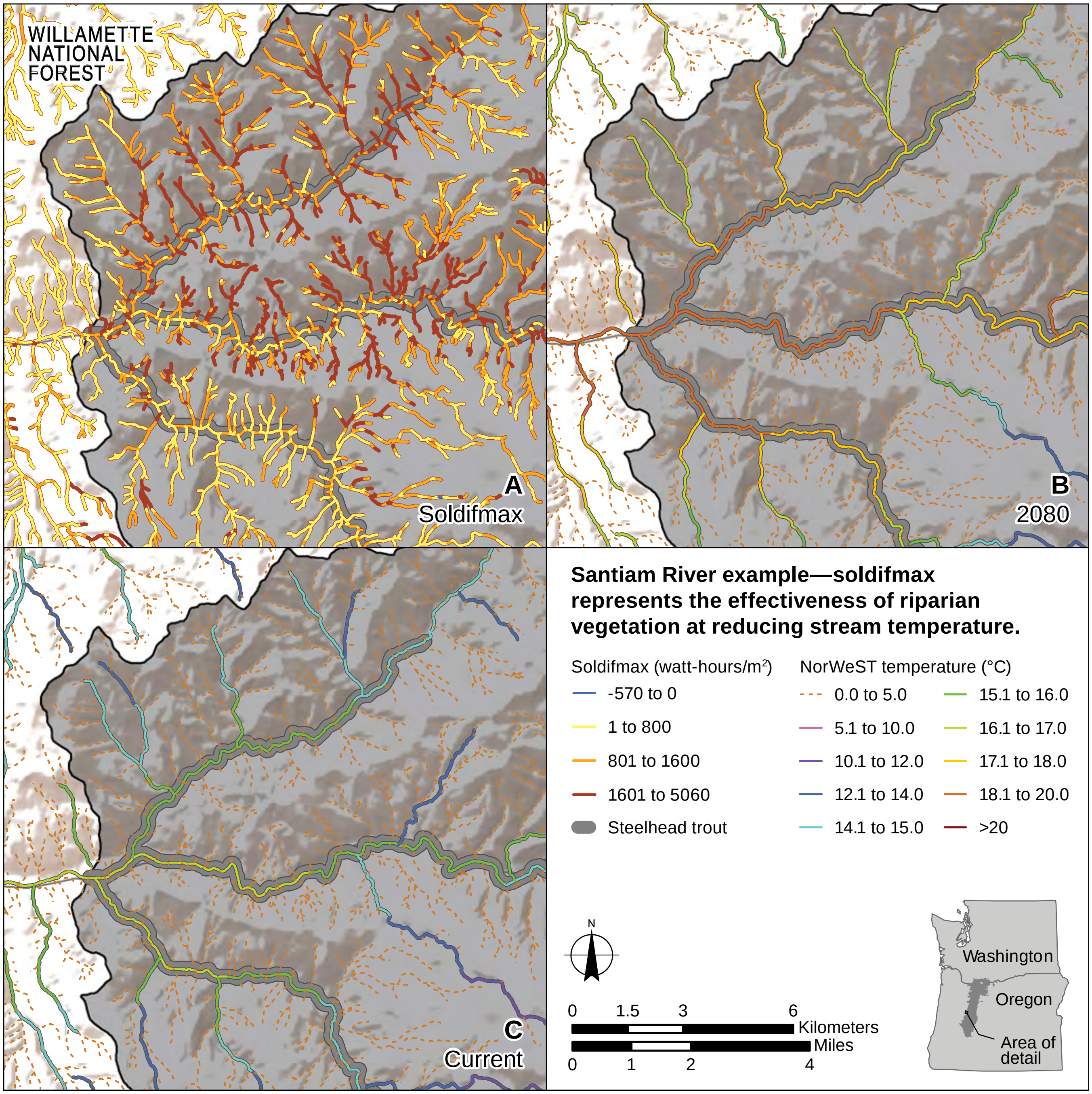

Figure 4.9—Simulated streams in South Santiam River for steelhead (summer and winter combined distribution) with effectiveness of riparian vegetation on water temperature (using (A) soldifmax metric), (B) projection for the 2080s from a composite average of 10 global climate models (under the A1B emission scenario) for the Western United States, and (C) summer stream temperatures during the current baseline period of the 2000s based on NorWeST analyses and the A1B emission scenario.

***Redband trout*—**Redband trout are found in watersheds in both the CRGNSA and Mount Hood NF, including the Deschutes River watershed. In the CMWAP assessment area, their distribution comprises 591 km of stream habitat (fig. 4.10, table 4.6). The lineage of redband trout found in the assessment area is the Columbia River redband trout (*O. m. gairdneri* [Richardson]), which occurs east of the Cascade Range in the Columbia River and Harney Basin (Currens et al.

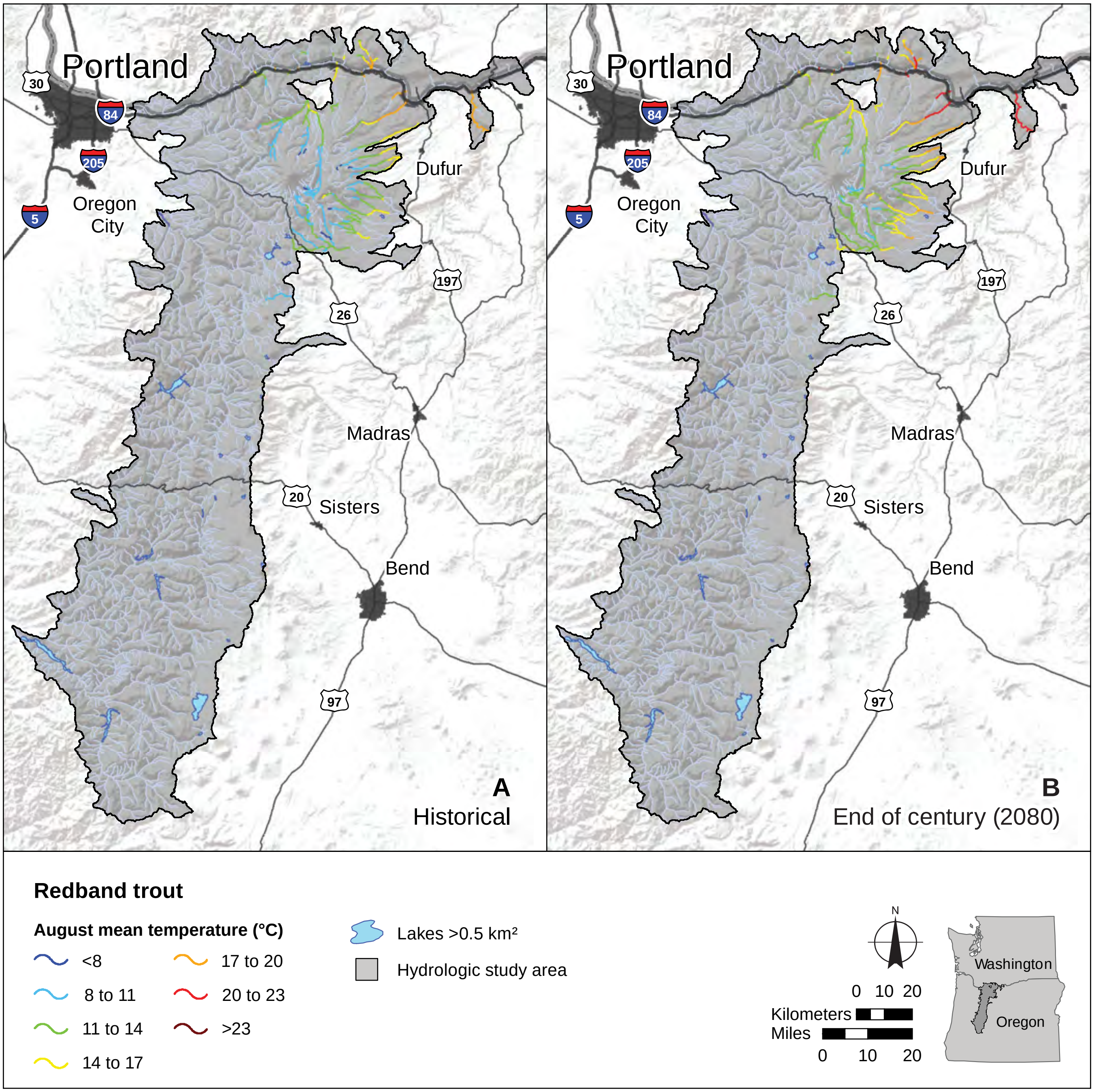

Figure 4.10—Summer stream temperatures in redband trout habitats during (A) the historical baseline period of the 2000s and (B) the 2080s based on NorWeST analyses and the A1B emission scenario.

2009). Columbia River redband trout is considered a species of special concern by the American Fisheries Society and the U.S. Department of the Interior, Fish and Wildlife Service.

Redband trout have moderate climate vulnerability because of their dependence on connected, coldwater habitats that are limited in availability (table 4.1). Distributions of redband trout depend on instream flows that vary by water year, with that variation directly tied to climate regimes. Redband trout are generally stream-living resident fishes, but if streams connect to lakes or reservoirs, they can express adfluvial migratory life histories. For example, during drought years, distributions of redband trout constrict, because there is less water and consequently less habitat available, especially in surface-flow systems, and thus migratory life histories may revert to resident life histories.

Coastal cutthroat trout—

Coastal cutthroat trout have the broadest north-south distribution of any cutthroat trout lineage, extending from Prince William Sound, Alaska south to the Eel River in northern California, and inland a few hundred kilometers from the Pacific coast (Penaluna et al. 2016). In the CMWAP assessment area, their distribution comprises 3097 km of stream habitat (table 4.7, fig. 4.11). Coastal cutthroat trout are well known for their diversity of life histories, including sea-run, lacustrine, fluvial, and headwater resident freshwater populations. Several life-history expressions often co-occur, so that one population may use a wide variety of habitat types, including rivers, tributaries, headwater streams, lakes, estuaries, and the nearshore ocean.

Depending on local conditions, coastal cutthroat trout spawn from late winter through spring, with peak activity in February. Fry emerge between March and June. Upstream movements of adults occur year round, probably owing to various forms using the river at different times, but peak in July and August on the Umpqua River (Flitcroft et al. 2016). Coastal cutthroat trout are generally the salmonid found farthest upstream in a network, and hence they are often the fish used to determine the upper distribution boundary of fish throughout their range. Since 1999, there have been a series of petitions for listing of coastal cutthroat trout under the Endangered Species Act because of a decline in some populations. However, it seems likely that they will be precluded from listing, owing to their broad distribution within watersheds, from headwater streams to river mouths.

Coastal cutthroat trout have moderate vulnerability to climate change because they have multiple life-history strategies, offering flexibility in their responses, even though they are heavily dependent on fresh water (table 4.1). Like Pacific salmon and steelhead, sea-run forms of cutthroat will experience changes in marine and freshwater environments in the future. However, unlike other Pacific salmon, cutthroat trout tend to use nearshore habitats. Owing to their narrow marine distribution and shorter migration distances (compared with other interior

Table 4.6—Streamflow and temperature characteristics for redband trout habitats based on changes associated with the A1B emission scenario[a]

Stream metric	Period	Number of high-flow days						
		<5	5 to 10	>10				
Winter 95-percentile flow	1980s	56.4 (9.6)	193.0 (32.7)	341.0 (57.7)				
	2040s	14.2 (2.4)	27.7 (4.7)	549.0 (92.9)				
	2080s	0	21.3 (3.6)	570.0 (96.4)				
		Flow $m^3 s^{-1}$						
		<0.034	0.034 to 0.085	>0.085				
Summer flow	1980s	18.1 (3.1)	69.6 (11.8)	503.0 (85.2)				
	2040s	22.9 (3.9)	146.0 (24.6)	423.0 (71.5)				
	2080s	40.2 (6.8)	147.0 (24.9)	404.0 (68.4)				
		Temperature °C						
		<8	8 to 11	11 to 14	14 to 17	17 to 20	20 to 23	>23
August temperature	1980s	14.3 (2.4)	213.0 (36.1)	226.0 (38.3)	85.2 (14.4)	51.9 (8.8)	0	0
	2040s	2.0 (0.3)	85.6 (14.5)	289.0 (48.9)	133.0 (22.5)	37.8 (6.4)	43.5 (7.4)	0
	2080s	0	36.6 (6.2)	273.0 (46.1)	170.0 (28.7)	63.8 (10.8)	48.8 (8.3)	0

[a] Habitat extent matches the 591 km shown in figure 4.10 and is based on the Forest Service Pacific Northwest Region fish distribution database. Values are stream kilometers, and those in parentheses are percentages of the total.

Table 4.7—Streamflow and temperature characteristics for coastal cutthroat trout habitats based on changes associated with the A1B emission scenario[a]

Stream metric	Period	Number of high-flow days						
		<5	5 to 10	>10				
Winter 95-percentile flow	1980s	270.0 (8.7)	326.0 (10.5)	2501.0 (80.8)				
	2040s	139.0 (4.5)	83.8 (2.7)	2874.0 (92.8)				
	2080s	9.9 (0.3)	133.0 (4.3)	2954.0 (95.4)				
		Flow $m^3 s^{-1}$						
		<0.034	0.034 to 0.085	>0.085				
Summer flow	1980s	101.0 (3.3)	392.0 (12.7)	2603.0 (84.1)				
	2040s	190.0 (6.1)	585.0 (18.9)	2322.0 (75.0)				
	2080s	238.0 (7.7)	656.0 (21.2)	2202.0 (71.1)				
		Temperature °C						
		<8	8 to 11	11 to 14	14 to 17	17 to 20	20 to 23	>23
August temperature	1980s	103.0 (3.3)	911.0 (29.4)	1308.0 (42.3)	593.0 (19.2)	68.1 (2.2)	112.0 (3.6)	0.6 (0.1)
	2040s	31.1 (1.0)	462.0 (14.9)	1355.0 (43.8)	956.0 (30.9)	145.0 (4.7)	112.0 (3.6)	35.7 (1.2)
	2080s	14.5 (0.5)	242.0 (7.8)	1179.0 (38.1)	1090.0 (35.2)	406.0 (13.1)	71.0 (2.3)	94.7 (3.1)

[a] Habitat extent matches the 3097 km shown in figure 4.11 and is based on the Forest Service Pacific Northwest Region fish distribution database. Values are stream kilometers, those in parentheses are percentages of the total.

populations of Pacific salmon), their response to climate change will depend on coastal conditions (Di Lorenzo and Mantua 2016). Under a warming climate, returning adults of the sea-run form and juveniles of various forms found farther down in the network may be more sensitive to increased temperatures on river mainstems.

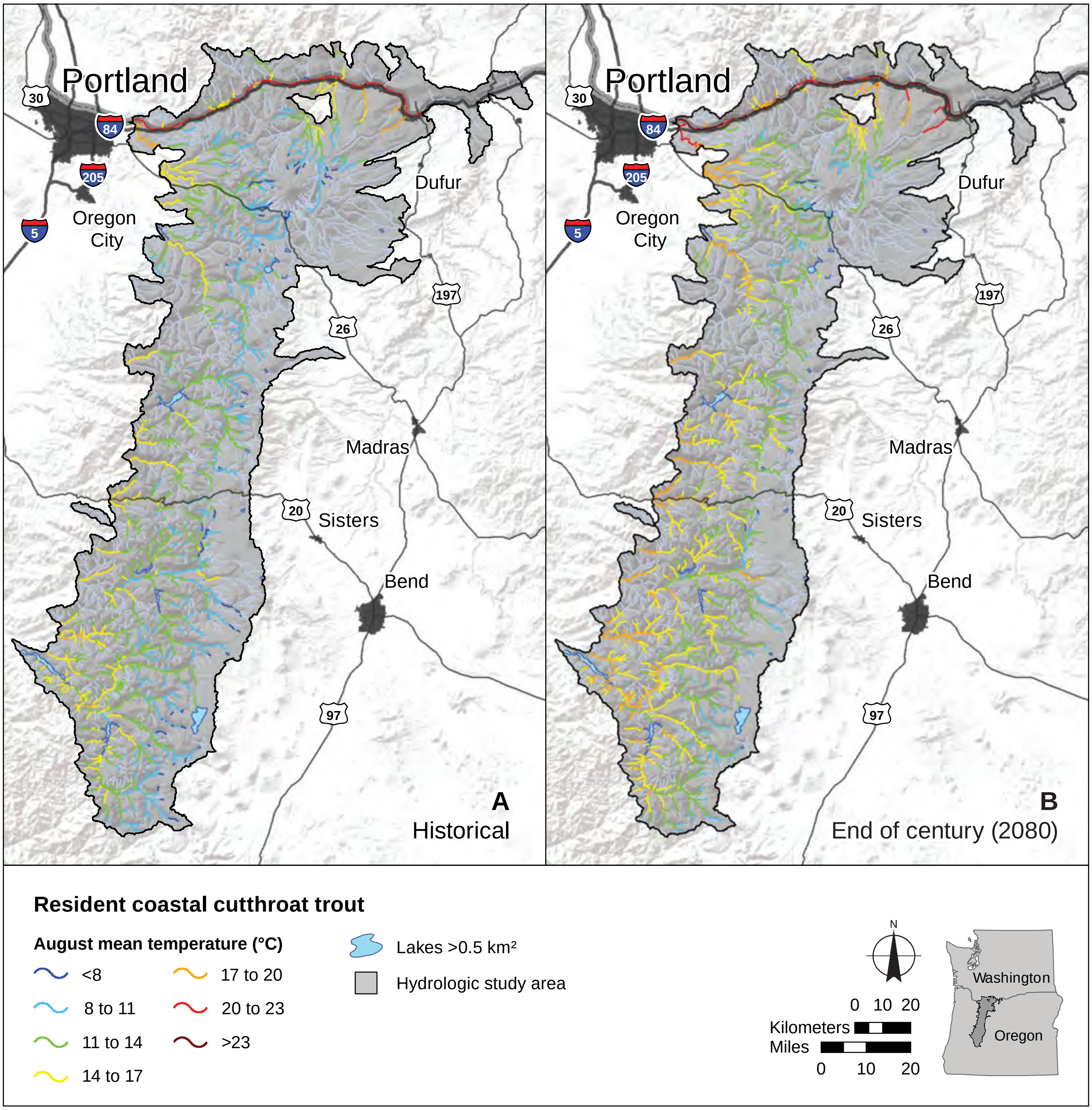

Figure 4.11—Summer stream temperatures in coastal cutthroat trout habitats during (A) the historical baseline period of the 2000s and (B) the 2080s based on NorWeST analyses and the A1B emission scenario.

For freshwater forms that are found higher up in the stream network, climate change may increase susceptibility to lower flows, increased temperatures, and the aftereffects of wildfire. Fire can increase risks of debris flows and remove the riparian shading that helps keep water temperatures cool. Flow reductions in headwater streams during seasonal low flows could push resident coastal cutthroat trout downstream and compromise their ability to cope with drought by reducing their habitat network of connected, perennially flowing water (Battin et al. 2007). The downstream displacement of headwater-rearing fish will expose them to warmer stream temperatures than those to which they are adapted, and possibly to harmful biological interactions with native and nonnative species found lower in the watershed. Conservation plans for coastal cutthroat trout include restoration to maintain cold water in both smaller tributaries and in mainstem river channels, along with enhancement of the abundance of pools and instream cover throughout the network by allowing large wood to naturally recruit to streams.

Pacific lamprey—

Pacific lamprey are distributed from Mexico north into Alaska and Asia, and into the interior west of the Rocky Mountains in North America. They are a sea-run fish, requiring connectivity among ocean, estuarine, and freshwater habitats to survive, similar to Pacific salmon and trout. Adult lamprey spend 1 to 3 years in the ocean and have a jawless, sucker-like mouth allowing them to parasitize other fish during their oceanic phase. They return to fresh water in spring, with upstream migrations occurring from May through July, resulting in spawning in fresh water the following March through July. Spawning usually occurs in low-gradient rivers (<2 percent slope), followed by a lengthy larval stage that lasts 3 to 7 years, which they spend burrowed into sandy substrates. At broad scales in fresh water, Pacific lamprey larvae prefer deeper waters and open riparian canopy, whereas patchiness in larval occurrence at fine scales is associated with low-water velocity, channel unit morphology (pool habitats), and availability of fine-grained sandy habitats suitable for burrowing (Torgersen and Close 2004). Lamprey migrate downstream during higher flows in winter and spring.

Sandy and Tualatin River populations are considered the most stable because they exist in basins with high historical variation in flow and temperature relative to projections based on climate change scenarios and consequently should be more adapted to change (USDI FWS 2017). However, their abundance has declined in the last 60 years, and distributions in eastern Oregon, eastern Washington, and Idaho are presumed extirpated or severely restricted. Although recent attention to Pacific lamprey has increased our understanding of this species in the region, it remains understudied.

In the assessment area, Pacific lamprey inhabit 282 km of stream habitat, most of it in the Lower Columbia-Sandy area (table 4.8, figs. 4.12 and 4.13), but a better understanding of their distribution is needed throughout the assessment area. Four major population groups have been identified for the Pacific lamprey distinct population segment (fig. 4.12): Lower Columbia-Sandy, McKenzie, Middle Columbia-Hood, and Middle Fork Willamette.

Altered hydrologic regimes and stream temperatures in fresh water caused by climate change could severely affect Pacific lamprey in the assessment area. For example, in a study focused on the survival of embryonic and newly hatched Pacific lamprey, survival was the highest at 18 °C and lowest at 22 °C, suggesting that temperatures above 20 °C cause severe stress (Meeuwig et al. 2005). In addition, water temperatures above 21 °C are expected to lower incidence of metamorphosis for sea lamprey (Holmes and Youson 1998). The same effect may occur in Pacific lamprey, although based on Meeuwig's (2005) work, the species likely has an even lower temperature threshold. This is especially ominous when populations in the Middle Fork Willamette and the Lower Columbia are projected to experience more stream kilometers over 20 °C by 2080 than they do now, especially in the Lower Columbia, which will have almost 74 more stream kilometers with temperatures warmer than 23 °C (table 4.8).

Owing to their longer residence time in fresh water, larval Pacific lamprey are considered highly vulnerable to climate change in the assessment area (table 4.1). The Lower Columbia-Sandy population inhabits streams projected to have more frequent occurrences of winter peak flows, which can affect their lengthy rearing period as larvae. Further, increased August stream temperatures (by 2080) may affect survival of larval lamprey and the timing of metamorphosis into their sea-going life stage (table 4.8). Increased water temperature could prematurely push juvenile lamprey into downstream migration toward estuary and ocean environments, exposing them to saltwater before they have made the physiological changes needed for osmoregulation. Wildfire or higher spring flows may lead to debris flows or scour, also problematic for lamprey larvae.

Fall-Spawning Fish

Fall-spawning fishes are vulnerable to seasonal changes in temperature and flow patterns in every season. Long-term trends toward lower flows and higher temperatures in summer may make coldwater refugia more difficult to find, particularly for species with long-term freshwater residency, such as bull trout, coho salmon, and stream-type Chinook salmon. Projected reductions in flow by the end of this century could decrease potential population sizes by intensifying competition for food and space (Luce and Holden 2009). In fall, delays in rain

Table 4.8—Streamflow and temperature characteristics for Pacific lamprey population groupings based on changes associated with the A1B emission scenario[a]

		Winter 95-percentile flow days			Summer flow $m^3 s^{-1}$			August temperature °C						
Population (HUC8 subbasin)	**Period**	**<5**	**5–10**	**>10**	**<0.034**	**0.034–0.085**	**>0.085**	**<8**	**8–11**	**11–14**	**14–17**	**17–20**	**20–23**	**>23**
Lower Columbia—Sandy	1980s	106.1	26.3	20.4	0	0	152.7	10.0	14.4	23.1	0	11.1	94.1	0
	2040s	96.9	9.1	46.7	0	0.7	152.0	5.4	12.5	24.1	5.6	1.0	64.3	39.9
	2080s	1.0	95.9	55.8	0	0.7	152.0	4.7	8.7	21.5	12.6	0	31.3	73.8
Middle Columbia—Hood	1980s	44.6	0	30.5	0	0	75.1	0	0	15.1	7.6	7.8	44.6	0
	2040s	44.6	0	30.5	0	0	75.1	0	0	0	22.1	0.6	12.8	39.7
	2080s	0	44.6	30.5	0	0	75.1	0	0	0	16.6	3.8	7.8	44.6
McKenzie	1980s	0	0	25.8	0	0	25.8	0	5.2	17.9	2.8	0	0	0
	2040s	0	0	25.8	0	0	25.8	0	0.9	4.3	20.6	0	0	0
	2080s	0	0	25.8	0	0	25.8	0	0	5.2	20.6	0	0	0
Middle Fork Willamette	1980s	0	0	28.9	0	0	28.9	0	0	0	22.2	6.6	0	0
	2040s	0	0	28.9	0	0	28.9	0	0	0	12.1	16.8	0	0
	2080s	0	0	28.9	0	0	28.9	0	0	0	4.8	24.1	0	0

[a] Habitat extent matches the 282 km shown in figure 4.12 and is based on the Forest Service Pacific Northwest Region fish distribution database. Values are stream kilometers.

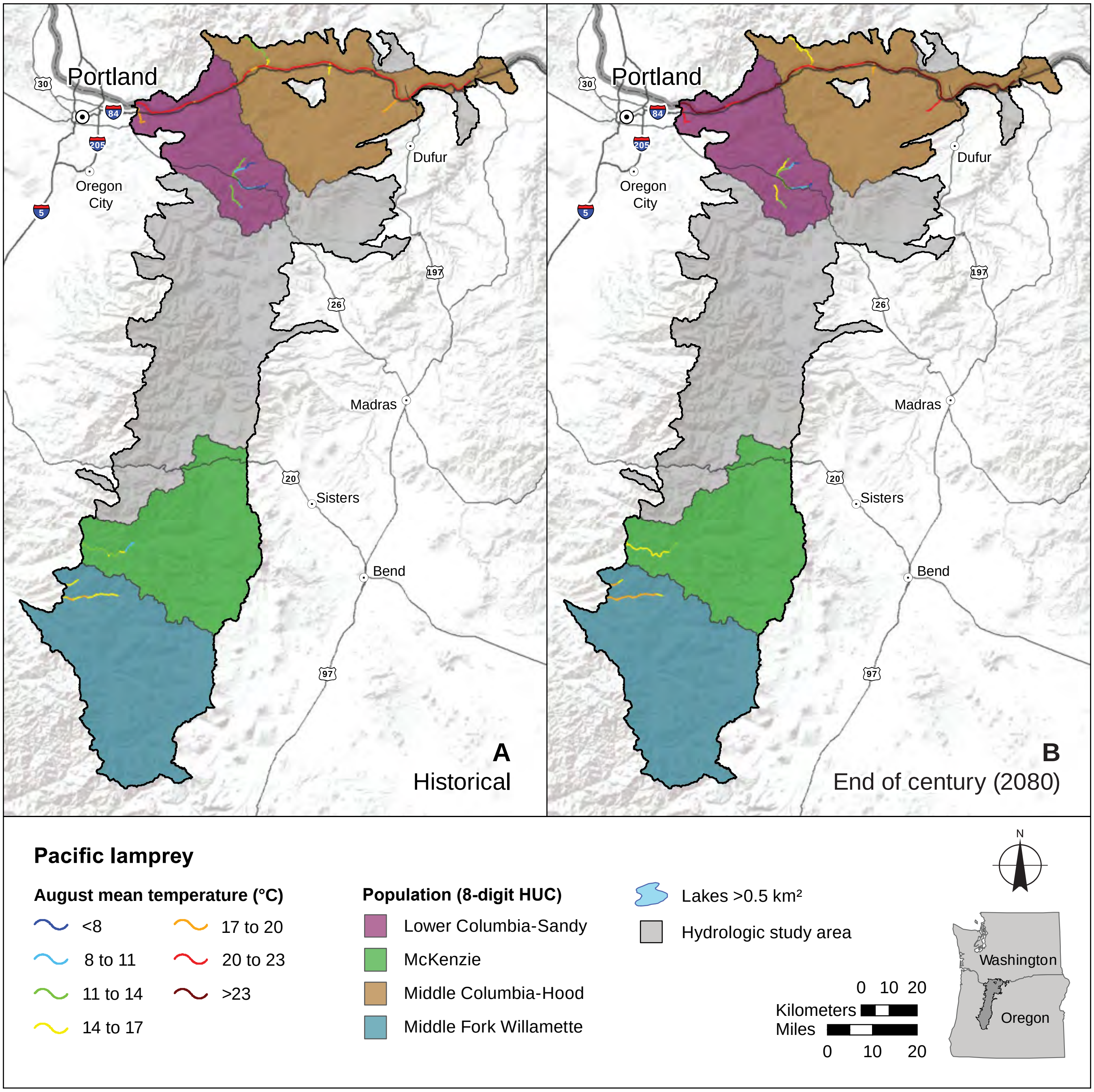

Figure 4.12—Summer stream temperatures in Pacific lamprey habitats during (A) the historical baseline period of the 2000s and (B) the 2080s based on NorWeST analyses and the A1B emission scenario. HUC = hydrologic unit code.

events and coincident lower flows may adversely affect access to stream reaches and spawning success. Shifts from snow-dominated to rain-dominated precipitation regimes or changes in storm patterns and delivery of precipitation can increase flood scour of incubating or newly emergent fishes (Goode et al. 2013). Scour effects vary depending on species and life history and are buffered by local variations in

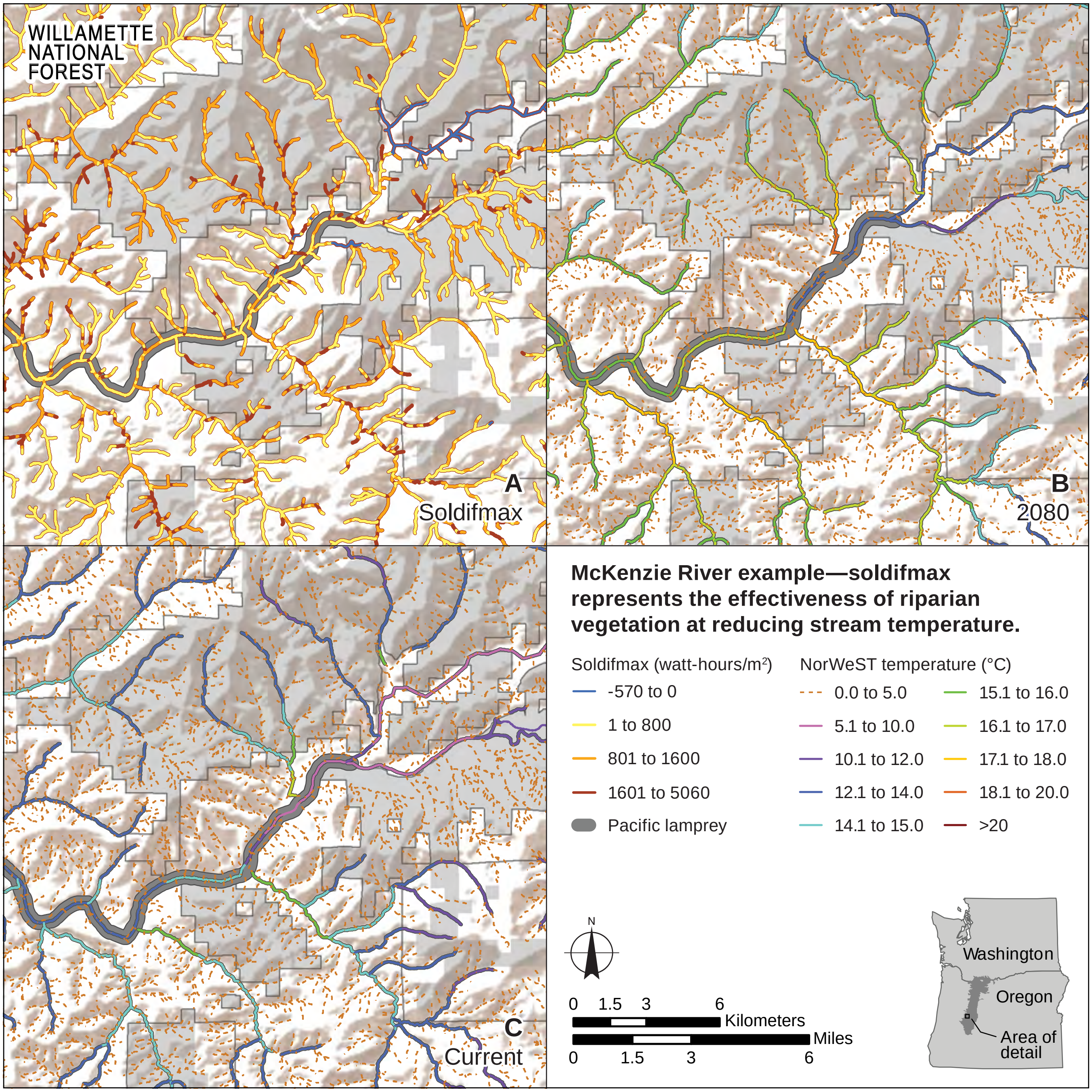

Figure 4.13—Simulated streams in the McKenzie River for Pacific lamprey (distribution in dark gray) with effectiveness of riparian vegetation on water temperature (using (A) soldifmax metric;), (B) future projection for the 2080s from a composite average of 10 global climate models (under the A1B emission scenario) for the Western United States, and (C) summer stream temperatures during the current baseline period of the 2000s based on NorWeST analyses and the A1B emission scenario.

channel confinement and geomorphology (Goode et al. 2013). Steeper valleys in confined areas where structural complexity is low have a higher probability of scour relative to unconfined floodplain streams (Sloat et al. 2016). Consequently, effects of scour may be greater for fishes such as coho salmon that use high-gradient streams (Sloat et al. 2016).

Bull trout—

Bull trout are native to Oregon, Washington, Montana, Idaho, Nevada, and southern Alaska. Juvenile bull trout generally rear for 1 to 3 years in headwater tributaries before moving downstream to larger rivers, lakes, or the Pacific Ocean. Bull trout require large, unfragmented, coldwater habitats to persist and are thus highly susceptible to human stressors (Dunham and Rieman 1999). Many large, stable populations of bull trout are adfluvial, and rearing takes place in lakes, reservoirs, or relatively pristine headwater habitats. Over the past few decades, the species has declined substantially from its historical distribution and abundance, owing to habitat degradation, overexploitation, reduced water quality, and decreased connectivity of critical habitat. Bull trout have been extirpated from California (McCloud River) since the 1970s, and only a single, isolated population exists in Nevada in the Jarbridge River. Consequently, they are listed as threatened in the conterminous United States under the Endangered Species Act. In the assessment area, their distribution covers 483 km of stream habitat (table 4.9, figs. 4.14 through 4.16), and populations are designated as Columbia River. Three core areas have been identified for bull trout, including Hood, Klickitat, and Upper Willamette, with Clackamas and White Salmon containing bull trout distributions outside of the core areas (fig. 4.14).

In the Upper Willamette core area, 17 percent of the streams supported optimal August temperatures (<11 °C) for bull trout in 1980. However, by 2080, only 4 percent of these streams are projected to remain within the optimal thermal range. This is the greatest potential loss among the three core areas. The Upper Willamette core area is also projected to see an increase in stream length experiencing high-flow events, described as locations with 10 or more days of 95th-percentile flows (from 151 km in 1980 to 178 km by 2080) (table 4.9). In contrast, other core areas are projected to have relatively stable peak-flow frequencies. The Klickitat core area is projected to have more stream length with warmer August temperatures than the other two areas, whereas the Hood core area retains more stream length within the optimal August temperature (4.5 percent in 1980 versus 2.5 percent in 2080) than the other two core areas, likely because it has more high-elevation terrain with colder air temperatures.

Bull trout may be particularly vulnerable to a warmer climate because cold water temperatures constrain their spawning (<9 °C) and early rearing (<12 °C), resulting in high vulnerability to climate change in the assessment area (fig. 4.14), especially in the Upper Willamette (fig. 4.14). Spawning of bull trout generally occurs in mid-August to October. Increased water temperatures can affect spawning distribution and abundance as a result of the loss of thermally suitable migratory habitat (<15 °C), which provides connectivity among populations. Managers can

Table 4.9—Streamflow and temperature characteristics for bull trout population groupings based on changes associated with the A1B emission scenario[a]

		Winter 95-percentile flow days			Summer flow m³ s⁻¹			August temperature °C						
Core	**Period**	**<5**	**5–10**	**>10**	**<0.034**	**0.034–0.085**	**>0.085**	**<8**	**8–11**	**11–14**	**14–17**	**17–20**	**20–23**	**>23**
Hood	1980s	0	5.7	43.1	0	0	48.8	6.6	15.7	17.7	8.8	0	0	0
	2040s	0	0	48.8	0	5.1	43.7	1.9	14.1	18.0	14.3	0.6	0	0
	2080s	0	0	48.8	0	6.3	42.5	0	11.9	15.1	15.0	6.8	0	0
Klickitat	1980s	0	0	17.0	0	0	17.0	0	0	0	17.0	0	0	0
	2040s	0	0	17.0	0	0	17.0	0	0	0	3.7	13.4	0	0
	2080s	0	0	17.0	0	0	17.0	0	0	0	0	17.0	0	0
Upper Willamette	1980s	0	26.6	150.9	2.3	1.1	174.1	8.7	70.5	84.8	13.6	0	0	0
	2040s	0	0	177.5	2.3	1.1	174.1	4.5	30.9	117.1	23.5	1.5	0	0
	2080s	0	0	177.5	2.3	1.1	174.1	0	17.9	117.0	36.7	6.0	0	0
Noncore—Columbia River (distribution in mainstem, small tributaries)	1980s	133.9	0	2.9	0	0	136.8	0	0	0	2.9	1.9	132.0	0
	2040s	133.9	0	2.9	0	0	136.8	0	0	0	0	2.9	61.0	72.9
	2080s	133.9	0	2.9	0	0	136.8	0	0	0	0	2.9	22.1	111.8
Noncore—White Salmon	1980s	0	0	9.4	0	0	9.4	0	0	8	1.4	0	0	0
	2040s	0	0	9.4	0	0	9.4	0	0	8	0	1.4	0	0
	2080s	0	0	9.4	0	0	9.4	0	0	2.5	5.5	1.4	0	0
Noncore—Clackamas	1980s	0	1.8	91.8	2.1	2.7	88.8	0	9.7	41.0	43.0	0	0	0
	2040s	0	0	93.6	2.6	2.2	88.8	0	0	46.6	44.6	2.5	0	0
	2080s	0	0	93.6	2.7	2.2	88.8	0	0	39.5	18.5	35.7	0	0

[a] Habitat extent matches the 483 km shown in figure 4.14 and is based on the Forest Service Pacific Northwest Region fish distribution database. Values are stream kilometers.

aim to connect coldwater habitats to benefit bull trout and other native coldwater fishes by both managing for effective riparian shading (fig. 4.15) or by maintaining desired temperatures below dams (fig. 4.16). Owing to poor conditions and loss of connectivity of habitat in lower rivers where many migratory fish attempt to

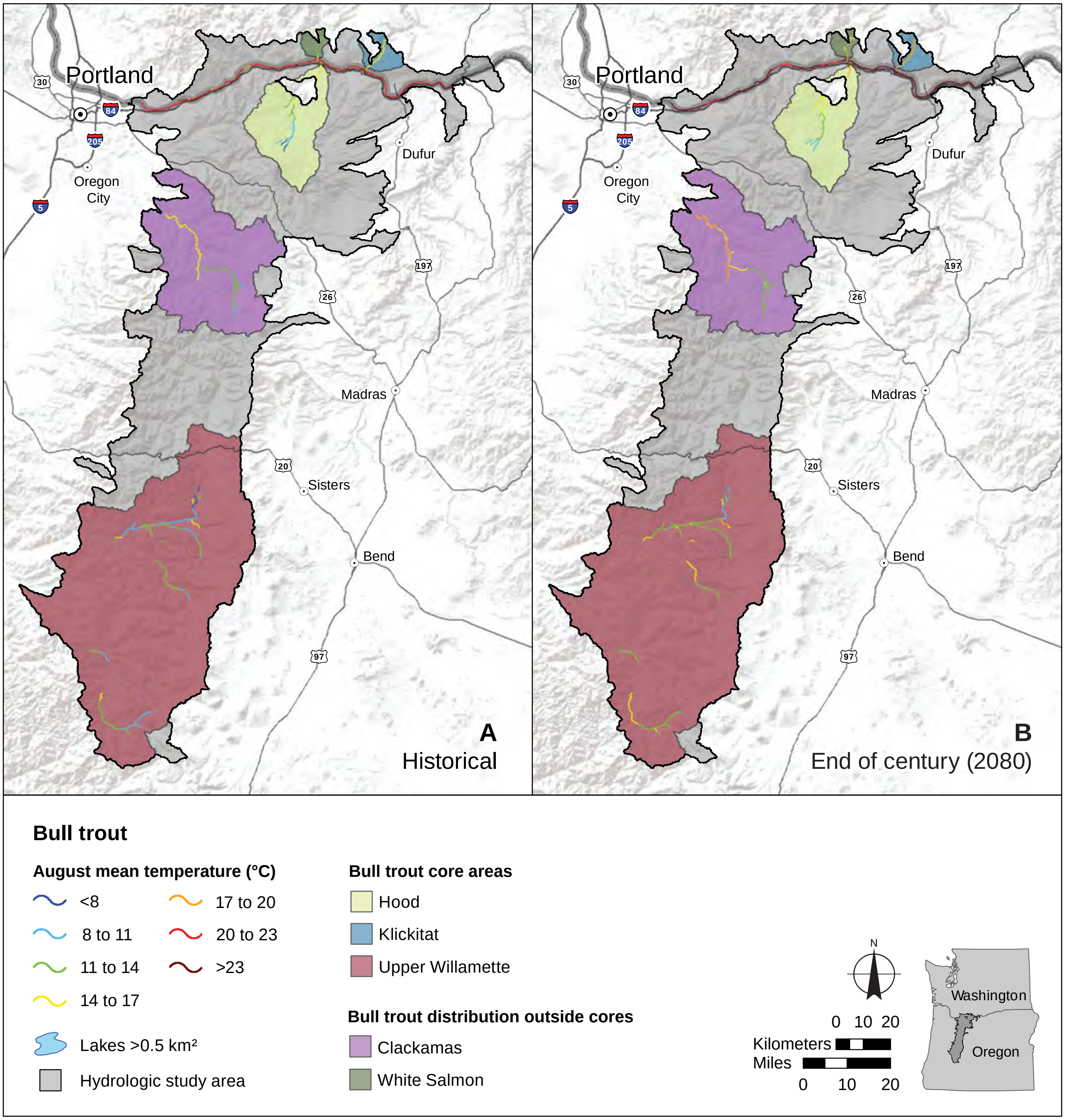

Figure 4.14—Summer stream temperatures in bull trout habitats during (A) the historical baseline period of the 2000s and (B) the 2080s based on NorWeST analyses and the A1B emission scenario.

overwinter (Al-Chokhachy et al. 2016), the abundance of large, migratory bull trout populations appears to be declining (Budy et al. 2017). In addition, bull trout populations exposed to high temperatures and frequent winter flooding may have lower genetic diversity (Kovach et al. 2015).

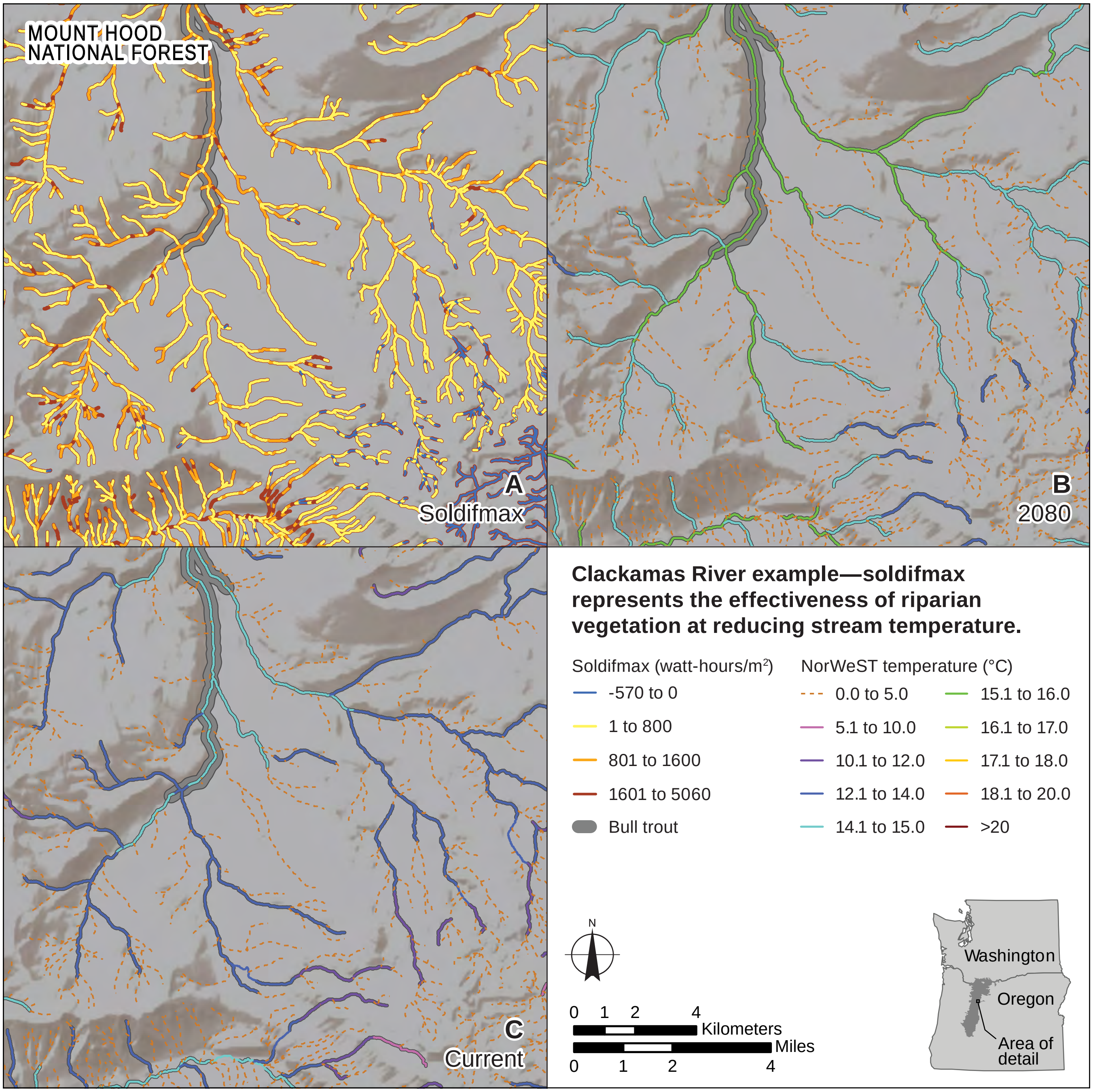

Figure 4.15—Simulated streams in Upper Clackamas River for bull trout (distribution in dark gray) with effectiveness of riparian vegetation on water temperature (using (A) soldifmax metric), (B) projection for the 2080s from a composite average of 10 global climate models (under the A1B emission scenario) for the Western United States, and (C) summer stream temperatures during the current baseline period of the 2000s based on NorWeST analyses and the A1B emission scenario.

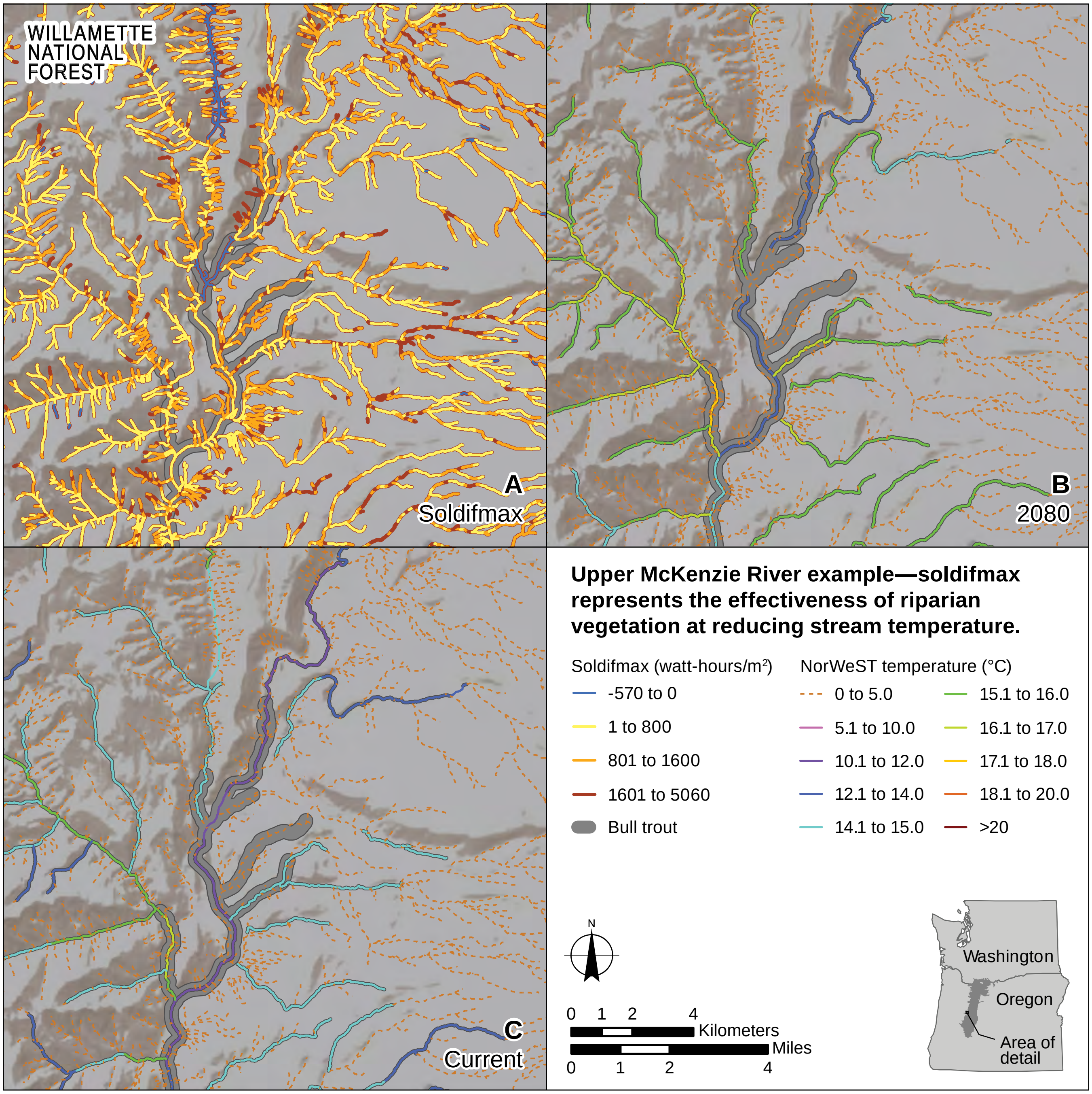

Figure 4.16—Simulated streams in Upper McKenzie River for bull trout (distribution in dark gray) with effectiveness of riparian vegetation on water temperature (using (A) soldifmax metric), (B) projection for the 2080s from a composite average of 10 global climate models (under the A1B emission scenario) for the Western United States, and (C) summer stream temperatures during the current baseline period of the 2000s based on NorWeST analyses and the A1B emission scenario.

Coho salmon—

Coho salmon are a sea-run Pacific salmon that range from central California to the northern Korean Peninsula in Asia. In the CMWAP assessment area, coho salmon habitat covers 463 km (table 4.10, fig. 4.17). Although most Columbia

River coho salmon originate from hatchery stock, natural coho populations still exist in the Clackamas and Sandy Rivers. Coho salmon are not naturally found in the Willamette River basin above Willamette Falls, but a hatchery program supplements the basin. However, hatchery-origin coho are not found in tributaries in the Willamette NF. In 2015, coho salmon returns across the region were far below returns from previous years, likely owing to warmer ocean temperature from El Niño and "the blob." Because major declines in coho populations have been noted since the 1970s, they are listed as a threatened species under the Endangered Species Act. Four major population groups have been identified for coho salmon in the Lower Columbia, including Clackamas, Sandy, Hood, and Lower Gorge tributaries (fig. 4.17).

Coho salmon generally spawn in small, unconfined, low-gradient tributaries to larger rivers (Burnett et al. 2007) as well as high-gradient streams (Sloat et al. 2016). They have a general preference for pools, alcoves, and American beaver ponds rather than habitats with higher flow velocities, like glides and riffles (Gonzalez et al. 2017, Nickelson et al. 1992). Growth and survival of juvenile coho salmon is higher in intermittent streams than in perennial mainstem streams (Ebersole et al. 2006, 2009). Coho salmon juveniles rear in fresh water longer than many other sea-run salmon, and smolts typically migrate to sea in the spring of their second year, from late March through July. They spend 1 to 3 years in the ocean before returning as adults to spawn in fresh water, migrating upstream from October through January.

Relative to other Pacific salmon, there is little variation in return timing of adults within coho populations, leading to tight run timing that varies with local temperature and flow patterns (Flitcroft et al. 2018). For example, in the Columbia River, upstream migrations at Ice Harbor Dam occur in September and October, but at Bonneville Dam, they occur from July to September. Often, migration distances to spawning areas are short, migration can be completed in a few days or weeks, and spawning usually occurs within one or two weeks of reaching the spawning grounds. Timing of hatching and emergence of coho salmon juveniles can vary greatly depending on local stream temperatures, but often by the end of the first growing season, differences in size are minimal (Campbell et al. 2018).

Patterns of temperature and discharge reflecting the hydrology and water management of upstream watersheds affect both juveniles and upstream migration responses of coho salmon (Flitcroft et al. 2018). Areas inhabited by coho salmon from the Hood population are projected to have more stream length experiencing high-flow conditions described as 10 or more days of 95th-percentile flows (increasing from 85 to 123 km by 2080; table 4.10). Other populations are not projected to experience the same increases in stream kilometers with higher winter

Table 4.10—Streamflow and temperature characteristics for coho salmon population groupings based on changes associated with the A1B emission scenario[a]

			Number of winter 95-percentile flow days			Summer flow $m^3 s^{-1}$			August temperature °C						
Evolutionarily significant unit	Population	Period	<5	5–10	>10	<0.034	0.034–0.085	>0.085	<8	8–11	11–14	14–17	17–20	20–23	>23
Lower Columbia	Sandy	1980s	3.5	0	35.2	0	0	38.6	0	1.5	7.1	3.0	27.1	0	0
		2040s	3.5	0	35.2	0	0	38.6	0	0	4.5	7.1	18.8	8.2	0
		2080s	3.5	0	35.2	0	0	38.6	0	0	2.5	8.6	3.2	24.3	0
Lower Columbia	Hood	1980s	15.0	24.9	84.8	0	3.2	121.6	0	52.7	51.7	17.6	2.8	0	0
		2040s	0	15.0	109.7	1.1	4.8	118.4	0	9.6	80.3	31.5	1.1	2.3	0
		2080s	0	2.1	122.6	1.1	8.7	115.0	0	0	70.2	38.7	13.1	2.8	0
Lower Columbia	Lower Gorge tributaries	1980s	39.9	0	58.0	5.4	9.5	82.9	0	0	17.2	32.1	9.4	39.2	0
		2040s	39.9	0	58.0	8.4	9.0	80.5	0	0	4.0	31.5	22.5	30.9	8.9
		2080s	0	39.9	58.0	8.4	9.0	80.5	0	0	3.0	17.6	33.0	9.6	34.6
Middle Columbia	Upper Gorge tributaries and White Salmon	1980s	0	0	28.9	0	7.7	21.1	0	0	11.7	12.4	0	3.9	0.9
		2040s	0	0	28.9	0	7.7	21.1	0	0	7.9	14.2	2.1	2.0	2.7
		2080s	0	0	28.9	1.0	6.7	21.1	0	0	2.5	15.9	5.7	1.2	3.6
None	None	1980s	76.5	0	59.0	0	2.6	132.9	0	1	11.0	21.3	25.6	76.5	0
		2040s	76.5	0	59.0	0	2.6	132.9	0	0	6.0	16.4	13.7	37.0	62.4
		2080s	0	76.5	59.0	0	5.1	130.4	0	0	3.0	13.1	18.7	24.2	76.5
Columbia segment separating two populations	Upper Gorge tributaries and Hood	1980s	38.1	0	0	0	0	38.1	0	0	0	0	1.2	36.9	0
		2040s	38.1	0	0	0	0	38.1	0	0	0	0	0	16.0	22.1
		2080s	0	38.1	0	0	0	38.1	0	0	0	0	0	16.9	21.3

Note: Clackamas population is not listed because there are no coho salmon within the assessment area.

[a] Habitat extent matches the 463 km shown in figure 4.17 and is based on the Forest Service Pacific Northwest Region fish distribution database. Values are stream kilometers. “None” represents fish outside of the other named populations.

flows. Throughout the range of coho salmon, mean August stream temperature is projected to increase for all populations in the assessment area. Warmer temperatures can accelerate egg incubation rates or growth, potentially desynchronizing the developmental phenology of juveniles from the temporal

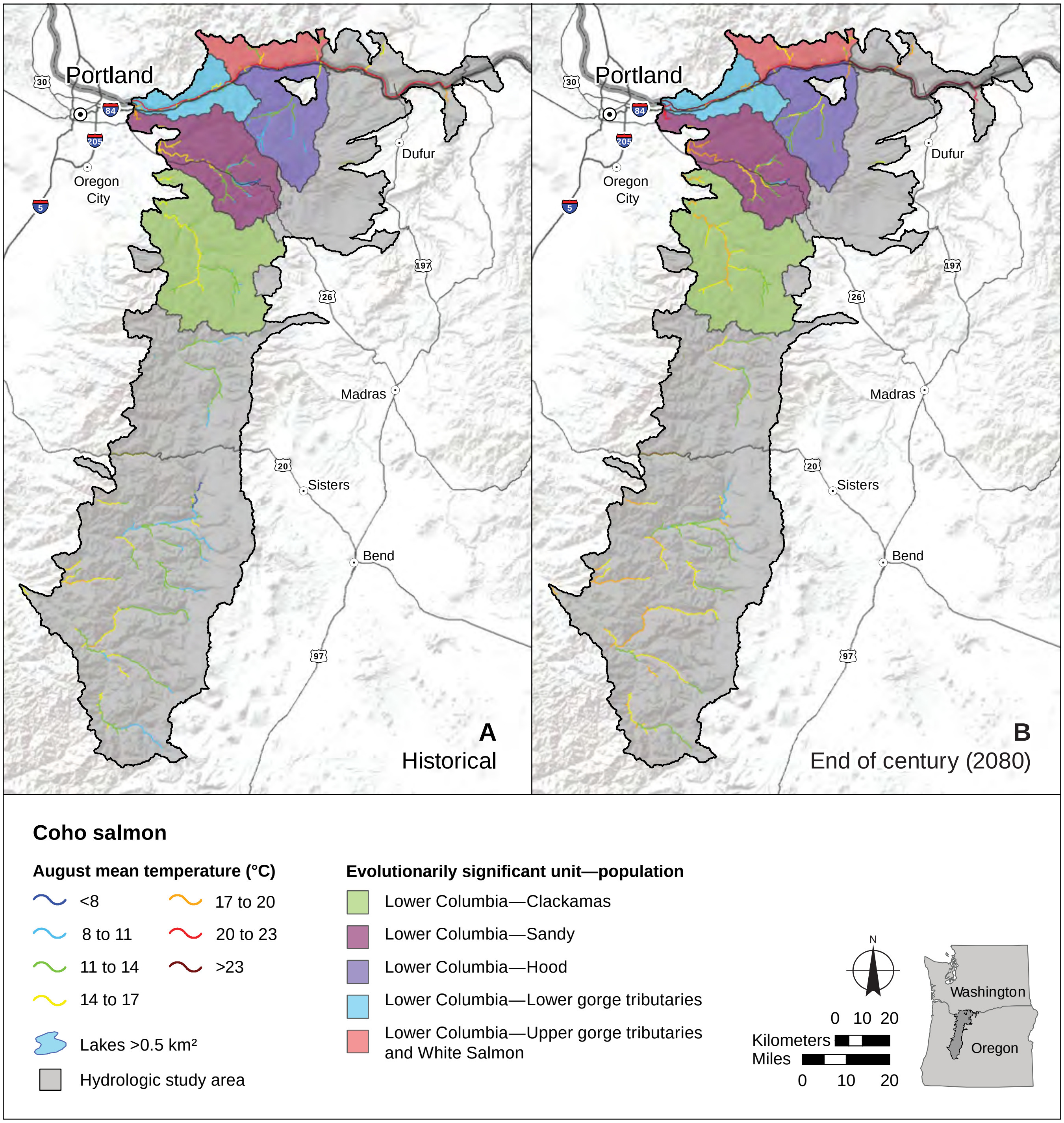

Figure 4.17—Summer stream temperatures in coho salmon habitats during (A) the historical baseline period of the 2000s, and (B) the 2080s based on NorWeST analyses and the A1B emission scenario.

availability of habitats necessary for subsequent life stages (Holtby 1988, Wainwright and Weitkamp 2013). The Wind River tributary of the Columbia River supports medium and high intrinsic potential habitat in Brush Creek above where coho are currently found. This area could be restored or managed for coho salmon to encourage expansion of their distribution (fig. 4.18). These findings corroborate results from Flitcroft et al. (2018), who projected that under climate change, no one key alteration in habitat conditions will be experienced equally by all coho salmon, thus each population will need to be evaluated separately. Coho salmon are considered highly vulnerable to climate change in the assessment area because they face cumulative acute effects during many stages of their life cycle (table 4.1).

Chinook salmon—

Chinook salmon are the largest-bodied species of Pacific salmon in the genus *Oncorhynchus*, ranging from southern California to Kotzebue Sound in Alaska. Chinook salmon spend their developmental stages of egg, fry, and juveniles lower in watersheds, generally in rivers rather than smaller streams, before smolting and moving to estuaries and then the ocean, where they spend 1 to 6 years before returning to fresh water to spawn and die. Of all Pacific salmon, they exhibit the greatest variability in their life stages (Crozier et al. 2019). Early-migrating stream-type (or spring) Chinook migrate upriver from May through July, whereas late-migrating ocean-type (or fall) Chinook migrate from September through December. Both spring and fall Chinook spawn from September through December. Chinook salmon in the Willamette River and Lower Columbia River (in the assessment area) are listed as threatened under the Endangered Species Act.

Juvenile Chinook generally undergo smoltification by April or May of each year, a time period projected to have highly variable flow and temperature regimes under climate change. High instream flows and warmer water temperatures have adverse effects on smolt migration (Sykes et al. 2009) by creating unfavorable conditions that narrow the window for outmigration. However, cool water temperatures and minimal flows can also delay migration.

Spring Chinook occupy 1097 km of stream habitat (table 4.11, fig. 4.19), consisting of 10 major population groups in the Lower Columbia and Upper Willamette. The Columbia River hosts the Hood, White Salmon, and Sandy populations, and the Upper Willamette River hosts the Clackamas, Calapooia, McKenzie, Middle Fork Willamette, Mollala, North Santiam, and South Santiam populations (fig. 4.19). For the Upper Willamette-Middle Fork population, an increase in stream kilometers with 10 or more days of 95th-percentile flows is expected. Spring Chinook populations in the assessment area are projected to experience warmer water temperatures by 2080, especially in the Middle Fork Willamette River (table 4.11). Spring Chinook return to fresh water in spring or

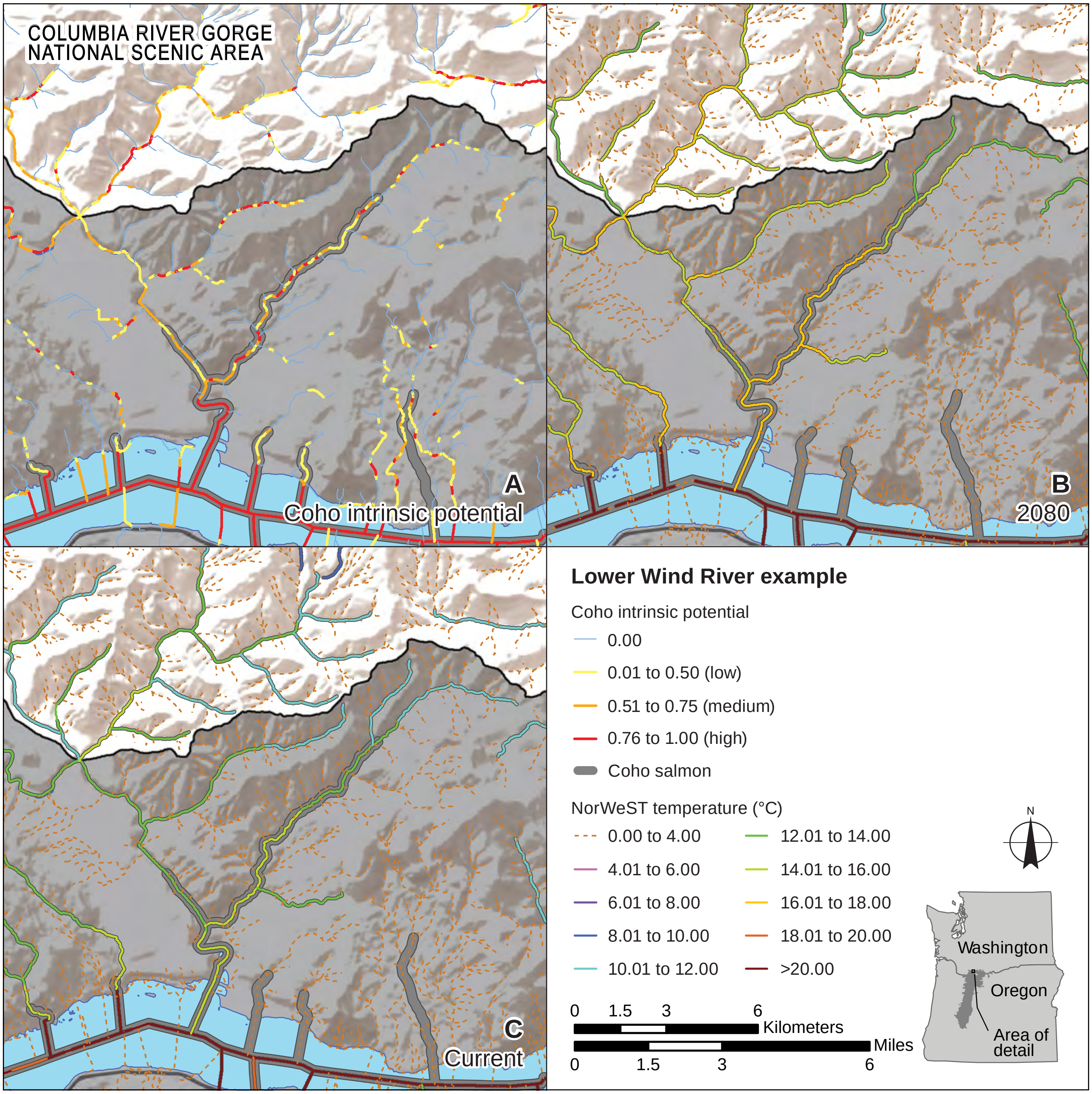

Figure 4.18—Coho salmon distribution (shown in dark gray) in simulated streams of the Lower Wind River with (A) habitat intrinsic potential (unitless index), (B) projection for the 2080s from a composite average of 10 global climate models (under the A1B emission scenario) for the Western United States, and (C) summer stream temperatures during the current baseline period of the 2000s based on NorWeST analyses and the A1B emission scenario.

early summer and hold in rivers and streams for several months before spawning, making them vulnerable to thermal stresses that may accumulate. Adults rest in large pools with cool water, which are less abundant in late summer and early fall. Holding and migrating adults may become increasingly stressed, which

Table 4.11—Streamflow and temperature characteristics for spring Chinook population groupings based on changes associated with the A1B emission scenario[a]

			Winter 95-percentile flow days			Summer flow $m^3 s^{-1}$			August temperature °C						
ESU	Population	Period	<5	5–10	>10	<0.034	0.034–0.085	>0.085	<8	8–11	11–14	14–17	17–20	20–23	>23
Lower Columbia	Hood	1980s	0	5.8	76.5	0	0.6	81.7	0	39.7	35.8	6.8	0	0	0
		2040s	0	0	82.3	0	2.4	79.8	0	5.8	64.4	11.6	0.6	0	0
		2080s	0	0	82.3	0	6.6	75.7	0	0	57.1	18.4	6.8	0	0
Lower Columbia	Sandy	1980s	13.3	35.8	95.3	1.7	1.3	141.5	9.3	25.4	51.1	45.2	13.4	0	0
		2040s	1.5	11.9	131.1	1.7	2.0	140.8	4.7	13.5	55.1	40.2	22.8	8.2	0
		2080s	1.5	1.1	141.9	1.7	2.0	140.8	2.9	9.8	42.5	38.6	38.8	11.9	0
Lower Columbia	White Salmon	1980s	0	0	9.4	0	0	9.4	0	0	8.0	1.4	0	0	0
		2040s	0	0	9.4	0	0	9.4	0	0	8.0	0	1.4	0	0
		2080s	0	0	9.4	0	0	9.4	0	0	2.5	5.5	1.4	0	0
Lower Columbia	None	1980s	78	0	46.3	2.8	5.0	116.6	0	0	15.6	18.9	12.0	77.3	0.6
		2040s	78	0	46.3	5.3	3.7	115.3	0	0	1.6	26.1	15.7	49.3	31.6
		2080s	0	78.0	46.3	5.3	4.2	114.8	0	0	0.1	18.8	19.7	29.4	56.4
Middle Columbia	None	1980s	59.6	5.5	16.2	0	0	81.2	0	0	5.5	9.5	6.7	59.6	0
		2040s	18.0	41.6	21.7	0	0	81.2	0	0	5.5	3.7	5.8	20.7	45.5
		2080s	0	59.6	21.7	0	0	81.2	0	0	2.5	3.0	9.5	6.7	59.6
Upper Willamette	Clackamas	1980s	0	0.8	143.6	2.1	3.6	138.6	0	4.4	64.9	75.1	0	0	0
		2040s	0	0	144.3	2.1	7.5	134.8	0	1.0	42.5	95.8	5.1	0	0
		2080s	0	0	144.3	2.1	7.5	134.8	0	0	33.3	57.0	54.1	0	0

			Winter 95-percentile flow days			Summer flow $m^3 s^{-1}$			August temperature °C						
ESU	**Population**	**Period**	**<5**	**5–10**	**>10**	**<0.034**	**0.034–0.085**	**>0.085**	**<8**	**8–11**	**11–14**	**14–17**	**17–20**	**20–23**	**>23**
Upper Willamette	Calapooia	1980s	0	0	13.0	0	0	13.0	0	0	3.3	9.7	0	0	0
		2040s	0	0	13.0	0	0	13.0	0	0	0	10.8	2.2	0	0
		2080s	0	0	13.0	0	0	13.0	0	0	0	5.7	7.3	0	0
Upper Willamette	McKenzie	1980s	2.6	16.4	156.9	1.4	3.3	171.2	10.7	68.0	81.2	16.1	0	0	0
		2040s	0	2.6	173.3	1.4	3.3	171.2	4.5	35.6	103.0	31.4	1.5	0	0
		2080s	0	0	176.0	1.4	5.5	169.0	0	23.5	96.5	46.8	9.2	0	0
Upper Willamette	Middle Fork Willamette	1980s	11.0	65.5	150.4	0.6	1.3	224.9	0	31.1	103.3	83.0	9.5	0	0
		2040s	0.7	9.4	216.7	0.6	2.8	223.4	0	6.5	77.5	105.5	37.4	0	0
		2080s	0	0.7	226.2	0.6	4.9	221.4	0	0	49.5	111.5	65.8	0	0
Upper Willamette	North Santiam	1980s	4.3	13.4	58.3	0	0.2	75.9	0	20.8	55.2	0	0	0	0
		2040s	0	0	76.0	0	0.2	75.9	0	1.2	65.7	9.1	0	0	0
		2080s	0	0	76.0	0	0.2	75.9	0	0	53.2	22.8	0	0	0
Upper Willamette	South Santiam	1980s	0	0	18.3	0	0	18.3	0	0	1.8	16.5	0	0	0
		2040s	0	0	18.3	0	0	18.3	0	0	0	12.1	6.2	0	0
		2080s	0	0	18.3	0	0	18.3	0	0	0	5.8	12.4	0	0

Note: Deschutes river portion of Middle Columbia evolutionarily significant unit (ESU) overlaps with Deschutes summer/fall-run ESU.

[a] Habitat extent matches the 1097 kilometers shown in figure 4.19 and is based on the Forest Service Pacific Northwest Region fish distribution database. Values are stream kilometers.

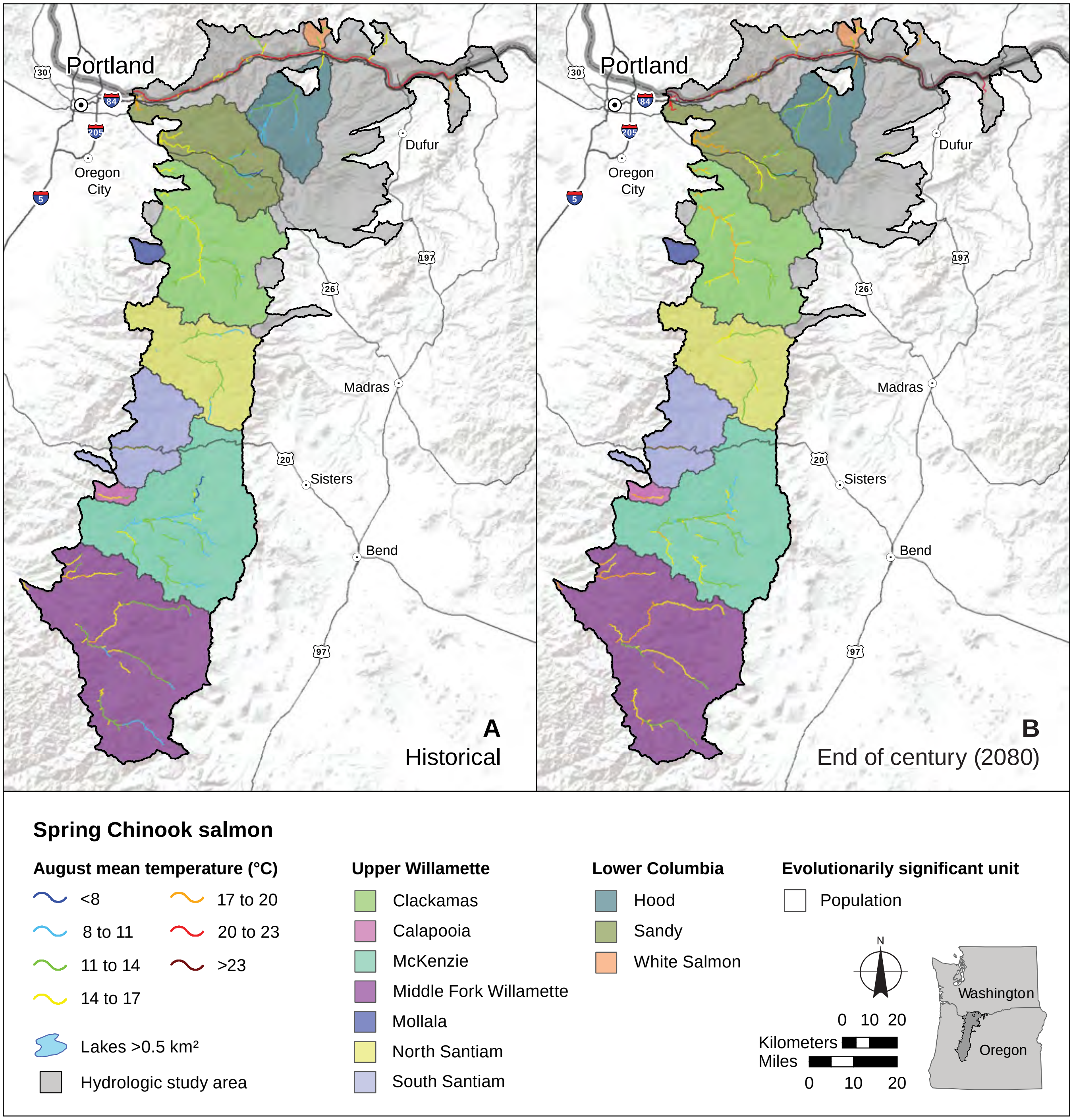

Figure 4.19—Summer stream temperatures in spring Chinook salmon habitats during the (A) historical baseline period of the 2000s and (B) the 2080s based on NorWeST analyses and the A1B emission scenario.

will diminish their reproductive potential and increase prespawning mortality (Bowerman et al. 2018). Cool-water refuges are likely to become even less available at those times as the climate and streams continue to warm.

Warmer water temperatures lead to changes in behavior, physiology, and growth, with negative implications for long-term persistence of Chinook salmon

(Kuehne et al. 2012), especially for spring Chinook. For example, the loss of summer prespawn staging habitats in rivers entering Puget Sound, Washington, could result in the replacement of spring Chinook salmon by fall Chinook, whose fall run timing avoids exposure to warm, low-flow summer conditions (Beechie et al. 2006). High temperatures can lead to oxygen limitation and mortality in summer-incubating Chinook eggs (Martin et al. 2017). For instance, egg-to-fry survival for winter-run Chinook in the Sacramento River in 2014 and 2015 was the lowest ever observed, possibly caused by the California drought. In another example, returns of adult spring Chinook on the Umpqua River were the lowest on record in 2018, with only 28 adults returning; the low numbers were attributed to stream temperatures near lethal limits and poor ocean conditions. Overall, spring Chinook in the assessment area are considered highly vulnerable to climate change (Crozier et al. 2019).

Fall Chinook salmon occupy less stream habitat than spring Chinook salmon, with only 274 km of stream habitat in the CMWAP assessment area (table 4.12, fig. 4.20). They comprise six major population groups in the Lower Columbia area, including Hood, Clackamas, Sandy, Lower Gorge tributaries, Upper Gorge tributaries, and White Salmon populations. Fall Chinook are more vulnerable to ocean conditions than spring Chinook, because they spend more time there as feeding adults. Under climate change, they will experience increasing strength of ENSO cycles (Fasullo et al. 2018) and decreasing net primary productivity, leading to a potential lack of food sources. Furthermore, in fresh water, areas inhabited by fall Chinook populations in the Lower Columbia-Lower Gorge tributaries are projected to have more streams with temperatures >23 °C in 2080 (table 4.12). Fall Chinook are moderately vulnerable to climate change (table 4.1). Stream habitats where there is high intrinsic potential for Chinook salmon could be prioritized for restoration to encourage distribution extension (e.g., fig. 4.21).

Chum salmon—

Chum salmon are distributed from North America along the mid-Oregon coast northward to Alaska and westward into Asia and may historically have been the most abundant of all Pacific salmon. Historically, they occurred in every tributary in the Columbia River up to the Walla Walla and Umatilla Rivers, with most of the population generally found below Celilo Falls (now inundated by The Dalles Dam). By 1951, they were found in only 13 core areas. Their numbers plummeted in the early 1950s, resulting in greater protections for the population in the Columbia River. Currently, they are considered to have very low population numbers and are at risk of extirpation. There are two main core populations remaining in the Columbia River: one located near Grays River and the other near Bonneville Dam.

Table 4.12—Streamflow and temperature characteristics for fall Chinook population groupings based on changes associated with the A1B emission scenario[a]

			Winter 95-percentile flow days			Summer flow $m^3 s^{-1}$			August temperature °C						
ESU	**Population**	**Period**	**<5**	**5–10**	**>10**	**<0.034**	**0.034–0.085**	**>0.085**	**<8**	**8–11**	**11–14**	**14–17**	**17–20**	**20–23**	**>23**
Lower Columbia	Hood	1980s	0	0	6.8	0	0	6.8	0	0	0	6.8	0	0	0
		2040s	0	0	6.8	0	0	6.8	0	0	0	6.2	0.6	0	0
		2080s	0	0	6.8	0	0	6.8	0	0	0	0	6.8	0	0
Lower Columbia	Lower Gorge tributaries	1980s	39.9	0	22.7	2.3	3.3	57.1	0	0	5.7	10.2	7.5	39.2	0
		2040s	39.9	0	22.7	4.8	0.8	57.1	0	0	0	9.8	12.9	30.9	8.9
		2080s	0	39.9	22.7	4.8	0.8	57.1	0	0	0	5.7	13.2	9.0	34.6
Lower Columbia	Sandy	1980s	1.5	0	60.9	0	0	62.3	0	0	2.2	46.7	13.4	0	0
		2040s	1.5	0	60.9	0	0	62.3	0	0	0	30.3	23.8	8.2	0
		2080s	1.5	0	60.9	0	0	62.3	0	0	0	9.3	41.2	11.9	0
Lower Columbia	Upper Gorge tributaries	1980s	38.1	0	16.9	0	2.2	14.7	0	0	5.5	6.9	4.5	38.1	0
		2040s	38.1	0	16.9	0	3.4	13.5	0	0	1.6	10.2	2.8	18.3	22.1
		2080s	0	38.1	16.9	0	3.9	13.0	0	0	0.1	6.9	6.5	20.3	21.3
Lower Columbia	White Salmon	1980s	0	0	9.4	0	0	9.4	0	0	8.0	1.4	0	0	0
		2040s	0	0	9.4	0	0	9.4	0	0	8.0	1.4	0	0	0
		2080s	0	0	9.4	0	0	9.4	0	0	2.5	5.5	1.4	0	0
Middle Columbia	None	1980s	59.6	0	18.2	0	0	59.7	0	0	0	9.5	8.7	41.6	0
		2040s	59.6	0	18.2	0	0	59.7	0	0	0	3.7	5.8	13.6	36.7
		2080s	0	59.6	18.2	0	0	59.7	0	0	0	0	9.5	8.7	41.6

Note: The Clackamas population is not listed because there are no Chinook within the assessment area. Deschutes river portion of Middle Columbia evolutionarily significant unit (ESU) overlaps with Deschutes summer/fall-run ESU.

[a] Habitat extent matches the 274 km shown in figure 4.20 and is based on the Forest Service Pacific Northwest Region fish distribution database. Values are stream kilometers. None represents fall Chinook salmon for the whole Middle Columbia.

Their current distribution in the Columbia River is from the mouth of the Columbia River to the Walla Walla River below Celilo Falls, just upstream of The Dalles Dam in the lower portions of tributaries.

Historically, chum salmon spawned from October through March in the Columbia River basin, in a variety of stream types ranging from small tributaries

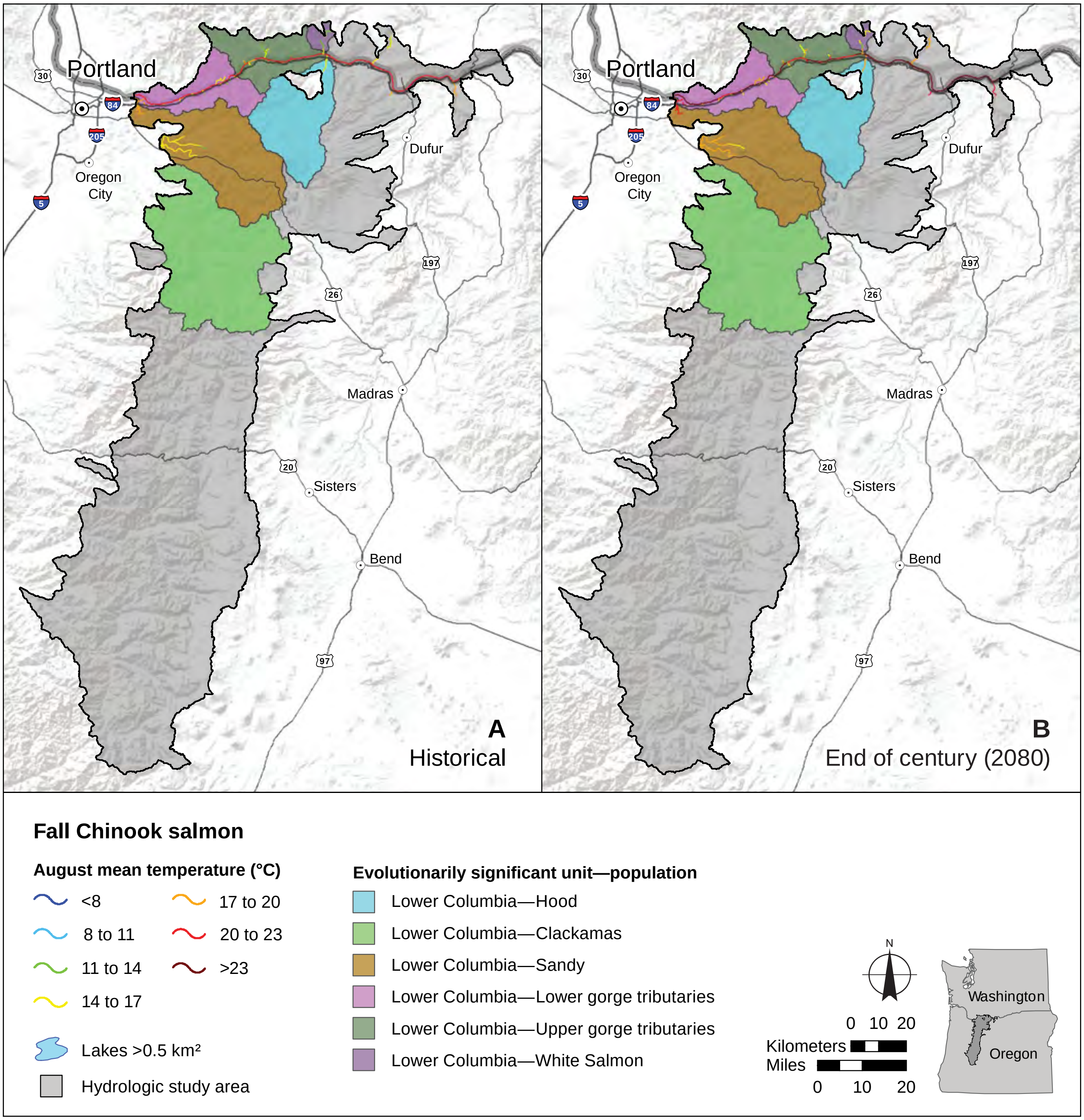

Figure 4.20—Summer stream temperatures in fall Chinook salmon habitats during (A) the historical baseline period of the 2000s, and (B) the 2080s based on NorWeST analyses and the A1B emission scenario.

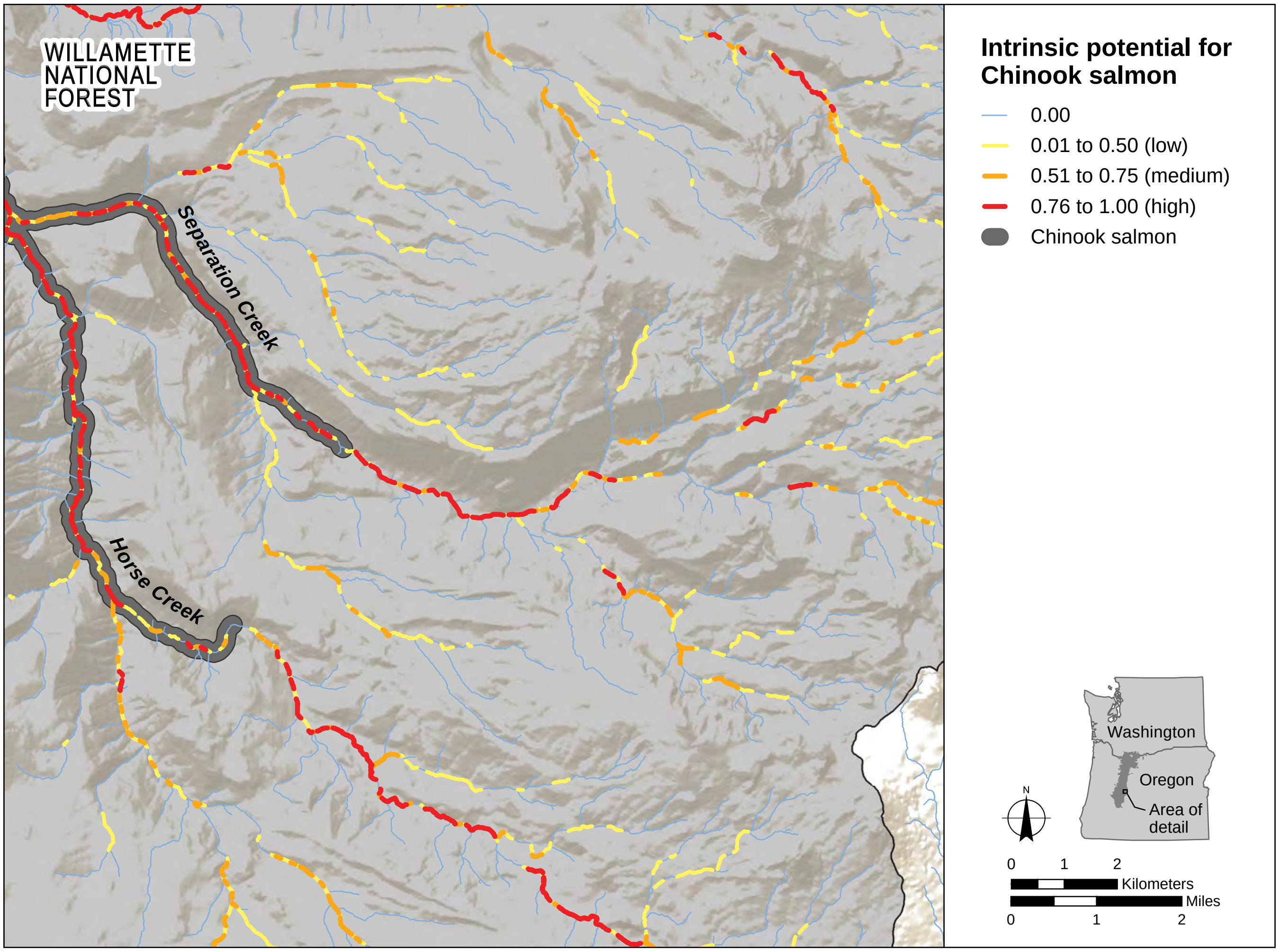

Figure 4.21—Chinook salmon distribution (shown in dark gray) in simulated streams of Separation and Horse Creeks with habitat intrinsic potential (unitless index) based on NetMap analyses.

to large mainstem rivers and side channels. The populations that remain spawn from October through December in small tributaries. Chum salmon emerge from February to April and generally migrate directly to the estuary or near-shore environment by April for rearing. It is important that they find high-quality habitat quickly, including good water quality, abundant food resources, and refuges from predators, as they lack energy reserves and the ability to swim well. Because they migrate downstream as fry, they can be especially vulnerable to predation by pinnipeds, birds, and other fishes, reducing their survival.

Chum salmon are found in 164 km of stream habitat in the assessment area (table 4.13). They comprise four major population groups in the Lower Columbia area, including Clackamas, Sandy, Lower Gorge tributaries, and Upper Gorge tributaries (fig. 4.22). Climate change is expected to affect chum salmon in fresh water as spawning adults and when eggs are in the gravels, in the estuarine and

Table 4.13—Streamflow and temperature characteristics for chum population groupings based on changes associated with the A1B emission scenario. Habitat extent matches the 164 km shown in fig. 4.21 and is based on the Forest Service Pacific Northwest Region fish distribution database[a]

			Winter 95-percentile flow days			Summer flow m^3 s^{-1}			August temperature °C						
ESU	**Population**	**Period**	**<5**	**5–10**	**>10**	**<0.034**	**0.034–0.085**	**>0.085**	**<8**	**8–11**	**11–14**	**14–17**	**17–20**	**20–23**	**>23**
Columbia	Lower Gorge tributaries	1980s	39.9	0	24.3	0	4.7	59.4	0	0	1.5	19.9	3.6	39.2	0
		2040s	39.9	0	24.3	0.8	6.3	57.0	0	0	0	9.8	14.4	30.9	8.9
		2080s	0	39.9	24.3	0.8	6.3	57.0	0	0	0	1.5	22.2	5.8	34.6
Columbia	Upper Gorge tributaries	1980s	92.6	0	0	0	0	92.6	0	0	0	0	1.2	91.4	0
		2040s	92.6	0	0	0	0	92.6	0	0	0	0	0	30.1	62.5
		2080s	74.6	18.0	0	0	0	92.6	0	0	0	0	0	16.9	75.7
None	None	1980s	8.1	0	0	0	0	8.1	0	0	0	0	0	8.1	0
		2040s	8.1	0	0	0	0	8.1	0	0	0	0	0	0	8.1
		2080s	8.1	0	0	0	0	8.1	0	0	0	0	0	0	8.1

Note: Clackamas and Sandy populations are not listed because there are no chum salmon within the assessment area.

[a] Values are stream kilometers. None represents fish outside of the named populations.

near-shore environment for rearing, and in the ocean where they grow to full size and mature as adults before returning to fresh water. Chum return timing and adult body size may already be affected by climate change. For example, in the Skagit River, chum salmon adults are returning to streams up to two weeks earlier and are spawning before the first fall rains, which they did not do historically (Rubenstein et al. 2019). Adult chum salmon in Japan decreased in body size from the 1970s to the 1990s, and models suggest the size difference may be due to temperature increases affecting metabolism and a reduction in food resources (Kishi et al. 2010). While in fresh water, populations of chum salmon are projected to experience increasing water temperatures by 2080, especially for the Upper Gorge tributaries of the Columbia River, where temperatures are projected to increase to higher than 23 °C (table 4.13).

Although chum salmon spend less time in fresh water than other Pacific salmon, they depend heavily on rearing in tidally influenced and estuarine habitats, making them sensitive to sea-level rise and degraded conditions in the Columbia River estuary. The estuary provides a critical rearing ground for chum salmon, making connectivity between freshwater spawning and estuarine habitats critical for the survival of early life stages. Chum salmon are considered moderately vulnerable to climate change (table 4.1).

Management Opportunities

Managing for and protecting the diversity of native fishes under climate change entails preservation of the genetic diversity and multiple life histories within populations, across a wide geographic range and variety of habitats. The first principle of “intelligent tinkering” is keeping every “cog and wheel” (Leopold 1949); for fishes of conservation interest, that means maintaining diversity within populations and among habitats. Long-term persistence of highly migratory fishes depends on continued and strategic conservation efforts in freshwater, estuarine, and marine habitats. Better and more widespread implementation of known practices that reduce the effects of existing stressors, including climate change, represents an important “no-regrets” strategy (Joyce et al. 2009).

Emerging views of aquatic ecosystems describe them as having a range of processes and attributes that are inherently complex, nonlinear, and dynamic (Penaluna et al. 2017, 2018; Reeves et al. 1995). Aquatic habitat conditions in dynamic areas such as the Pacific Northwest vary as natural processes promote habitat change over space and time (Penaluna et al. 2018). Maintaining broad areas of complex habitat under such dynamic conditions makes partnerships among landowners and regulatory agencies critical to the conservation of fishes.

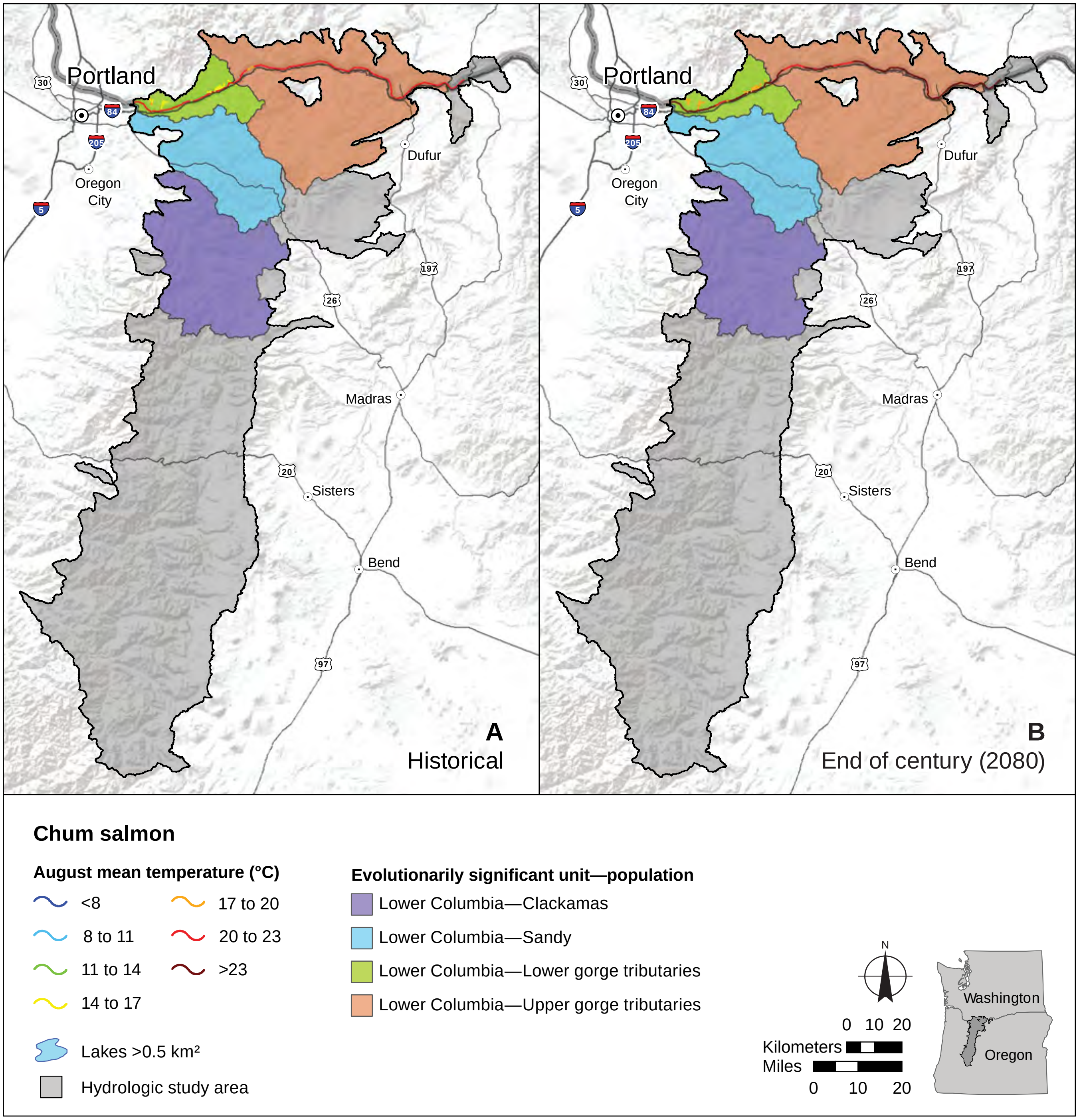

Figure 4.22—Summer stream temperatures in chum salmon habitats during (A) the historical baseline period of the 2000s, and (B) the 2080s based on NorWeST analyses and the A1B emission scenario.

Native salmonids of the Pacific Northwest are adapted to dynamic landscape conditions over time. However, habitat fragmentation resulting from human development, modification of flow regimes by dams, and land-use practices have compromised extensive areas. Further, river passage blocked by dams and culverts counters the strong adaptive benefit of long-distance movement for these migratory fishes. This leaves some populations vulnerable to additional stressors associated with climate change. National Oceanic and Atmospheric Administration Fisheries has developed a science strategy to manage for climate change that involves building science infrastructure, tracking trends, detecting early warning signs, and developing mechanistic understandings of interacting factors and robust management solutions (Link et al. 2015). Here, we discuss a few of these proposed management suggestions; see Reeves et al. (2018) and Penaluna et al. (2018) for more detail.

Promote Connected Heterogeneous Habitats Across Broad Spatial Extents

The overall goal for fish and aquatic conservation and restoration is to ensure the long-term persistence of self-sustaining populations across species' native ranges. Maintaining the diversity and connectivity of habitats across broad spatial extents allows for the expression of biocomplexity. Management practices that encourage adaptation to climate change will help to support species resilience and persistence.

The Columbia River serves as the main corridor (or swimway) for fishes in the CMWAP assessment area, affecting migratory sea-run fishes, adfluvial bull trout, and freshwater-resident populations. Consequently, prioritizing coldwater refugia on the Columbia River is a useful strategy, especially because most late-21st-century projections described here suggest that there will be high temperatures along the Columbia River mainstem in the future. For example, restoring aquatic and estuarine habitats for cold water along the Columbia River, regardless of land ownership, will support habitat connectivity and provide the greatest opportunity for continued persistence and success of fish populations.

Most of the focal fishes considered here have a sea-run life history and are dependent on the connectivity of habitats across freshwater-estuarine-marine ecosystems. Although freshwater habitat is only one environment necessary for sea-run fishes to complete their life cycle, it is irreplaceable for spawning and early juvenile survival. Land management agencies can affect habitat conditions and diversity in freshwater-adjacent landscapes, making restoration of these areas a key focus of conservation efforts.

Restoration activities, such as reestablishing hydrological connectivity across streams and floodplains, restoring natural flow regimes, and repairing aggraded channels, can create a protective buffer against climate change impacts on fresh water and fish (Beechie et al. 2012). For freshwater-living forms of species, such as adfluvial bull trout, fluvial and headwater resident coastal cutthroat trout, and *O. mykiss*, particularly redband trout, long-term maintenance of connectivity among suitable habitats and populations is important for maintaining life-history diversity. Consequently, conservation plans for all focal fishes may focus on maintaining cold water and a diversity of connected heterogeneous habitats across the region to minimize risk at the subpopulation level (e.g., in fig. 4.21).

Prioritize Natural Regimes for Disturbance

If managers emulate or allow natural disturbance regimes to occur at presettlement frequencies and magnitudes across the landscape to the extent possible, a mosaic of biophysical conditions and other regimes will develop over time. Locally complex habitat conditions created by natural disturbances provide a template for biological diversity. Periodic disturbances play an important role in creating and sustaining habitat and biological complexity on the landscape, so it is desirable that management actions, where possible, emulate disturbance processes at appropriate spatial and temporal scales. In this regard, the temporal and spatial scales of disturbance are fundamental metrics for understanding and managing ecosystems (Hessburg et al. 2015, Miller et al. 2003). In areas where emulating natural disturbance regimes may not be possible, managers can try to capture the natural variability in the system for key characteristics, such as temperature, streamflow, wildfire, and sediment and wood delivery. Conservation plans that prioritize periodic disturbance may be most effective at maintaining the persistence of native fishes.

Manage Flows and Water Temperatures Below Dams

Dams can lead to a loss of freshwater habitat from fragmentation, likely contributing to the decline of many migratory fishes. For example, there are some genetically unaltered populations of redband trout in tributaries to the Deschutes River both above and below reservoirs, but more than 10 percent of populations in and around reservoirs are hybridized with related subspecies (Matala et al. 2008). Therefore, flow management from reservoirs and habitat restoration efforts that favor redband trout over introduced fishes may help secure populations. Likewise, the Upper McKenzie River has two dams with cold water in their reservoirs, including Smith Reservoir and Trail Bridge Reservoir, which can provide bull trout with coldwater habitat despite climate change (fig. 4.16).

Restore Streams and Riparian Areas and Maintain Roads

The protection and careful management of stream habitats, riparian canopy for shade and inputs of organic matter, and roads in upstream forests improve habitats downstream (Luce et al. 2001, Spies et al. 2002). Protecting and restoring habitats that are resilient to climatic variability and change will improve the long-term survival of native fishes (Penaluna et al. 2018). In Separation and Horse Creeks on the Willamette NF, there may be areas of habitat with intrinsic potential above the current distribution of Chinook salmon that could be restored to encourage expansion of their distribution (fig. 4.20). Similarly, there may be areas above the current distribution of coho salmon in the Lower Wind River where habitats with intrinsic potential could be restored to encourage population expansion (fig. 4.17). Managers may also be able to mitigate increasing stream temperatures by enhancing riparian forest shade. For example, in the South Santiam River, tributaries and portions of the mainstem are expected to be more responsive to riparian vegetation than other portions of the network (fig. 4.9). In the Upper Clackamas River basin, the mainstem of Berry Creek is another place where riparian vegetation may be effective in keeping stream temperatures cool for bull trout (fig. 4.13).

Prevent or Eradicate Invasive Species

Once introduced, invasive species can be difficult or expensive to control. Climate change may enhance habitat suitability for invasive fishes, thereby changing interactions and survival potential of native fishes (Wenger et al. 2011). Invasive species, especially warm water fishes, including sunfish and bass species, will likely become more abundant in the assessment area, and may increase the risk of exposure to nonnative disease, competition, and predation of native fishes. Smallmouth bass (*Micropterus dolomieu* Lacepède) ia an invasive warm water predator expected to pose an increasing threat to Chinook salmon subyearlings, especially in the Columbia River (Lawrence et al. 2014). However, restoration of riparian forests to maintain low water temperatures can thermally restrict the expansion of smallmouth bass (Lawrence et al. 2014). Although invasive species pose risks to native species and ecosystems, their introduction can provide food and recreational opportunities (chapter 7). For example, there is a popular smallmouth bass fishery on the Columbia River, especially between the dams around the Columbia Gorge. Therefore, a mix of management approaches across large landscapes may be most successful in achieving multiple objectives.

Build Partnerships Across Ownerships and Land Uses

Federal lands in the Pacific Northwest have a limited capacity to provide high-quality habitat for some fishes (e.g., Burnett et al. 2007, Reeves et al. 2018) or lie upstream of major dam complexes, where habitats are extensive and high quality, but movement into the habitats is limited (Thurow 2000). The location of federal lands in the Columbia River basin precludes habitats, such as low-gradient, lower order streams, floodplain wetlands, and oxbow lakes, which provide critical habitat for some fishes. Thus, conservation efforts by federal forest managers may benefit from partnerships with nonfederal landowners and other nongovernmental entities. For example, to manage and conserve Pacific lamprey in the McKenzie River, partnerships between Willamette NF and downstream landowners would be instrumental. Managers may need to adapt area- or watershed-specific goals and objectives to maintain multiple interconnected populations. A comprehensive "all lands" management approach will need to include a process for enhancing habitat quality on highly modified lands across all land ownerships.

Research Needs

Although aquatic ecosystems and fishes may be resilient to climate change and multiple stressors, some responses will likely be complex and surprising. Consequently, understanding how species will respond to climate change effects and interactions with other stressors is essential. Monitoring the effectiveness of aquatic conservation plans across all lands and the status of fishes in the assessment area will continue to be important as models of future effects are refined. Vulnerability assessments would be improved with inventories for culverts, road conditions, and the effects of culverts and roads on fish passage and habitat quality across the assessment area. We also lack sufficient quantitative data about the amount, pattern, and type of restoration activities that have occurred in upland and riparian forests and their effects on aquatic ecosystems (Reeves et al. 2018). Climate models that can more accurately project changes, particularly models that capture thermal variability in space and time, would improve our understanding of consequences for fish habitat. Ultimately, the conservation of freshwater habitats and their associated fishes depends on our ability to implement solutions that allow these habitats and species to coexist with a growing scope of human influences.

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Literature Cited

Al-Chokhachy, R.; Alder, J.; Hostetler, S. [et al.]. 2013. Thermal controls of Yellowstone cutthroat trout and invasive fishes under climate change. Global Change Biology. 19: 3069–3081.

Al-Chokhachy, R.; Schmetterling, D.; Clancy, C. [et al.]. 2016. Are brown trout replacing or displacing bull trout populations in a changing climate? Canadian Journal of Fisheries and Aquatic Sciences. 73: 1395–1404.

Arismendi, I.; Johnson, S.L.; Dunham, J.B. [et al.]. 2012. The paradox of cooling streams in a warming world: regional climate trends do not parallel variable local trends in stream temperature in the Pacific continental United States. Geophysical Research Letters. 39: L10401.

Battin, J.; Wiley, M.W.; Ruckelshaus, M.H. [et al.]. 2007. Projected impacts of climate change on salmon habitat restoration. Proceedings of the National Academy of Sciences, USA. 104: 6720–6725.

Beechie, T.; Pess, G.; Morley, S. [et al.]. 2012. Watershed assessments and identification of restoration needs. In: Roni, P.; Beechie, T., eds. Stream and watershed restoration: a guide to restoring riverine processes and habitats. Chichester, United Kingdom: John Wiley & Sons, Ltd.: 50–113.

Behrenfeld, M.J.; O'Malley, R.T.; Siegel, D.A. [et al.]. 2006. Climate-driven trends in contemporary ocean productivity. Nature. 444: 752.

Benda, L.; Miller, D.; Andras, K. [et al.]. 2007. NetMap: a new tool in support of watershed science and resource management. Forest Science. 53: 206–219.

Benjamin, J.R.; Connolly, P.J.; Romine, J.G.; Perry, R.W. 2013. Potential effects of changes in temperature and food resources on life history trajectories of juvenile *Oncorhynchus mykiss.* Transactions of the American Fisheries Society. 142: 208–220.

Bowerman, T.; Roumasset, A.; Keefer, M.L. [et al.]. 2018. Prespawn mortality of female Chinook salmon increases with water temperature and percent hatchery origin. Transactions of the American Fisheries Society. 147: 31–42.

Brannon, E.L.; Amend, D.F.; Cronin, M.A. [et al.]. 2004. The controversy about salmon hatcheries. Fisheries. 29: 12–31.

Brinson, M.M.; Malvárez, A.I. 2002. Temperature freshwater wetlands: types, status, and threats. Environmental Conservation. 2: 115–133.

Budy, P.; Bowerman, T.; Al-Chokhachy, R. [et al.]. 2017. Quantifying long-term population trends of threatened bull trout: challenges, lessons learned, and opportunities. Canadian Journal of Fisheries and Aquatic Sciences. 74: 2030–2034.

Burnett, K.M.; Reeves, G.H.; Miller, D.J. [et al.]. 2007. Distribution of salmon-habitat potential relative to landscape characteristics and implications for conservation. Ecological Applications. 17: 66–80.

Campbell, E.Y.; Dunham, J.B.; Reeves, G.H.; Wondzell, S.M. 2018. Phenology of hatching, emergence, and end-of-season body size in young-of-year coho salmon in thermally contrasting streams draining the Copper River Delta, Alaska. Canadian Journal of Fisheries and Aquatic Sciences. 76: 185–191.

Cohen, J.M.; Lajeunesse, M.J.; Rohr, J.R. 2018. A global synthesis of animal phenological responses to climate change. Nature Climate Change. 8: 224–228.

Crozier, L.G.; McClure, M.M.; Beechie, T. [et al.]. 2019. Climate vulnerability assessment for Pacific salmon and steelhead in the California current large marine ecosystem. PLoS ONE. 14: e0217711.

Crozier, L.G.; Scheuerell, M.D.; Zabel, R.W. 2011. Using time series analysis to characterize evolutionary and plastic responses to environmental change: a case study of a shift toward earlier migration date in sockeye salmon. The American Naturalist. 178: 755–773.

Currens, K.P.; Schreck, C.B.; Li, H.W. 2009. Evolutionary ecology of redband trout. Transactions of the American Fisheries Society. 138: 797–817.

Daufresne, M.; Lengfellner, K.; Sommer, U. 2009. Global warming benefits the small in aquatic ecosystems. Proceedings of the National Academy of Sciences, USA. 106: 12788–12793.

Di Lorenzo, E.; Mantua, N. 2016. Multi-year persistence of the 2014/15 North Pacific marine heatwave. Nature Climate Change. 6: 1042.

Dunham, J.B.; Rieman, B.E. 1999. Metapopulation structure of bull trout: influences of physical, biotic, and geometrical landscape characteristics. Ecological Applications. 9: 642–655.

Ebersole, J.L.; Colvin, M.E.; Wigington, P.J., Jr. [et al.]. 2009. Modeling stream network-scale variation in coho salmon overwinter survival and smolt size. Transactions of the American Fisheries Society. 138: 564–580.

Ebersole, J.L.; Wigington, P.J.; Baker, J.P. [et al.]. 2006. Juvenile coho salmon growth and survival across stream network seasonal habitats. Transactions of the American Fisheries Society. 135: 1681–1697.

Fasullo, J.T.; Otto-Bliesner, B.L.; Stevenson, S. 2018. ENSO's changing influence on temperature, precipitation, and wildfire in a warming climate. Geophysical Research Letters. 45: 9216–9225.

Flitcroft, R.; Arismendi, I.; Davis, C. [et al.]. 2018. Using expressed behavior to evaluate vulnerability of coho salmon (*Oncorhynchus kisutch*) upriver migrants to future hydrologic regimes: management implications and conservation planning. Aquatic Conservation and Marine Ecosystems. 29: 1093–1094.

Flitcroft, R.L.; Lewis, S.L.; Arismendi, I. [et al.]. 2016. Linking hydroclimate to fish phenology and habitat use with ichthyographs. PLoS ONE. 11: e0168831.

Gonzalez, R.; Dunham, J.; Lightcap, S. [et al.]. 2017. Large wood and instream habitat for juvenile coho salmon and larval lampreys in a Pacific Northwest stream. North American Journal of Fisheries Management. 37: 683–699.

Goode, J.R.; Buffington, J.M.; Tonina, D. [et al.]. 2013. Potential effects of climate change on streambed scour and risks to salmonid survival in snow-dominated mountain basins. Hydrological Processes. 27: 750–765.

Goode, J.R.; Luce, C.H.; Buffington, J.M. 2012. Enhanced sediment delivery in a changing climate in semi-arid mountain basins: implications for water resource management and aquatic habitat in the northern Rocky Mountains. Geomorphology. 139–140: 1–15.

Hessburg, P.F.; Churchill, D.J.; Larson, A.J. [et al.]. 2015. Restoring fire–prone inland Pacific landscapes: seven core principles. Landscape Ecology. 30: 1805–1835.

Holmes, J.A.; Youson, J.H. 1998. Extreme and optimal temperatures for metamorphosis in sea lampreys. Transactions of the American Fisheries Society. 127: 206–211.

Holtby, L.B. 1988. Effects of logging on stream temperatures in Carnation Creek, British Columbia, and associated impacts on the coho salmon (*Oncorhynchus kisutch*). Canadian Journal of Fisheries and Aquatic Sciences. 45: 502–515.

Isaak, D.J.; Luce, C.H.; Horan, D.L. [et al.]. 2018. Global warming of salmon and trout rivers in the northwestern U.S.: road to ruin or path through purgatory? Transactions of the American Fisheries Society. 147: 566–587.

Isaak, D.J.; Wenger, S.J.; Peterson, E.E. [et al.]. 2017a. NorWeST summer temperature model and scenarios for the western U.S.: a crowd-sourced database and new geospatial tools foster a user-community and predict broad climate warming of rivers and streams. Water Resources Research. 53: 9181–9205.

Isaak, D.J.; Wenger, S.J.; Young, M.K. 2017b. Big biology meets microclimatology: defining thermal niches of ectotherms at landscape scales for conservation planning. Ecological Applications. 27: 977–990.

Isaak, D.; Wollrab, S.; Horan, D.; Chandler, G. 2012. Climate change effects on stream and river temperatures across the northwest U.S. from 1980–2009 and implications for salmonid fishes. Climatic Change. 113: 499–524.

Isaak, D.; Young, M.K.; Luce, C. [et al.]. 2016. Slow climate velocities of mountain streams portend their role as refugia for cold-water biodiversity. Proceedings of the National Academy of Sciences, USA. 113: 4374–4379.

Jentsch, A.; Kreyling, J.; Beierkuhnlein, C. 2007. A new generation of climate-change experiments: events, not trends. Frontiers in Ecology and the Environment. 5: 365–374.

Johnson, S.L. 2004. Factors influencing stream temperatures in small streams: substrate effects and a shading experiment. Canadian Journal of Fisheries and Aquatic Sciences. 61: 913–923.

Joyce, L.A.; Blate, G.M.; McNulty, S.G. [et al.]. 2009. Managing for multiple resources under climate change: national forests. Environmental Management. 44: 1022–1032.

Kendall, N.W.; McMillan, J.R.; Sloat, M.R. [et al.]. 2014. Anadromy and residency in steelhead and rainbow trout (*Oncorhynchus mykiss*): a review of the processes and patterns. Canadian Journal of Fisheries and Aquatic Sciences. 72: 319–342.

Kishi, M.J.; Kaeriyama, M.; Ueno, H.; Kamezawa, Y. 2010. The effect of climate change on the growth of Japanese chum salmon (*Oncorhynchus keta*) using a bioenergetics model coupled with a three-dimensional lower trophic ecosystem model (NEMURO). Deep Sea Research Part II: Topical Studies in Oceanography. 57: 1257–1265.

Kovach, R.P.; Joyce, J.E.; Echave, J.D. [et al.]. 2013. Earlier migration timing, decreasing phenotypic variation, and biocomplexity in multiple salmonid species. PLoS ONE. 8: e53807.

Kovach, R.P.; Muhlfeld, C.C.; Wade, A.A. [et al.]. 2015. Genetic diversity is related to climatic variation and vulnerability in threatened bull trout. Global Change Biology. 21: 2510–2524.

Kuehne, L.M.; Olden, J.D.; Duda, J.J. 2012. Costs of living for juvenile Chinook salmon (*Oncorhynchus tshawytscha*) in an increasingly warming and invaded world. Canadian Journal of Fisheries and Aquatic Sciences. 69: 1621–1630.

Larson, J.S.; Gunson, J.R. 1983. Status of the beaver in North America. Acta Zoologica Fennica. 174: 91–93.

Lawrence, D.J.; Stewart-Koster, B.; Olden, J.D. [et al.]. 2014. The interactive effects of climate change, riparian management, and a nonnative predator on stream-rearing salmon. Ecological Applications. 24: 895–912.

Leopold, A. 1949. A Sand County almanac. 1949. New York: Ballantine. 240 p.

Link, J.S.; Griffis, R.; Busch, S., eds. 2015. NOAA Fisheries climate science strategy. NOAA Technical Memorandum NMFS-F/SPO-155. Silver Springs, MD: U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service. 70 p.

Littell, J.; Mauger, G.S.; Salathé, E.P. [et al.]. 2014. Uncertainty and extreme events in future climate and hydrologic projections for the Pacific Northwest: providing a basis for vulnerability and core/corridor assessments. Final report to the Northwest Climate Science Center. Seattle, WA: University of Washington, Climate Impacts Group. 19 p. http://cses.washington.edu/db/pdf/Litteletal2014_CSCFinalReport717.pdf. (7 November 2019).

Luce, C.H.; Holden, Z.A. 2009. Declining annual streamflow distributions in the Pacific Northwest United States, 1948–2006. Geophysical Research Letters. 36: L16401.

Luce, C.H.; Rieman, B.E.; Dunham, J.B. [et al.]. 2001. Incorporating aquatic ecology into decisions on prioritization of road decommissioning. Water Resources Impact. 3: 8–14.

Luce, C.H.; Staab, B.P.; Kramer, M.G. [et al.]. 2014. Sensitivity of summer stream temperatures to climate variability in the Pacific Northwest. Water Resources Research. 50: 1–16.

Magnuson, J.J.; Crowder, L.B.; Medvick, P.A. 1979. Temperature as an ecological resource. American Zoologist. 19: 331–343.

Martin, B.T.; Pike, A.; John, S.N. 2017. Phenomenological vs. biophysical models of thermal stress in aquatic eggs. Ecology Letters. 20: 50–59.

Matala, A.P.; Marx, S.; Wise, T.G. 2008. A genetically distinct wild redband trout (*Oncorhynchus mykiss gairdneri*) population in Crane Prairie Reservoir, Oregon, persists despite extensive stocking of hatchery rainbow trout (*O. m. irideus*). Conservation Genetics. 9: 1643–1652.

May, C.L.; Gresswell, R.E. 2004. Spatial and temporal patterns of debris–flow deposition in the Oregon Coast Range, USA. Geomorphology. 57: 135–149.

McIntosh, B.A.; Sedell, J.R.; Thurow, R.F. [et al.]. 2000. Historical changes in pool habitats in the Columbia River basin. Ecological Applications. 10: 1478–1496.

McKay, L.; Bondelid, T.; Dewald, T. [et al.]. 2012. NHDPlus version 2: user guide. http://www.horizon-systems.com/NHDPlusData/NHDPlusV21/Documentation/NHDPlusV2_User_Guide.pdf. (16 September 2016).

Meengs, C.C.; Lackey, R.T. 2005. Estimating the size of historical Oregon salmon runs. Reviews in Fisheries Science. 13: 51–66.

Meeuwig, M.H.; Bayer, J.M.; Seelye, J.G. 2005. Effects of temperature on survival and development of early life stage Pacific and western brook lampreys. Transactions of the American Fisheries Society. 134: 19–27.

Millennium Ecosystem Assessment. 2005. Ecosystems and human well-being: synthesis. Washington, DC: Island Press. 137 p.

Miller, D.; Luce, C.; Benda, L. 2003. Time, space, and episodicity of physical disturbance in streams. Forest Ecology and Management. 178: 121–140.

Miller, K.M.; Li, S.; Kaukinen, K.H. [et al.]. 2011. Genomic signatures predict migration and spawning failure in wild Canadian salmon. Science. 331: 214–217.

Mount, J.F. 1995. California rivers and streams: the conflict between fluvial process and land use. Berkeley, CA: University of California Press. 376 p.

Muhlfeld, C.C.; Albeke, S.E.; Gunckel, S.L. 2015. Status and conservation of interior redband trout in the Western United States. North American Journal of Fisheries Management. 35: 31–53.

Muhlfeld, C.C.; Kovach, R.P.; Jones, L.A. [et al.]. 2014. Invasive hybridization in a threatened species is accelerated by climate change. Nature Climate Change. 4: 620.

Neuheimer, A.B.; Taggart, C.T. 2007. The growing degree-day and fish size-at-age: the overlooked metric. Canadian Journal of Fisheries and Aquatic Sciences. 64: 375–385.

Nickelson, T.E.; Solazzi, M.F.; Johnson, S.L.; Rodgers, J.D. 1992. Effectiveness of selected stream improvement techniques to create suitable summer and winter rearing habitat for juvenile coho salmon (*Oncorhynchus kisutch*) in Oregon coastal streams. Canadian Journal of Fisheries and Aquatic Sciences. 49: 790–794.

Northcote, T.G.; Hartman, G.F. 2004. Fishes and forestry: worldwide watershed interactions and management. Oxford, United Kingdom: Blackwell Publishing. 793 p.

Papadaki, C.; Soulis, K.; Muñoz-Mas, R. [et al.]. 2016. Potential impacts of climate change on flow regime and fish habitat in mountain rivers of the south-western Balkans. Science of the Total Environment. 540: 418–428.

Parmesan, C.; Yohe, G. 2003. A globally coherent fingerprint of climate change impacts across natural systems. Nature. 421: 37–42.

Penaluna, B.E.; Abadía-Cardoso, A.; Dunham, J.B. [et al.]. 2016. Conservation of native Pacific trout diversity in western North America. Fisheries. 41: 286–300.

Penaluna, B.E.; Dunham, J.B.; Railsback, S.F. [et al.]. 2015. Local variability mediates vulnerability of trout populations to land use and climate change. PLoS ONE. 10: e0135334.

Penaluna, B.E.; Olson, D.H.; Flitcroft, R.L. [et al.]. 2017. Aquatic biodiversity in forests: a weak link in ecosystem services resilience. Biodiversity and Conservation. 26: 3125–3155.

Penaluna, B.E.; Reeves, G.H.; Barnett, Z.C. [et al.]. 2018. Using natural disturbance and portfolio concepts to guide aquatic-riparian ecosystem management. Fisheries. 43: 406–422.

Peterson, D.P.; Wenger, S.J.; Rieman, B.E.; Isaak, D.J. 2013. Linking climate change and fish conservation efforts using spatially explicit decision support tools. Fisheries. 38: 112–127.

Platts, W.S. 1991. Livestock grazing. In: Meehan, W.R., ed. Influences of forest and rangeland management on salmonid fishes and their habitats. Spec. Pub. 19. Bethesda, MD: American Fisheries Society: 389–423.

Quinn, T.P.; Myers, K.W. 2004. Anadromy and the marine migrations of Pacific salmon and trout: Rounsefell revisited. Reviews in Fish Biology and Fisheries. 14: 421–442.

Rand, P.S.; Hinch, S.G.; Morrison, J. [et al.]. 2006. Effects of river discharge, temperature, and future climates on energetics and mortality of adult migrating Fraser River sockeye salmon. Transactions of the American Fisheries Society. 135: 655–667.

Reeves, G.H.; Benda, L.E.; Burnett, K.M. [et al.]. 1995. A disturbance-based ecosystem approach to maintaining and restoring freshwater habitats of evolutionarily significant units of anadromous salmonids in the Pacific Northwest. American Fisheries Society Symposium. 17: 334–349.

Reeves, G.H.; Olson, D.H.; Wondzell, S.M. [et al.]. 2018. The aquatic conservation strategy of the Northwest Forest Plan—a review of the relevant science after 23 years. In: Spies, T.A.; Stine, P.A.; Gravenmier, R. [et al.], tech. coords. Synthesis of science to inform land management within the Northwest Forest Plan area. Gen. Tech. Rep. PNW-GTR-966. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 461–624. Chapter 7.

Rubenstein, M.A.; Christophersen, R.; Ransom, J.I. 2019. Trophic implications of a phenological paradigm shift: bald eagles and salmon in a changing climate. Journal of Applied Ecology. 56: 769–778.

Sabater, S.; Elosegi, A.; Ludwig, R., eds. 2018. Multiple stressors in river ecosystems: status, impacts and prospects for the future. Amsterdam, The Netherlands: Elsevier. 404 p.

Safeeq, M.; Grant, G.E.; Lewis, S.L.; Tague, C.L. 2013. Coupling snowpack and groundwater dynamics to interpret historical streamflow trends in the western United States. Hydrological Processes. 27: 655–668.

Sinokrot, B.A.; Stefan, H.G. 1993. Stream temperature dynamics: measurements and modeling. Water Resources Research. 29: 2299–2312.

Sloat, M.R.; Reeves, G.H.; Christiansen, K.R. 2016. Stream network geomorphology mediates predicted vulnerability of anadromous fish habitat to hydrologic change in southeast Alaska. Global Change Biology. 23: 604–620.

Spies, T.A.; Reeves, G.H.; Burnett, K.M. [et al.]. 2002. Assessing the ecological consequences of forest policies in a multi-ownership province in Oregon. In: Liu, J.; Taylor, W.H., eds. Integrating landscape ecology into natural resource management. Cambridge, United Kingdom: Cambridge University Press: 179–207.

Sykes, G.E.; Johnson, C.J.; Shrimpton, J.M. 2009. Temperature and flow effects on migration timing of Chinook salmon smolts. Transactions of the American Fisheries Society. 138: 1252–1265.

Thackeray, S.J.; Henrys, P.A.; Hemming, D. [et al.]. 2016. Phenological sensitivity to climate across taxa and trophic levels. Nature. 535: 241–245.

Torgersen, C.E.; Close, D.A. 2004. Influence of habitat heterogeneity on the distribution of larval Pacific lamprey (*Lampetra tridentata*) at two spatial scales. Freshwater Biology. 49: 614–630.

U.S. Department of the Interior, Fish and Wildlife Service [USDI FWS]. 2017. Pacific lamprey climate change vulnerability assessment. https://nplcc.blob.core.windows.net/media/Default/2013_Documents/Climate_Change_Vulnerability/Pacific Lamprey Climate Change Vulnerability Assessment Final 09_29_17 (1).pdf. (16 March 2019).

Van Doornik, D.M.; Teel, D.J.; Kuligowski, D.R. [et al.]. 2007. Genetic analyses provide insight into the early ocean stock distribution and survival of juvenile coho salmon off the coasts of Washington and Oregon. North American Journal of Fisheries Management. 27: 220–237.

Ver Hoef, J.M.; Peterson, E.; Theobald, D. 2006. Spatial statistical models that use flow and stream distance. Environmental and Ecological Statistics. 13: 449–464.

Wainwright, T.C.; Weitkamp, L.A. 2013. Effects of climate change on Oregon Coast coho salmon: habitat and life-cycle interactions. Northwest Science. 87: 219–243.

Ward, E.J.; Anderson, J.H.; Beechie, T.J. [et al.]. 2015. Increasing hydrologic variability threatens depleted anadromous fish populations. Global Change Biology. 21: 2500–2509.

Wenger, S.J.; Isaak, D.J.; Luce, C.H. [et al.]. 2011. Flow regime, temperature, and biotic interactions drive differential declines of trout species under climate change. Proceedings of the National Academy of Sciences, USA. 108: 14175–14180.

Wenger, S.J.; Luce, C.H.; Hamlet, A.F. [et al.]. 2010. Macroscale hydrologic modeling of ecologically relevant flow metrics. Water Resources Research. 46: W09513.

Wondzell, S.M.; Diabat, M.; Haggerty, R. 2018. What matters most: Are future stream temperatures more sensitive to changing air temperatures, discharge, or riparian vegetation? Journal of the American Water Resources Association. 55: 116–132.

Chapter 4 Appendix

Table 4A.1: Summary of conditions for flow and stream temperature characteristics over the historical and future climate periods by 6th-code hydrologic unit (HUC; basin)

		Winter 95-percentile flow					Mean summer flow (cm)					August mean stream temperature (°C)				
HUC number	Stream length (km)	1980s	2040s	2080s	Days increased from 1980 to 2040	Days increased from 1980 to 2080	1980s	2040s	2080s	Percentage change from 1980 to 2040 (CHGCMS 2040)	Percentage change from 1980 to 2080 (CHGCMS 2080)	1980s	2040s	2080s	Change from 1980 to 2040	Change from 1980 to 2080
170701050103	30.2	4.2	5.5	8.4	1.3	0	4258.1	3325.0	2667.0	-17.0	-28.7	21.7	23.3	24.3	1.6	2.6
170701050201	30.8	12.5	15.1	15.7	2.7	0	0.1	0.1	0.1	-33.0	-38.1	10.8	12.1	13.0	1.4	2.3
170701050203	42.4	13.8	16.0	15.9	2.1	0	0.1	0.1	0.1	-8.0	-12.2	12.8	14.2	15.1	1.4	2.3
170701050301	54.8	10.5	14.1	15.4	3.7	0	0.2	0.1	0.1	-34.6	-39.5	11.1	12.4	13.3	1.4	2.3
170701050401	23.4	4.3	5.5	8.6	1.2	0	4491.3	3502.7	2813.0	-17.5	-29.5	21.1	22.6	23.6	1.5	2.6
170701050403	39.0	12.8	15.7	16.0	2.9	0	0.1	0.1	0.1	-13.7	-18.5	11.8	13.2	14.1	1.4	2.3
170701050404	12.4	14.2	15.7	15.9	1.5	0	0.6	0.5	0.5	-8.6	-12.1	19.2	20.7	21.7	1.5	2.5
170701050405	12.0	15.8	15.2	15.2	-0.6	0	0.2	0.2	0.2	-2.8	-4.4	18.2	19.6	20.6	1.5	2.5
170701050406	22.6	2.3	3.8	7.5	1.5	0	5205.4	4060.5	3261.5	-20.5	-34.5	21.7	23.2	24.3	1.6	2.6
170701050501	60.3	3.5	7.2	10.5	3.7	0	1.2	0.7	0.3	-45.5	-71.4	9.0	10.3	11.2	1.3	2.2
170701050502	35.0	6.8	11.3	13.5	4.5	0	1.7	0.9	0.5	-50.1	-70.0	8.0	9.4	10.2	1.3	2.2
170701050503	21.6	10.1	14.8	15.7	4.7	0	0.2	0.1	0.1	-47.2	-52.9	7.9	9.2	10.0	1.3	2.2
170701050504	25.8	10.0	13.0	13.8	3.0	0	0.4	0.2	0.1	-59.9	-73.8	7.5	8.8	9.7	1.3	2.2
170701050505	33.9	13.6	15.0	15.1	1.3	0	0.7	0.3	0.3	-31.1	-40.2	10.3	11.7	12.6	1.4	2.2
170701050506	62.4	-162.8	-161.1	-160.7	1.7	0	2.6	1.4	0.8	-27.7	-38.5	12.8	14.2	15.1	1.4	2.3
170701050601	48.5	11.0	13.6	14.3	2.5	0	0.8	0.4	0.3	-46.8	-56.8	9.9	11.3	12.2	1.3	2.2
170701050602	34.4	12.6	14.5	14.8	2.0	0	0.4	0.3	0.2	-30.8	-37.4	11.7	13.1	14.0	1.4	2.3
170701050603	47.4	12.1	14.5	15.0	2.4	0	0.9	0.5	0.4	-33.1	-39.2	10.8	12.2	13.1	1.4	2.3
170701050701	34.7	14.6	15.5	15.4	0.9	0	0.1	0.1	0.1	-7.9	-11.6	12.0	13.4	14.3	1.4	2.3
170701050703	21.7	13.9	14.6	14.6	0.7	0	4.6	2.7	2.0	-15.8	-22.3	14.9	16.3	17.3	1.4	2.4
170701050811	9.5	11.8	13.6	14.2	1.9	0	13.1	9.2	6.9	-29.8	-47.1	12.2	13.5	14.5	1.4	2.3
170701050905	12.1	14.0	14.8	15.0	0.8	0	1.5	1.1	1.0	-25.6	-30.4	11.1	12.4	13.3	1.4	2.3
170701051008	34.2	13.2	15.1	15.2	1.9	0	3.7	2.2	1.9	-30.1	-37.0	13.3	14.7	15.6	1.4	2.3
170701051101	13.8	14.9	14.6	14.6	-0.4	0	0.2	0.2	0.2	-4.9	-7.8	16.4	17.9	18.9	1.5	2.4

		Winter 95-percentile flow					Mean summer flow (cm)					August mean stream temperature (°C)				
HUC number	Stream length (km)	1980s	2040s	2080s	Days increased from 1980 to 2040	Days increased from 1980 to 2080	1980s	2040s	2080s	Percentage change from 1980 to 2040 (CHGCMS 2040)	Percentage change from 1980 to 2080 (CHGCMS 2080)	1980s	2040s	2080s	Change from 1980 to 2040	Change from 1980 to 2080
170701051102	22.0	13.7	15.2	15.2	1.5	0	0.1	0.1	0.1	-8.5	-12.5	12.0	13.4	14.3	1.4	2.3
170701051103	15.5	14.5	14.9	14.8	0.5	0	0.3	0.3	0.3	-5.0	-7.8	16.7	18.2	19.1	1.5	2.4
170701051105	34.6	7.1	8.0	10.2	0.9	0	3236.2	2523.8	2027.1	-13.6	-22.9	19.1	20.6	21.6	1.5	2.5
170701051106	49.7	7.4	8.8	10.9	1.4	0	2881.4	2245.6	1803.3	-16.8	-26.3	18.6	20.2	21.1	1.5	2.5
170701051201	21.7	12.5	14.1	14.4	1.6	0	0.3	0.2	0.2	-30.2	-36.3	9.9	11.3	12.1	1.3	2.2
170701051202	52.9	15.0	15.1	14.9	0.1	0	0.3	0.3	0.2	-19.1	-25.1	13.5	14.9	15.8	1.4	2.3
170701051203	22.7	12.6	13.8	14.0	1.2	0	0.7	0.5	0.4	-31.8	-38.7	12.4	13.8	14.8	1.4	2.3
170701051204	37.1	9.1	9.9	11.5	0.8	0	2453.9	1911.8	1535.6	-18.7	-27.8	17.7	19.2	20.2	1.5	2.5
170701060409	16.5	11.4	13.8	15.2	2.4	0	27.8	19.5	14.9	-29.9	-46.6	15.9	17.4	18.3	1.5	2.4
170703060401	40.8	7.0	13.1	15.3	6.1	0	1.1	0.4	0.3	-63.4	-74.3	12.5	13.9	14.8	1.4	2.3
170703060601	36.0	11.9	16.2	16.3	4.3	0	0.1	0.1	0.1	-21.0	-27.1	9.9	11.3	12.1	1.3	2.2
170703060801	29.6	6.5	12.3	15.1	5.8	0	0.6	0.2	0.2	-63.9	-69.7	11.7	13.1	14.0	1.4	2.3
170703060802	23.2	11.6	14.2	15.5	2.6	0	0.2	0.1	0.1	-21.6	-25.5	12.3	13.7	14.6	1.4	2.3
170703060803	23.8	12.5	14.5	15.6	2.0	0	0.2	0.2	0.2	-17.3	-20.7	13.4	14.8	15.7	1.4	2.3
170703060804	25.3	8.4	12.9	15.4	4.5	0	0.6	0.3	0.3	-38.8	-43.7	13.5	14.9	15.9	1.4	2.3
170703060901	53.3	9.8	14.9	16.1	5.1	0	0.2	0.1	0.1	-28.9	-35.2	10.6	11.9	12.8	1.4	2.3
170703060902	40.1	9.4	14.5	15.7	5.1	0	0.2	0.1	0.1	-48.4	-54.6	8.8	10.1	11.0	1.3	2.2
170703060903	79.9	5.0	10.4	13.7	5.4	0	1.1	0.5	0.3	-54.3	-69.9	10.2	11.5	12.4	1.3	2.2
170703060904	37.7	13.9	15.0	15.1	1.1	0	0.1	0.1	0.1	-12.3	-16.5	12.8	14.2	15.1	1.4	2.3
170703060905	28.3	11.7	13.8	15.1	2.2	0	0.2	0.2	0.2	-25.7	-29.6	13.2	14.6	15.5	1.4	2.3
170703060906	27.1	8.1	13.6	15.1	5.6	0	5.0	2.7	2.0	-46.4	-60.5	13.9	15.3	16.2	1.4	2.4
170703060907	30.8	6.8	12.4	15.7	5.6	0	0.2	0.1	0.1	-46.2	-51.1	13.0	14.4	15.4	1.4	2.3
170703061106	14.5	14.7	14.8	14.5	0.0	0	0.3	0.3	0.3	-2.9	-4.8	16.7	18.1	19.1	1.5	2.4
170703061205	29.5	12.1	14.0	14.7	1.9	0	68.9	50.4	43.8	-16.4	-22.6	18.7	20.2	21.2	1.5	2.5
170800010101	54.6	8.1	11.3	12.9	3.2	0	0.7	0.4	0.2	-50.5	-67.5	9.1	10.2	11.0	1.1	2.0
170800010102	22.6	10.9	13.3	14.0	2.4	0	1.2	0.6	0.4	-42.8	-54.0	11.6	12.9	13.8	1.2	2.1
170800010201	24.3	7.8	11.8	13.8	4.1	0	0.7	0.4	0.3	-48.0	-64.3	10.1	11.3	12.1	1.2	2.0
170800010202	82.7	7.0	10.8	12.7	3.8	0	0.8	0.5	0.3	-44.8	-62.4	8.5	9.6	10.4	1.1	1.9

		Winter 95-percentile flow					Mean summer flow (cm)					August mean stream temperature (°C)				
HUC number	Stream length (km)	1980s	2040s	2080s	Days increased from 1980 to 2040	Days increased from 1980 to 2080	1980s	2040s	2080s	Percentage change from 1980 to 2040 (CHGCMS 2040)	Percentage change from 1980 to 2080 (CHGCMS 2080)	1980s	2040s	2080s	Change from 1980 to 2040	Change from 1980 to 2080
170800010301	22.7	10.1	15.0	15.9	4.9	0	0.1	0.1	0.1	-46.3	-52.6	8.6	9.7	10.5	1.1	1.9
170800010302	51.6	3.7	9.6	13.7	5.9	0	1.1	0.5	0.3	-59.2	-74.2	8.6	9.7	10.5	1.1	1.9
170800010303	35.3	12.1	14.6	15.2	2.5	0	1.4	0.6	0.5	-31.5	-39.9	10.4	11.6	12.5	1.2	2.1
170800010304	34.7	12.0	14.3	14.8	2.2	0	2.5	1.3	1.1	-37.4	-46.3	12.7	14.0	14.9	1.3	2.2
170800010401	49.2	12.7	13.8	14.0	1.1	0	3.7	2.1	1.5	-27.9	-38.4	12.4	13.7	14.6	1.3	2.2
170800010402	69.4	12.8	13.6	13.8	0.7	0	5.9	3.4	2.5	-27.2	-36.6	14.6	15.9	16.9	1.4	2.3
170800010501	26.1	12.5	14.1	14.4	1.6	0	0.2	0.1	0.1	-33.8	-42.4	10.6	11.8	12.6	1.2	2.1
170800010502	29.5	12.4	14.0	14.2	1.6	0	0.4	0.3	0.3	-31.0	-38.5	9.8	10.9	11.8	1.2	2.0
170800010503	42.4	13.5	14.1	14.3	0.6	0	0.7	0.5	0.5	-24.2	-31.9	10.8	12.1	12.9	1.2	2.1
170800010504	27.6	13.9	14.3	14.3	0.4	0	0.2	0.2	0.2	-21.5	-29.3	11.2	12.4	13.3	1.2	2.1
170800010505	34.1	13.9	14.5	14.6	0.6	0	0.5	0.4	0.3	-22.7	-30.2	13.2	14.5	15.5	1.3	2.2
170800010506	27.5	13.9	14.3	14.3	0.4	0	2.5	1.9	1.7	-22.4	-29.9	14.5	15.8	16.8	1.4	2.3
170800010701	33.0	14.3	14.4	14.3	0.0	0	0.2	0.1	0.1	-19.6	-27.1	11.5	12.8	13.6	1.2	2.1
170800010703	54.6	12.8	13.1	13.2	0.3	0	8.6	5.5	4.4	-21.9	-29.8	16.0	17.4	18.5	1.4	2.4
170800010801	47.7	12.6	13.0	13.3	0.4	0	533.9	415.9	334.1	-21.1	-28.6	12.8	14.1	15.1	1.3	2.2
170800010802	61.1	12.3	12.6	12.9	0.3	0	646.5	503.7	404.6	-20.5	-28.5	13.4	14.7	15.6	1.3	2.3
170800010803	35.1	11.4	11.8	12.7	0.4	0	1302.7	1014.9	815.3	-20.3	-29.5	12.5	13.8	14.7	1.3	2.2
170800010804	74.5	10.9	11.4	12.4	0.5	0	1491.7	1162.1	933.6	-16.6	-24.7	17.0	18.4	19.5	1.5	2.5
170900010101	33.4	2.8	7.7	11.9	4.9	0	1.7	0.8	0.3	-55.2	-81.2	9.0	10.1	10.9	1.1	2.0
170900010102	14.9	10.2	13.5	14.1	3.2	0	0.3	0.1	0.1	-50.8	-58.4	9.1	10.2	11.0	1.1	2.0
170900010103	19.1	9.2	12.8	13.9	3.6	0	2.5	1.2	0.5	-51.1	-71.2	10.1	11.3	12.2	1.2	2.0
170900010104	26.0	8.8	12.7	13.8	3.9	0	0.6	0.3	0.2	-54.1	-72.4	9.0	10.2	11.0	1.1	2.0
170900010105	38.1	12.8	13.8	14.1	1.0	0	0.3	0.2	0.2	-27.8	-36.7	10.2	11.4	12.2	1.2	2.0
170900010106	55.5	11.9	13.1	13.7	1.2	0	1.4	0.7	0.4	-33.5	-45.7	11.1	12.4	13.2	1.2	2.1
170900010201	37.5	11.1	13.0	13.5	2.0	0	0.2	0.1	0.1	-39.9	-49.0	10.8	12.0	12.9	1.2	2.1
170900010202	32.0	12.2	12.9	13.1	0.7	0	0.6	0.4	0.3	-30.4	-40.5	12.9	14.2	15.2	1.3	2.2
170900010301	38.6	4.9	10.2	13.4	5.3	0	1.1	0.4	0.2	-64.1	-78.4	8.3	9.4	10.2	1.1	1.9

		Winter 95-percentile flow					Mean summer flow (cm)					August mean stream temperature (°C)				
HUC number	Stream length (km)	1980s	2040s	2080s	Days increased from 1980 to 2040	Days increased from 1980 to 2080	1980s	2040s	2080s	Percentage change from 1980 to 2040 (CHGCMS 2040)	Percentage change from 1980 to 2080 (CHGCMS 2080)	1980s	2040s	2080s	Change from 1980 to 2040	Change from 1980 to 2080
170900010302	36.3	9.8	12.6	13.6	2.8	0	1.9	0.7	0.4	-48.2	-59.5	10.2	11.4	12.3	1.2	2.0
170900010303	40.5	10.6	12.6	13.3	2.0	0	3.3	1.4	0.9	-44.3	-57.4	12.4	13.7	14.6	1.3	2.2
170900010401	21.0	9.7	12.8	13.7	3.0	0	0.8	0.4	0.3	-54.7	-61.7	8.3	9.5	10.3	1.1	1.9
170900010402	36.9	11.7	13.0	13.3	1.3	0	0.3	0.2	0.2	-39.5	-47.9	9.5	10.7	11.5	1.2	2.0
170900010403	63.8	12.5	13.0	13.2	0.6	0	1.3	0.8	0.7	-31.8	-41.4	11.8	13.0	13.9	1.2	2.1
170900010501	26.5	13.3	14.0	14.3	0.7	0	0.2	0.1	0.1	-26.1	-35.1	12.4	13.7	14.6	1.3	2.2
170900010502	92.4	13.1	13.5	13.9	0.4	0	2.0	1.1	0.7	-28.1	-40.1	13.0	14.3	15.2	1.3	2.2
170900010503	49.6	12.8	13.1	13.2	0.3	0	0.3	0.2	0.2	-24.9	-35.7	13.0	14.3	15.2	1.3	2.2
170900010504	10.3	13.2	13.1	13.4	0.0	0	0.1	0.1	0.1	-23.1	-33.2	13.5	14.8	15.8	1.3	2.3
170900010505	25.1	12.8	13.3	13.6	0.5	0	10.4	5.8	4.1	-33.5	-46.7	12.6	13.9	14.8	1.3	2.2
170900010602	17.2	6.9	11.8	13.7	4.9	0	1.7	0.6	0.3	-62.8	-73.8	9.3	10.4	11.3	1.1	2.0
170900010603	35.2	10.5	12.5	13.3	2.0	0	2.7	1.0	0.7	-42.8	-53.7	11.4	12.6	13.5	1.2	2.1
170900010604	48.4	11.7	12.8	13.4	1.1	0	3.5	1.5	1.1	-41.9	-53.2	12.2	13.5	14.4	1.3	2.2
170900010605	38.3	13.0	13.5	13.5	0.4	0	0.2	0.1	0.1	-26.9	-36.2	11.3	12.5	13.4	1.2	2.1
170900010606	27.3	13.3	13.6	13.6	0.2	0	0.4	0.3	0.3	-26.3	-36.0	12.4	13.7	14.6	1.3	2.2
170900010607	40.1	12.9	13.2	13.4	0.3	0	1.7	0.9	0.7	-29.3	-39.8	13.2	14.5	15.4	1.3	2.2
170900010608	67.7	12.9	13.2	13.3	0.3	0	2.4	1.2	0.9	-30.4	-41.2	13.5	14.9	15.8	1.3	2.3
170900010701	42.6	13.0	13.3	13.5	0.3	0	8.9	4.9	3.6	-28.6	-39.4	14.0	15.3	16.3	1.3	2.3
170900010703	82.9	13.6	13.6	13.7	0.1	0	2.9	1.6	1.2	-24.5	-35.1	14.4	15.8	16.8	1.4	2.3
170900010801	45.2	13.3	13.3	13.2	0.0	0	0.2	0.1	0.1	-22.4	-31.9	13.3	14.7	15.6	1.3	2.3
170900010901	39.6	13.7	13.6	13.7	0.0	0	0.2	0.1	0.1	-24.8	-34.5	12.5	13.8	14.7	1.3	2.2
170900010902	27.8	13.5	13.6	13.6	0.1	0	0.2	0.1	0.1	-24.4	-34.1	13.5	14.8	15.7	1.3	2.3
170900010903	49.0	13.5	13.5	13.6	-0.1	0	0.3	0.3	0.2	-23.5	-33.0	13.6	14.9	15.9	1.3	2.3
170900010904	49.6	13.6	13.5	13.6	-0.1	0	0.8	0.6	0.5	-23.1	-33.0	14.7	16.1	17.1	1.4	2.3
170900010905	69.4	13.5	13.5	13.5	0.0	0	0.2	0.2	0.2	-23.4	-33.3	13.9	15.2	16.2	1.3	2.3
170900030301	43.2	13.6	13.5	13.6	-0.1	0	0.3	0.2	0.2	-23.0	-31.7	13.5	14.8	15.8	1.3	2.3
170900040101	45.3	2.0	5.5	9.0	3.4	0	1.2	0.8	0.5	-40.4	-65.0	5.8	6.8	7.5	1.0	1.7
170900040102	44.5	8.8	11.8	13.1	3.0	0	2.6	1.5	0.9	-48.5	-63.6	8.8	9.9	10.8	1.1	1.9

		Winter 95-percentile flow					Mean summer flow (cm)					August mean stream temperature (°C)				
HUC number	Stream length (km)	1980s	2040s	2080s	Days increased from 1980 to 2040	Days increased from 1980 to 2080	1980s	2040s	2080s	Percentage change from 1980 to 2040 (CHGCMS 2040)	Percentage change from 1980 to 2080 (CHGCMS 2080)	1980s	2040s	2080s	Change from 1980 to 2040	Change from 1980 to 2080
170900040103	42.0	9.5	12.5	13.7	3.0	0	0.8	0.3	0.2	-54.6	-66.0	8.7	9.9	10.7	1.1	1.9
170900040104	16.7	11.9	13.4	13.9	1.5	0	1.4	0.7	0.5	-43.1	-53.1	10.4	11.6	12.4	1.2	2.1
170900040105	33.7	12.2	12.9	13.4	0.7	0	5.5	3.1	2.0	-32.8	-45.9	11.6	12.9	13.8	1.2	2.1
170900040201	33.8	11.1	13.6	14.3	2.5	0	0.2	0.1	0.1	-45.5	-53.7	11.5	12.7	13.6	1.2	2.1
170900040202	35.0	12.1	13.5	13.7	1.4	0	0.6	0.4	0.3	-40.3	-48.9	10.2	11.4	12.2	1.2	2.0
170900040203	25.9	11.6	13.1	13.1	1.5	0	0.4	0.2	0.2	-39.7	-47.6	11.3	12.5	13.4	1.2	2.1
170900040204	15.9	12.0	13.5	13.9	1.5	0	3.2	1.7	1.5	-46.0	-53.6	8.2	9.4	10.2	1.1	1.9
170900040205	30.4	12.2	13.1	13.3	0.9	0	0.3	0.2	0.2	-39.6	-47.1	12.0	13.2	14.1	1.3	2.2
170900040206	68.5	12.6	13.6	13.9	1.0	0	1.6	0.9	0.8	-39.2	-47.2	10.3	11.5	12.3	1.2	2.0
170900040207	32.4	2.5	6.9	11.4	4.4	0	1.0	0.5	0.2	-54.4	-80.3	7.4	8.5	9.3	1.1	1.9
170900040208	22.4	7.6	11.5	13.2	3.9	0	6.2	2.7	1.3	-52.4	-73.1	12.9	14.2	15.1	1.3	2.2
170900040209	12.6	11.5	13.3	13.6	1.8	0	22.9	11.6	8.1	-49.5	-64.5	9.7	10.8	11.7	1.2	2.0
170900040301	23.3	8.7	12.6	14.2	3.9	0	0.5	0.2	0.1	-61.4	-68.9	8.4	9.6	10.4	1.1	1.9
170900040302	23.6	11.4	13.0	13.6	1.6	0	0.4	0.2	0.2	-42.6	-50.2	9.4	10.6	11.4	1.2	2.0
170900040303	27.5	12.4	13.4	14.0	1.1	0	0.9	0.5	0.4	-35.0	-43.6	11.2	12.5	13.3	1.2	2.1
170900040304	30.6	12.8	13.5	13.9	0.8	0	1.3	0.8	0.6	-34.4	-43.0	11.7	12.9	13.8	1.2	2.1
170900040305	37.8	12.1	13.2	13.7	1.1	0	0.3	0.2	0.2	-34.9	-42.9	10.3	11.5	12.3	1.2	2.0
170900040306	18.7	11.0	12.7	13.4	1.7	0	0.5	0.2	0.2	-51.3	-60.6	10.8	12.0	12.9	1.2	2.1
170900040307	23.2	13.5	13.7	13.7	0.1	0	0.7	0.5	0.4	-26.8	-35.4	11.5	12.8	13.6	1.2	2.1
170900040308	7.2	12.8	13.6	14.0	0.8	0	6.7	4.2	3.6	-37.9	-46.3	11.7	12.9	13.8	1.2	2.1
170900040401	24.9	13.3	13.5	13.6	0.2	0	0.3	0.2	0.2	-26.4	-34.5	11.9	13.1	14.0	1.3	2.2
170900040402	59.8	13.8	13.7	13.8	-0.1	0	0.3	0.2	0.2	-24.7	-33.3	11.9	13.1	14.0	1.3	2.2
170900040403	19.1	14.2	13.9	13.9	-0.3	0	0.3	0.2	0.2	-23.9	-32.6	12.3	13.6	14.5	1.3	2.2
170900040501	55.5	13.7	13.7	13.8	0.0	0	0.3	0.2	0.2	-25.4	-34.6	12.5	13.8	14.7	1.3	2.2
170900040502	35.4	12.6	13.4	13.7	0.8	0	25.1	13.8	10.0	-37.4	-50.2	11.9	13.1	14.0	1.3	2.2
170900040701	69.4	13.7	13.6	13.6	-0.1	0	0.2	0.2	0.2	-22.8	-32.0	14.0	15.3	16.3	1.3	2.3
170900040702	98.4	13.5	13.6	13.8	0.1	0	8.4	4.8	3.6	-26.4	-36.7	13.6	14.9	15.9	1.3	2.3

		Winter 95-percentile flow					Mean summer flow (cm)					August mean stream temperature (°C)				
HUC number	Stream length (km)	1980s	2040s	2080s	Days increased from 1980 to 2040	Days increased from 1980 to 2080	1980s	2040s	2080s	Percentage change from 1980 to 2040 (CHGCMS 2040)	Percentage change from 1980 to 2080 (CHGCMS 2080)	1980s	2040s	2080s	Change from 1980 to 2040	Change from 1980 to 2080
170900050101	19.0	8.0	11.6	13.3	3.6	0	1.0	0.6	0.3	-45.4	-70.8	8.0	9.1	9.9	1.1	1.9
170900050102	24.9	4.8	11.3	14.3	6.5	0	1.5	0.7	0.3	-61.2	-82.3	9.2	10.3	11.1	1.1	2.0
170900050103	18.2	14.3	14.7	14.8	0.5	0	0.2	0.1	0.1	-22.4	-29.7	11.6	12.9	13.8	1.2	2.1
170900050104	55.5	12.2	14.0	14.4	1.7	0	1.3	0.7	0.4	-38.8	-50.8	10.9	12.1	13.0	1.2	2.1
170900050105	18.5	13.2	13.9	14.2	0.7	0	2.6	1.4	0.9	-33.1	-46.9	11.7	12.9	13.8	1.2	2.1
170900050201	51.4	11.5	13.9	14.4	2.4	0	0.2	0.1	0.1	-51.1	-59.6	10.2	11.3	12.2	1.2	2.0
170900050202	30.7	12.8	13.8	14.2	1.0	0	0.5	0.3	0.2	-40.4	-48.4	11.3	12.5	13.4	1.2	2.1
170900050203	66.9	5.0	10.9	13.6	5.9	0	0.9	0.3	0.1	-59.4	-82.1	11.0	12.2	13.1	1.2	2.1
170900050204	33.3	2.6	5.6	8.7	2.9	0	1.4	0.9	0.6	-38.7	-61.9	10.2	11.4	12.3	1.2	2.0
170900050205	49.0	11.1	13.1	13.9	2.0	0	2.7	1.3	0.8	-44.6	-58.9	10.9	12.1	13.0	1.2	2.1
170900050206	24.6	6.6	10.6	12.8	4.0	0	0.9	0.6	0.3	-41.8	-65.7	7.3	8.4	9.2	1.1	1.8
170900050207	57.5	13.1	13.8	14.1	0.8	0	3.5	1.9	1.2	-32.9	-44.1	11.3	12.5	13.4	1.2	2.1
170900050208	11.3	13.4	13.8	14.1	0.4	0	5.7	3.1	2.0	-30.7	-43.1	12.6	13.8	14.8	1.3	2.2
170900050301	38.5	13.8	13.9	14.0	0.1	0	0.2	0.1	0.1	-25.8	-34.4	12.3	13.5	14.5	1.3	2.2
170900050302	23.5	13.8	13.8	13.9	0.0	0	0.3	0.2	0.2	-24.6	-33.0	12.8	14.1	15.0	1.3	2.2
170900050303	8.5	13.2	13.3	13.5	0.1	0	0.2	0.2	0.1	-24.1	-32.3	11.8	13.0	13.9	1.2	2.1
170900050304	20.1	13.5	13.5	13.6	0.0	0	4.5	2.6	1.8	-25.8	-35.9	12.4	13.7	14.6	1.3	2.2
170900050501	23.8	11.6	13.0	13.5	1.4	0	0.3	0.1	0.1	-43.1	-52.3	11.0	12.2	13.1	1.2	2.1
170900050502	33.6	12.8	13.4	13.8	0.6	0	0.6	0.3	0.3	-34.5	-43.0	12.8	14.1	15.0	1.3	2.2
170900050503	31.1	13.4	13.6	13.6	0.1	0	1.0	0.6	0.5	-27.5	-36.2	14.2	15.6	16.6	1.3	2.3
170900060101	32.8	12.6	13.5	13.8	0.9	0	0.2	0.2	0.1	-30.1	-38.4	12.1	13.3	14.3	1.3	2.2
170900060102	41.9	12.9	13.3	13.5	0.3	0	0.3	0.2	0.2	-30.5	-39.4	12.2	13.4	14.4	1.3	2.2
170900060103	24.1	13.4	13.4	13.4	0.0	0	1.2	0.9	0.8	-25.6	-34.0	13.6	14.9	15.9	1.3	2.3
170900060104	20.8	13.5	13.4	13.3	-0.1	0	1.6	1.2	1.0	-24.7	-33.2	14.4	15.8	16.8	1.4	2.3
170900060201	29.4	13.3	13.2	13.2	-0.1	0	0.2	0.1	0.1	-23.8	-32.3	11.3	12.5	13.4	1.2	2.1
170900060202	19.8	13.3	13.4	13.5	0.0	0	0.5	0.4	0.3	-26.0	-34.7	13.0	14.3	15.3	1.3	2.2
170900060203	21.6	13.5	13.5	13.5	0.0	0	0.2	0.1	0.1	-24.5	-33.0	11.2	12.5	13.3	1.2	2.1
170900060204	22.0	13.7	13.7	13.7	0.1	0	0.2	0.2	0.2	-26.1	-34.8	12.0	13.3	14.2	1.3	2.2

		Winter 95-percentile flow					Mean summer flow (cm)					August mean stream temperature (°C)				
HUC number	Stream length (km)	1980s	2040s	2080s	Days increased from 1980 to 2040	Days increased from 1980 to 2080	1980s	2040s	2080s	Percentage change from 1980 to 2040 (CHGCMS 2040)	Percentage change from 1980 to 2080 (CHGCMS 2080)	1980s	2040s	2080s	Change from 1980 to 2040	Change from 1980 to 2080
170900060205	26.9	13.5	13.4	13.5	-0.1	0	0.1	0.1	0.1	-22.8	-31.5	12.2	13.5	14.4	1.3	2.2
170900060206	24.0	13.6	13.4	13.5	-0.1	0	0.2	0.2	0.2	-23.2	-32.2	14.6	15.9	16.9	1.4	2.3
170900060207	23.4	13.7	13.6	13.7	-0.1	0	0.8	0.6	0.5	-24.9	-33.8	13.6	14.9	15.9	1.3	2.3
170900060208	30.2	13.5	13.5	13.7	0.0	0	1.4	1.0	0.9	-25.7	-34.5	14.1	15.5	16.4	1.3	2.3
170900060301	33.9	13.3	13.4	13.6	0.1	0	0.2	0.2	0.2	-27.9	-35.9	12.0	13.2	14.2	1.3	2.2
170900060302	23.8	13.5	13.4	13.5	-0.1	0	0.5	0.3	0.3	-24.1	-32.3	13.9	15.2	16.2	1.3	2.3
170900060303	38.6	13.5	13.4	13.4	-0.1	0	0.2	0.2	0.1	-23.6	-31.9	13.5	14.8	15.8	1.3	2.3
170900060501	20.4	13.1	13.0	12.9	-0.1	0	0.3	0.2	0.2	-22.4	-31.2	15.0	16.4	17.3	1.4	2.4
170900090406	37.1	13.2	13.6	13.5	0.4	0	0.6	0.4	0.4	-24.4	-33.1	12.2	13.5	14.4	1.3	2.2
170900110101	16.7	13.6	14.2	14.5	0.6	0	0.3	0.2	0.2	-38.4	-46.7	11.9	13.1	14.0	1.3	2.2
170900110102	23.0	14.4	14.3	14.2	-0.1	0	0.2	0.1	0.1	-19.6	-26.7	11.6	12.8	13.7	1.2	2.1
170900110103	34.4	13.3	14.2	14.6	0.9	0	0.9	0.6	0.5	-33.7	-40.6	12.6	13.9	14.8	1.3	2.2
170900110104	33.4	13.1	14.6	15.1	1.5	0	0.3	0.2	0.2	-37.3	-44.5	11.0	12.2	13.1	1.2	2.1
170900110105	28.9	14.0	15.5	15.7	1.4	0	0.1	0.1	0.1	-23.7	-29.6	10.3	11.5	12.4	1.2	2.1
170900110106	32.9	14.6	15.5	15.6	0.9	0	0.5	0.3	0.3	-22.1	-28.2	12.2	13.4	14.3	1.3	2.2
170900110107	46.8	14.5	15.1	15.2	0.6	0	1.1	0.8	0.7	-21.0	-27.2	12.6	13.9	14.8	1.3	2.2
170900110201	33.4	12.3	15.5	15.8	3.2	0	0.2	0.1	0.1	-27.2	-36.6	9.6	10.8	11.6	1.2	2.0
170900110202	38.5	7.7	12.5	15.1	4.8	0	0.7	0.3	0.1	-52.3	-70.7	9.4	10.6	11.4	1.2	2.0
170900110203	56.8	14.1	15.4	15.6	1.4	0	0.8	0.5	0.3	-24.0	-32.4	10.1	11.3	12.1	1.2	2.0
170900110204	36.6	12.7	16.0	16.3	3.3	0	0.1	0.1	0.1	-26.0	-32.2	10.2	11.4	12.2	1.2	2.0
170900110205	42.0	13.8	15.4	15.6	1.6	0	1.9	1.1	0.9	-26.0	-35.1	10.9	12.1	13.0	1.2	2.1
170900110301	28.7	11.3	15.5	16.2	4.2	0	0.1	0.1	0.1	-20.7	-26.8	10.7	11.9	12.8	1.2	2.1
170900110302	22.1	9.4	15.2	16.5	5.8	0	0.1	0.1	0.1	-34.2	-40.4	9.6	10.8	11.6	1.2	2.0
170900110303	28.1	12.5	16.3	16.3	3.8	0	0.1	0.1	0.1	-18.2	-24.3	9.7	10.8	11.7	1.2	2.0
170900110304	19.0	12.6	15.3	15.6	2.7	0	0.2	0.2	0.1	-23.2	-29.3	8.7	9.8	10.6	1.1	1.9
170900110305	41.9	12.3	15.8	16.1	3.6	0	0.5	0.4	0.4	-21.9	-28.1	10.3	11.5	12.3	1.2	2.0
170900110306	28.7	11.4	14.7	15.5	3.3	0	1.0	0.8	0.7	-29.2	-34.9	11.1	12.3	13.2	1.2	2.1
170900110401	42.1	13.3	14.8	15.2	1.5	0	6.3	4.2	3.7	-28.9	-36.5	13.4	14.7	15.6	1.3	2.3

HUC number	Stream length (km)	Winter 95-percentile flow					Mean summer flow (cm)					August mean stream temperature (°C)				
		1980s	2040s	2080s	Days increased from 1980 to 2040	Days increased from 1980 to 2080	1980s	2040s	2080s	Percentage change from 1980 to 2040 (CHGCMS 2040)	Percentage change from 1980 to 2080 (CHGCMS 2080)	1980s	2040s	2080s	Change from 1980 to 2040	Change from 1980 to 2080
170900110402	41.2	13.0	14.9	15.0	1.9	0	0.4	0.3	0.3	-23.2	-29.6	10.3	11.4	12.3	1.2	2.0
170900110403	43.5	13.3	14.5	14.7	1.2	0	0.5	0.4	0.3	-26.5	-33.5	11.6	12.8	13.7	1.2	2.1
170900110404	36.3	14.0	14.1	14.0	0.1	0	0.3	0.2	0.2	-20.2	-28.0	11.3	12.5	13.4	1.2	2.1
170900110405	70.6	13.4	14.5	14.5	1.1	0	0.2	0.2	0.2	-22.4	-29.5	12.0	13.3	14.2	1.3	2.2
170900110406	15.8	13.3	14.9	15.3	1.6	0	15.7	10.8	9.5	-30.7	-39.1	15.1	16.5	17.5	1.4	2.4
170900110501	31.8	12.8	14.3	14.7	1.6	0	0.3	0.2	0.2	-30.3	-37.3	11.9	13.2	14.1	1.3	2.2
170900110502	51.4	13.5	13.5	13.4	0.1	0	0.2	0.2	0.2	-16.5	-22.8	13.9	15.2	16.1	1.3	2.3
170900110601	29.6	13.1	13.4	13.3	0.3	0	0.2	0.2	0.1	-17.4	-24.3	12.7	14.0	14.9	1.3	2.2

Chapter 5: Climate Change Effects on Vegetation and Disturbance

Matthew J. Reilly, Becky K. Kerns, John B. Kim, Steven A. Acker, Jessica L. Hudec, Holly Kearns, Elizabeth Willhite, Jane Kertis, and Jessica E. Halofsky[1]

Introduction

Climate change is expected to have profound effects on the structure, composition, and function of ecosystems across the United States over the next century (Clark et al. 2016, Peterson et al. 2014a, Vose et al. 2012). However, interactions among climate, disturbance, and vegetation change are often complex. Understanding the geographic variability in projected changes is essential to anticipating the implications of these changes and developing strategies to adapt to them.

The Columbia River Gorge National Scenic Area (CRGNSA), Mount Hood National Forest (MTH), and Willamette National Forest (WIL) Adaptation Partnership (CMWAP) assessment area covers about 1.1 million ha. The assessment area spans the northern portion of the Oregon Cascade Range into southern Washington west of the Cascade crest, and includes portions of the eastern Cascades, the Willamette Valley, and the Columbia Plateau (fig. 5.1). The environmental setting, climate, and legacies of past forest management in the CMWAP are reflected in a wide range of forest conditions, as well as many unique nonforest ecosystems.

Much of the assessment area is in the western Cascade Range and is composed of moist forests, which are dominated by Douglas-fir (*Pseudotsuga menziesii* [Mirb.]) Franco) and western hemlock (*Tsuga heterophylla* [Raf.] Sarg). Moist forests at upper elevations include those dominated by noble fir (*Abies procera* Rehder) and Pacific silver fir (*A. amabilis* [Douglas ex Louden] Douglas ex Forbes). Cold forests include mountain hemlock (*T. mertensiana* [Bong.] Carrière), subalpine fir (*A. lasiocarpa* [Hook.] Nutt.), and whitebark pine (*Pinus albicaulis* Engelm.). The northeastern part of the CMWAP assessment area includes dry forests and woodlands commonly dominated by Douglas-fir, grand fir (*A. grandis*

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[1] **Matthew J. Reilly** is a research forester, **Becky K. Kerns** is a research ecologist, and **John B. Kim** is a biological scientist, Pacific Northwest Research Station, Forestry Sciences Laboratory, 3200 SW Jefferson Way, Corvallis, OR 97331; **Steven A. Acker** is an ecologist (retired), Pacific Northwest Region, Area Ecology Program, 16400 Champion Way, Sandy, OR 97055; **Jessica L. Hudec** is an ecologist, Pacific Northwest Region, Area Ecology Program, 2455 Highway 141, Trout Lake, WA 98650; **Holly Kearns** is a plant pathologist and **Elizabeth Willhite** is an entomologist, Pacific Northwest Region, State and Private Forestry, Forest Health Protection, 16400 Champion Way, Sandy, OR 97055; **Jane Kertis** is an ecologist (retired), Pacific Northwest Region, Area Ecology Program, 3200 SW Jefferson Way, Corvallis, OR 97331; **Jessica E. Halofsky** is the director, Western Wildland Environmental Threat Assessment Center and Northwest Climate Hub Pacific Northwest Research Station, 3625 93rd Avenue SW, Olympia, WA 98512.

[Douglas ex D. Don] Lindl.), and ponderosa pine (*P. ponderosa* Lawson & C. Lawson). Oregon white oak (*Quercus garryana* Douglas ex Hook.) also occurs in drier locations, and though it is relatively rare, it provides unique habitat conditions and is an important component of biodiversity. Other important components of regional biodiversity and habitats to consider include meadows and wetlands at middle to lower elevations as well as high-elevation subalpine and alpine habitats.

This chapter provides a biogeographic assessment of the projected effects of climate change on vegetation. We first provide some historical perspective, extending back the last 10,000 years during the Holocene. Next, we discuss the role of disturbance on historical stand and landscape dynamics to provide a context for understanding the historical range of variability in forest conditions. We then describe the results of a computer simulation model that projects changes in the geographic distribution of vegetation types and biomes with climate change to identify where and when potential vegetation change may occur. Finally, we synthesize existing knowledge to identify current and future vulnerabilities to climate and fire in different vegetation types.

We define vulnerability as "the extent to which a species or population is threatened with decline, reduced fitness, genetic loss, or extinction owing to climate change" (Dawson et al. 2011). Collectively, climate change vulnerability is a function of three main components including sensitivity, exposure, and adaptive capacity, all of which we assess based on current scientific knowledge. Sensitivity refers to the degree to which change in climate will affect the persistence or fitness of a species or population. Exposure refers to the potential for climate change to affect an organism, species, or landscape. Adaptive capacity refers to the potential of a species or population to survive and persist by migrating or adjusting in situ to changes in climate. Our assessment of climate change vulnerability in this chapter is primarily derived from empirical observations of past and current changes in forests of the region. Despite a wealth of scientific knowledge about climate change in the assessment area, uncertainties remain as the current depth of knowledge differs among the different components of vulnerability.

Environmental Setting and Current Vegetation

The CMWAP assessment area spans the length of the central Cascade Range in western Oregon and includes a small area along the Columbia River in Washington (fig. 5.1). Most of the assessment area is in the western Cascades, but portions of MTH and CRGNSA include forests of the eastern Cascade slopes and foothills. CRGNSA also includes portions of the Willamette Valley and the Columbia Plateau. To the south, WIL falls almost entirely within the western Cascades.

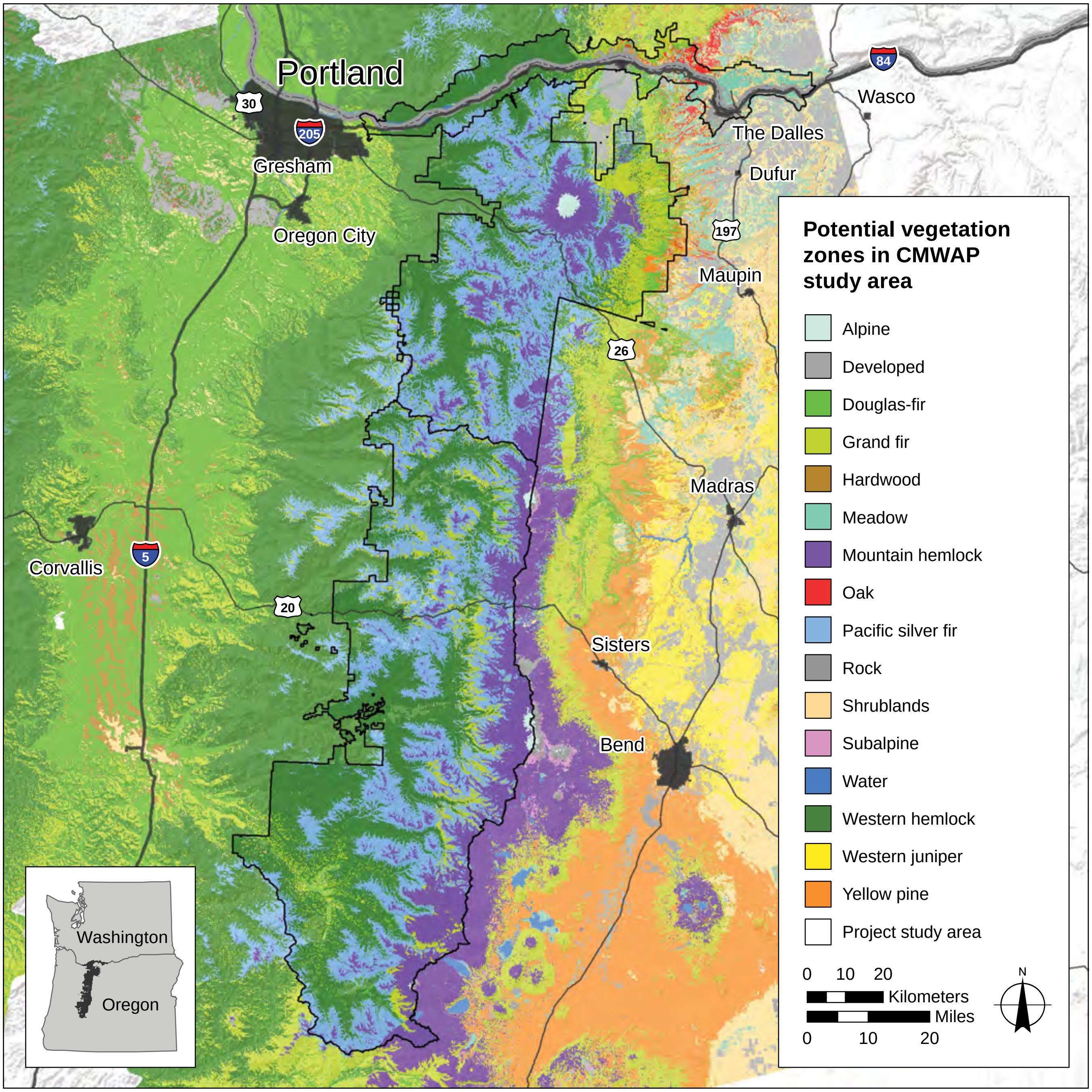

Figure 5.1—Geographic distribution of vegetation zones across the Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest (CMWAP) assessment area.

We use a hierarchical framework to classify the assessment area into different vegetation types (table 5.1). At the broadest level, we distinguish among moist, cold, and dry vegetation groups. Within each of these groups, multiple vegetation zones are distributed across a broad range of environmental and climatic conditions (fig. 5.1).[2] Vegetation zones represent biophysical settings that are referred to by the most common shade-tolerant species occurring within a particular setting; therefore, existing or current vegetation often varies within zones depending on seral stage (i.e., successional stage or stage of structural development) and time since disturbance. For example, the most abundant vegetation zone in the western Cascades, western hemlock, is currently dominated by Douglas-fir but would be dominated by western hemlock in the absence of disturbance.

Vegetation zones provide an ecological framework for discussing climate and vegetation change across broad geographic extents. Vegetation zones have overlapping species pools but are characterized by unique plant community assemblages, similar but internally variable biophysical conditions, and historical disturbance regimes that differ geographically (Winthers et al. 2005). Vegetation zones also have characteristic pathways of structural development that differ in complexity and reflect regional gradients in productivity and historical and contemporary disturbance regimes (Reilly and Spies 2015).

We further separate some vegetation zones into moist, dry, cold, warm, and intermediate based on indicator species in the understory. The goal of this classification is to better account for geographic variability in vegetation composition, disturbance regimes, and climatic conditions. We provide a broad overview of the composition and geographic distribution of the major vegetation zones. A more detailed and comprehensive characterization of plant communities, including patterns of structural development and successional change, is found in Franklin and Dyrness (1988).

Moist vegetation zones make up about 60 percent of the assessment area and are primarily located west of the Cascade crest (table 5.1, fig. 5.1). The western hemlock zone comprises much of the lower elevations and is dominated primarily by Douglas-fir, with increasing levels of shade-tolerant western hemlock in mature and late-seral stands. Western redcedar (*Thuja plicata* Donn ex. D. Don) is also present in moist vegetation zones across a wide range of environmental settings, but it is most prevalent at lower elevations on moist sites. Several species of hardwoods, including bigleaf maple (*Acer macrophyllum* Pursh) and red alder (*Alnus rubra*

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[2] Simpson, M.L. Vegetation zones and subzones across the Pacific Northwest. Unpublished data and map. Available from https://www.ecoshare.info/category/gis-data-vegzones. On file with: USDA Forest Service, Central Oregon Area Ecology and Forest Health Protection Service Centers, 63095 Deschutes Market Road, Bend, OR 97701.

Table 5.1—Crosswalk of different vegetation classifications and area of different vegetation types by National Forest System unit

MC2 functional types	Group	Zone	Type	CMWAP assessment area	Willamette National Forest	Mount Hood National Forest	Columbia River Gorge NSA	Dominant species
				Hectares				
Moist temperate needleleaf forest	Moist	Western hemlock	Moist	272 004	167 764	85 440	18 799	Douglas-fir, western hemlock, western redcedar, bigleaf maple, Pacific madrone, grand fir
			Intermediate	97 241	75 875	21 086	280	
			Dry	14 908	13 047	591	1 271	
			Cold	8599	1458	6 770	371	
		Pacific silver fir	Intermediate	2171	0	2165	7	Pacific silver fir, noble fir, Douglas-fir, lodgepole pine, western white pine
			Warm	95 829	49 466	45 869	494	
			Cold	313 473	186 180	123 846	3448	
Temperate needleleaf forest	Dry	Grand fir	Moist	96 138	52 250	41 120	2767	Grand fir, Douglas-fir, ponderosa pine, western white pine, incense cedar, sugar pine
			Dry	1204	175	1026	3	
		Douglas-fir	Moist	19 184	11 870	6895	420	
			Dry	1394	21	464	909	
Dry temperate needleleaf forest	Dry	Yellow pine	Ponderosa pine	4301	0	4070	231	Ponderosa pine, western juniper, Jeffrey pine, incense cedar
			Jeffrey pine	55	0	55	0	
		Western juniper	Western juniper	9	0	9	0	
Subalpine forest	Cold	Subalpine	Subalpine	5317	2487	2830	0	Mountain hemlock, subalpine fir, whitebark pine, Engelmann spruce, lodgepole pine, western white pine
		Mountain hemlock	Dry	64	51	13	0	
			Moist	122 633	65 253	57 296	84	
			Cold	59 175	48 631	10 545	0	
N/A	Other	Hardwood	Hardwood	187	0	186	1	Red alder, bigleaf maple
		Shrub	Shrub	1379	562	270	546	
		Oak	Oak	488	0	290	198	Oregon white oak
		Meadow	Meadow	1135	0	884	250	
Temperate warm mixed	Warm, moist	Sitka spruce, western hemlock	Sitka spruce, moist western hemlock	0	0	0	0	Sitka spruce, Douglas-fir, western hemlock, western redcedar, red alder, bigleaf maple, Pacific madrone, grand fir
Subtropical mixed forest				0	0	0	0	

NA = not applicable. CMWAP = Columbia River Gorge National Scenic Area (NSA), Mount Hood National Forest, Willamette National Forest Adaptation Partnership.

Bong.), are common, and black cottonwood (*Populus trichocarpa* Torr. & A. Gray ex. Hook.) may be present in floodplains and along rivers and streams. Oregon white oak and Pacific madrone (*Arbutus menziesii* Pursh) may also be present at lower elevations.

The Pacific silver fir zone occurs at middle elevations where more precipitation falls as snow. This zone is dominated by noble fir and Pacific silver fir, which increases in importance in mature and late-seral stands. Douglas-fir may also be found at the lower end of this vegetation zone, and Alaska cedar (*Callitropsis nootkatensis* [D. Don] D.P. Little) may be present on cool, north-facing aspects.

At the highest elevations, the mountain hemlock zone is often dominated by monospecific stands of mountain hemlock, although lodgepole pine (*Pinus contorta* var. *latifolia* Engelm. ex S. Watson) is common in early-seral stages of development. Western white pine (*P. monticola* Douglas ex. D. Don) may also be a component of the mountain hemlock zone in all stages of development.

The geographic distribution of dry forest vegetation zones is primarily limited to the east side of the Cascade crest. The western juniper (*Juniperus occidentalis* Hook.) zone is found at the lowest elevations in the warmest and driest portions of the assessment area and is dominated by woodlands composed of western juniper and several species of shrubs and perennial grasses. The ponderosa pine zone is dominated by woodlands and forests composed mostly of ponderosa pine and multiple species of shrubs and perennial grasses. On the east side of MTH, ponderosa pine and Oregon white oak commonly occur together (Topik et al. 1988). The Douglas-fir and grand fir zones occur at intermediate elevations and levels of precipitation relative to other dry vegetation zones. These zones are commonly referred to as "mixed conifer" and may be composed of ponderosa pine in the overstory with more shade-tolerant Douglas-fir and grand fir in the understory and mid story (Topik et al. 1988). At the highest elevations, subalpine forests and woodlands are dominated by subalpine fir, Engelmann spruce (*Picea engelmannii* Parry ex Engelm.), western white pine, lodgepole pine, and whitebark pine.

The assessment area is divided into three management units—CRGNSA, MTH, and WIL (figs. 5.2 through 5.4) that differ considerably in terms of climate, biophysical setting, and the vegetation zones that occur within them (table 5.1, figs. 5.2 through 5.4). WIL makes up the southern portion of the assessment area (fig. 5.2) and includes some of the most productive forests in the Pacific Northwest. Pacific silver fir cold and western hemlock moist each make up about 25 percent of the WIL. The rest of the assessment area consists mostly of western hemlock intermediate (11 percent), mountain hemlock moist (10 percent), grand fir moist (8 percent), Pacific silver fir warm (7 percent), and mountain hemlock cold (7 percent).

MTH (fig. 5.2) makes up most of the northern part of the assessment area and is dominated primarily by moist and cold forests. Pacific silver fir cold (30 percent) and western hemlock moist (20 percent) together make up about half of MTH. The rest of MTH is dominated by mountain hemlock moist (14 percent), Pacific silver fir warm (11 percent), grand fir moist (10 percent), and western hemlock intermediate

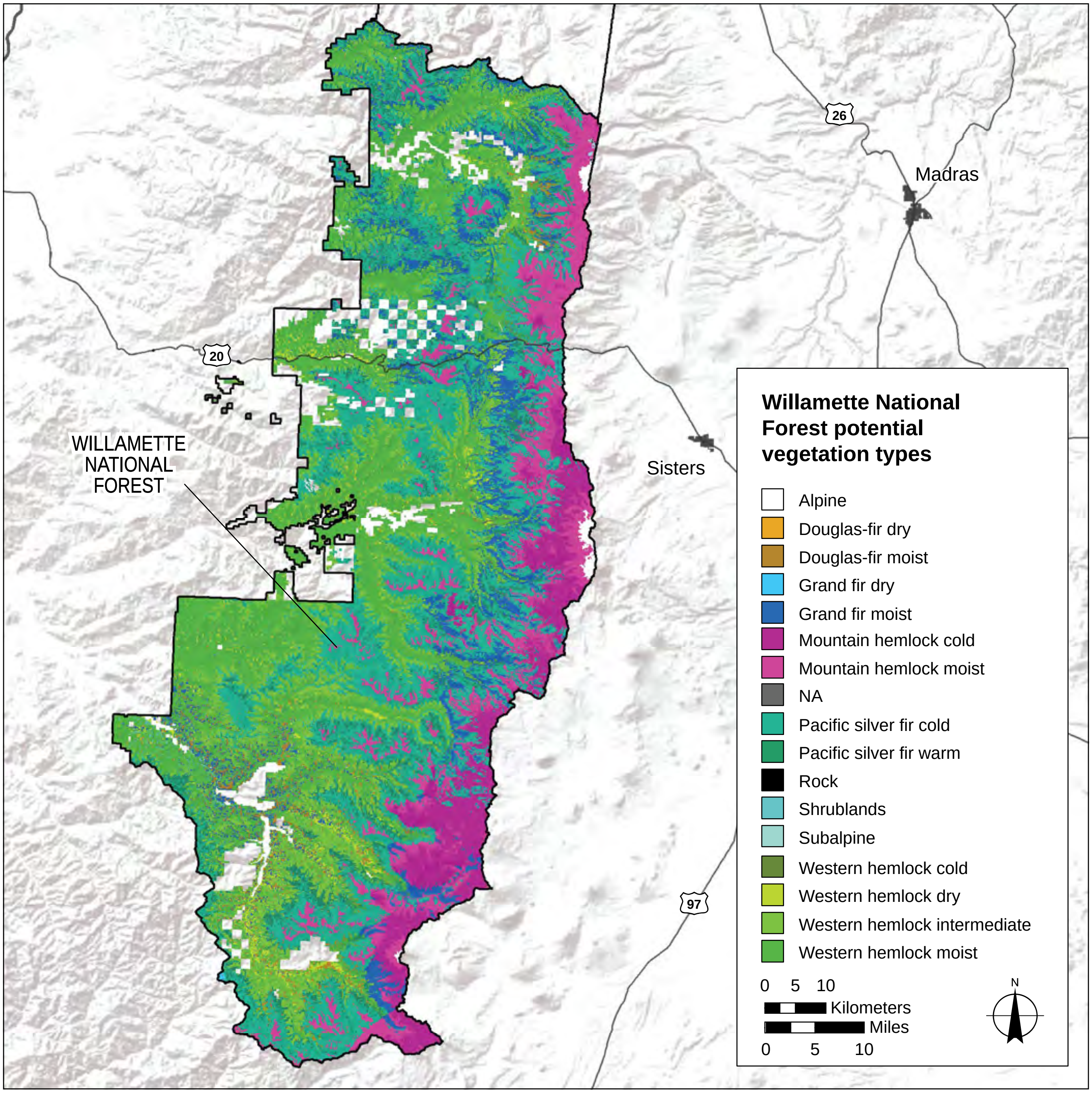

Figure 5.2—Geographic distribution of vegetation zones across Willamette National Forest.

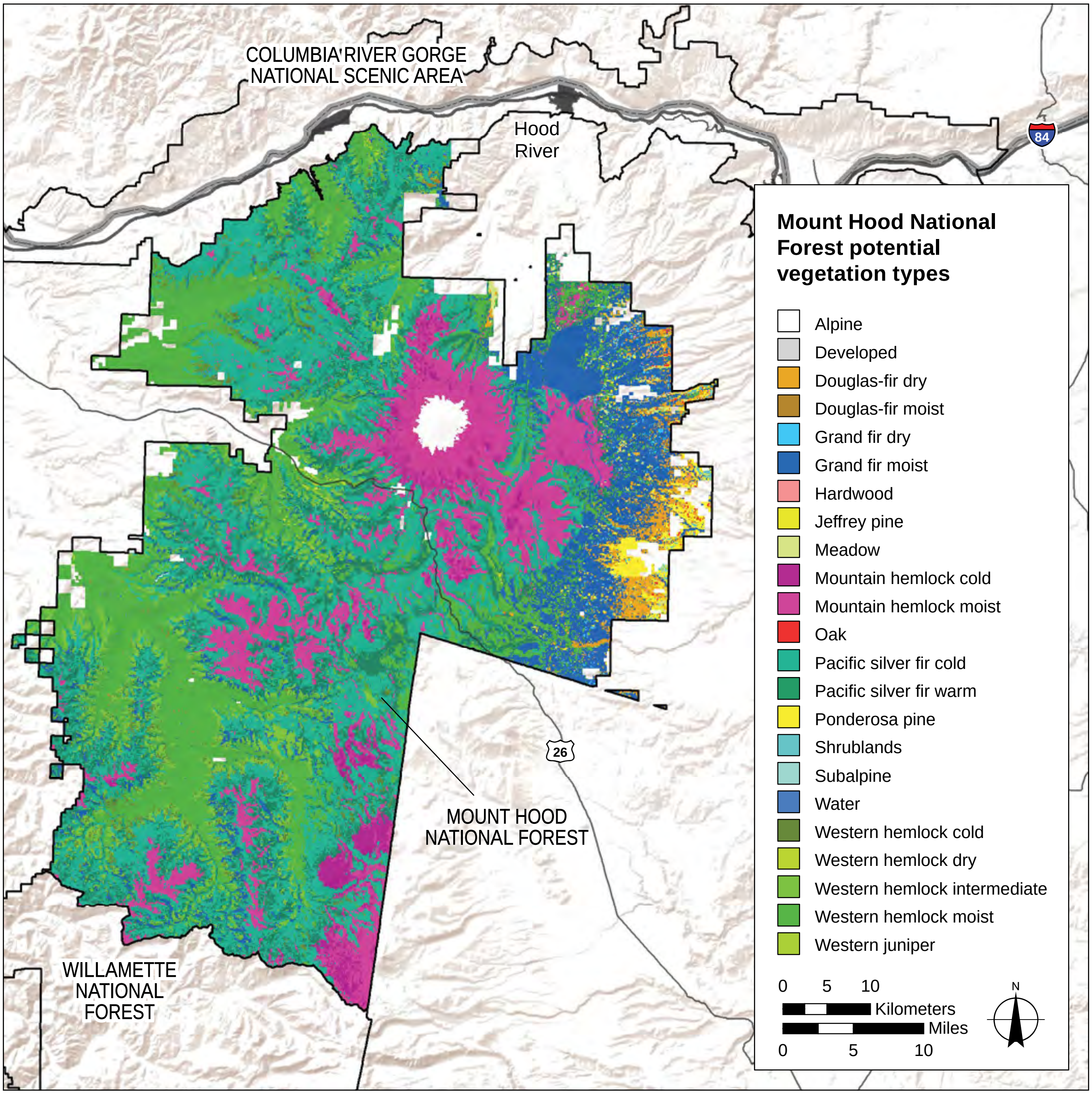

Figure 5.3—Geographic distribution of vegetation zones across Mount Hood National Forest. NA = not applicable.

(5 percent). Dry forests are less abundant but comprise most of the northeastern part of the assessment area and consist primarily of grand fir moist, Douglas-fir moist, and ponderosa pine moist. Oregon white oak is a small component of MTH at lower elevations to the east of Mount Hood.

CRGNSA (fig. 5.4) is the smallest but most varied and complex of the study units, with a prominent gradient consisting of moist forests in the western part of the unit that transition to dry forests and shrublands in the eastern part. CRGNSA

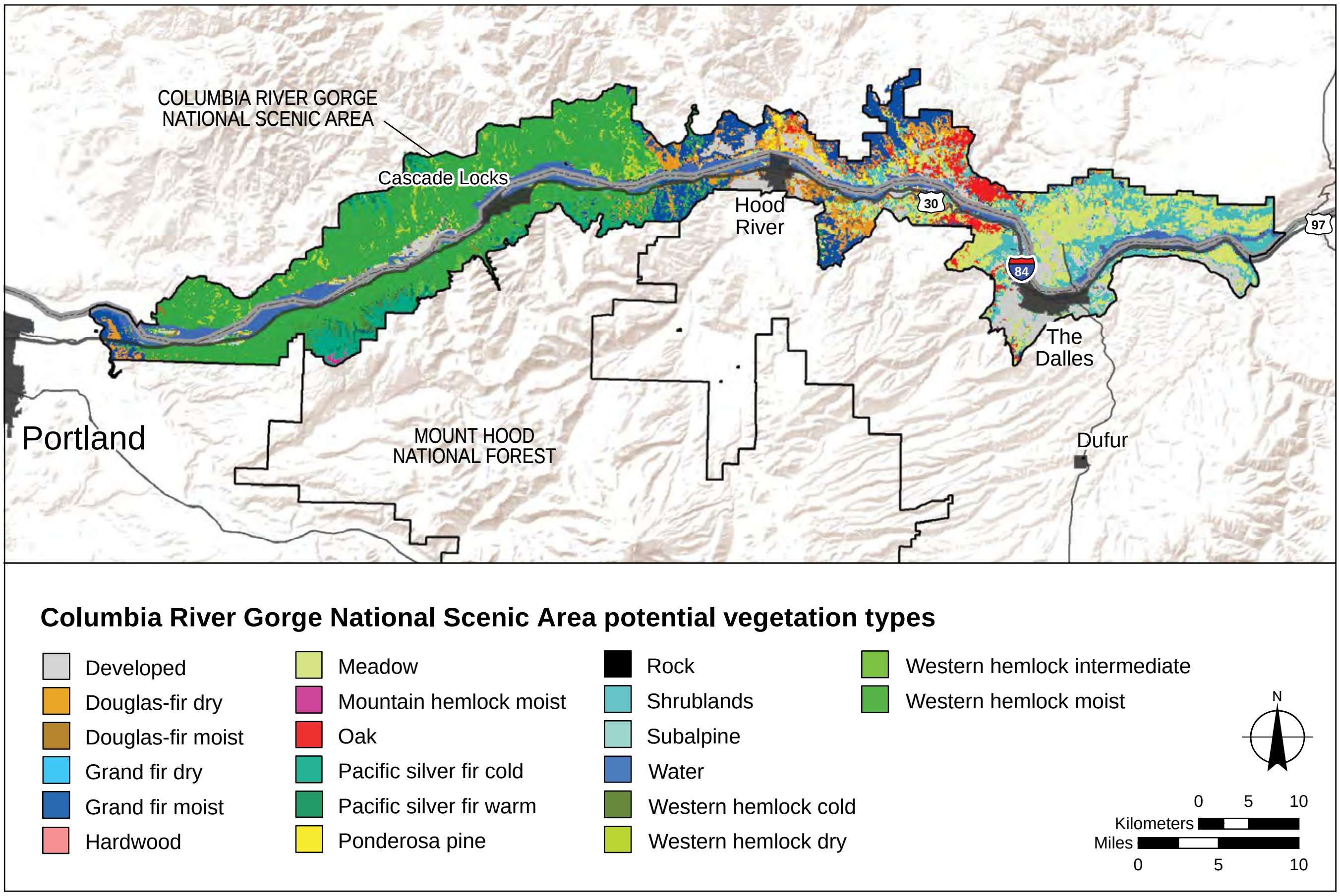

Figure 5.4—Geographic distribution of vegetation zones across Columbia River Gorge National Scenic Area.

is composed mostly of western hemlock moist (61 percent). The rest of this unit consists mostly of Pacific silver fir cold (11 percent), grand fir moist (10 percent), western hemlock dry (4 percent), and Douglas-fir dry (3 percent). Oregon white oak is also present at lower elevations in the eastern side of CRGNSA.

Paleoecological History and Holocene Dynamics

Looking back at how the vegetation of the assessment area responded to climatic variability and change in the past can provide important context for understanding the potential ecological effects of climate change in the future. Paleoecological studies examine temporal patterns of charcoal and pollen in lake sediment cores. These are used as proxies for past environmental conditions and for reconstructing changes in vegetation composition over time (Whitlock et al. 2003). These studies are limited in terms of their spatial and temporal resolution but offer important historical context and broaden our understanding of the historical range of variability at millennial time scales. In some cases, it is possible to identify individual species from pollen, while in others, the taxonomic resolution may be limited to genus.

Collectively, these studies indicate that the vegetation of the Pacific Northwest experienced tremendous ecological change over the past ~12,000 years during the Holocene. Multiple periods of quasi-stability were punctuated by distinctive periods of transition and rapid change catalyzed by shifts in climate, fire activity, and indigenous populations (Walsh et al. 2015, 2018).

Knowledge of vegetation changes during the Holocene is rich in the Pacific Northwest, and there are several studies from the cooler and wetter Washington western Cascades, the wetter Oregon Coast Range, and the drier and warmer Klamath Mountains in southwestern Oregon and northern California. Although the climatic and environmental settings of these studies differ from that of the CMWAP assessment area, they share many of the same species and exhibit similar patterns of long-term change.

Complex interactions between a fluctuating climate and fire drove vegetation change during the Holocene (Bartlein et al. 1998, Crausbay et al. 2017, Marlon et al. 2009, Walsh et al. 2015, Whitlock 1992, Whitlock et al. 2008). Species responded individualistically to changes in climate, sometimes forming species assemblages that lack contemporary analogs (Whitlock et al. 2003). Species ranges expanded and contracted over time, with some species persisting in refugia where local conditions allowed persistence in regions where climate was generally inhospitable (Gavin et al. 2014). Refugia likely played an important role in the persistence of populations through the numerous climatic transitions that occurred since the last glacial maximum (Bennett and Provan 2008, Hampe and Jump 2011).

The early Holocene—roughly 12,000 to 8,000 years before present (BP)—was a time of rapid vegetation change with species assemblages that lack modern analogs (Whitlock 1992). Following glacial retreat, increased summer insolation led to higher summer temperatures and drier conditions than the present, while lower winter insolation led to cooler and wetter winters, likely amplifying seasonality and summer drought compared to present day climate (Bartlein et al. 1998). Fire activity was relatively low at the beginning of the early Holocene but increased and remained high until roughly 8,000 BP (Briles et al. 2005, Walsh et al. 2015). As summers warmed and glaciers receded, forests replaced nonforested areas and open woodlands, and xerophytic species increased at many low-elevation sites across western Oregon and Washington (Walsh et al. 2015).

In the early Holocene, Douglas-fir, red alder, and oak (*Quercus* spp.) replaced spruce and pine at lower elevations in the Coast Range and western Cascades (Cwynar 1987, Grigg and Whitlock 1998, Long et al. 1998, Sea and Whitlock 1995, Walsh et al. 2008). On the Olympic Peninsula, herbaceous tundra was replaced by subalpine fir (Gavin et al. 2001). Middle elevations of the eastern Cascades of Oregon were dominated by open pine (*Pinus* spp.) forests, initially with an understory of sagebrush (*Artemesia* spp.), which likely transitioned into a closed-forest environment with a greater abundance of true fir (*Abies* spp.). Middle elevations of the Klamath Mountains in Oregon and California were dominated by open woodlands composed of pine, oak, and incense cedar (*Calocedrus decurrens* [Torr.] Florin) (Briles et al. 2005, Daniels et al. 2005, Mohr et al. 2000).

Climate shifted toward cooler, wetter conditions with decreasing summer insolation during the middle Holocene (~8,000 to 4,000 BP) (Bartlein et al. 1998). Fire activity decreased during this time (Briles et al. 2005, Walsh et al. 2015), and modern species assemblages formed in some parts of the Pacific Northwest (Whitlock et al. 1992). Western redcedar and western hemlock increased during this period across low- and middle-elevation forests of the Coast Range, Cascade Range, and Puget Trough (Cwynar 1987, Prichard et al. 2009, Walsh et al. 2008). Species composition shifted toward Pacific silver fir, mountain hemlock, and Alaska yellow-cedar on the Olympic Peninsula (Gavin et al. 2001). In the Klamath Mountains, expansion of pine, fir, and cypress (*Cupressaceae* spp.) species also indicated cooler, wetter conditions during this period (Briles et al. 2005, Daniels et al. 2005, Mohr et al. 2000). Fire activity started increasing again around 5,500 years BP, except at lower elevations (Walsh et al. 2015).

Fire activity continued to increase during most of the late Holocene (~4,000 years BP to present) despite evidence that this period remained cool and moist (Bartlein et al. 1998, Walsh et al. 2015). During this time, climate had limited influence on fire activity, and American Indian burning played a greater role at centennial and millennial scales (Walsh et al. 2018). In the western Cascades of Oregon, Douglas-fir, western hemlock, and mountain hemlock increased in abundance while red alder decreased despite relatively high fire activity (Minckley and Long 2016, Walsh et al. 2017). Modern forests in the Douglas-fir and white fir (*Abies concolor* [Gordon & Glend.] Lindl. ex Hildebr.) zones established roughly 2,000 years ago in the Klamath Mountains, where fire activity also increased during this time despite cool and moist conditions (Briles et al. 2005, 2008; Daniels et al. 2005; Mohr et al. 2000). There is little evidence in the pollen record to suggest major changes in the composition of vegetation assemblages across most of Oregon and Washington during this time (Walsh et al. 2008, 2015; Whitlock 1992).

Over the past 1,000 years, the influence of American Indian burning was particularly important until Euro-American contact in the late 1700s, when populations were drastically reduced from European disease (Walsh et al. 2018). The warmest temperatures occurred during the Medieval Climate Anomaly (MCA; 900–1250 AD), and the coldest temperatures occurred during the Little Ice Age (LIA; 1450–1850 AD, Steinman et al. 2014. Precipitation also varied during this time, but there is less consensus about this in the literature. Cook et al. (2004)

argued that a period of drought occurred during the MCA, but more recent evidence suggests a wet MCA and dry LIA (Steinman et al. 2014). Fire frequency increased during the MCA in the Klamath Mountains (Daniels et al. 2005, Mohr et al. 2000) and the rest of Oregon and Washington (Walsh et al. 2015).

Climate fluctuations associated with sea-surface temperatures in the Pacific Ocean also became more apparent over the past 1,000 years (Nelson et al. 2011). Warming and cooling of sea-surface temperatures in the equatorial Pacific Ocean, referred to as the El Niño Southern Oscillation (ENSO), result in periodic (2 to 7 years) anomalies that affect regional air temperature and precipitation. During the El Niño phase of ENSO, winter and spring conditions are generally warmer and drier than average (McCabe and Dettinger 1999). During the opposite La Niña phase, winter and spring are generally wetter and cooler, leading to deeper than average snowpack (Gershunov et al. 1999). The Pacific Decadal Oscillation (PDO) is defined by fluctuations in sea-surface temperature in the Pacific Ocean and has longer characteristic periodicity of warm and cool phases at 20 to 30 years (Mantua et al. 1997). The PDO is not consistent over time at these frequencies (McAfee 2014) and has exhibited variable regime transitions during the preinstrumental period (Gedalof and Smith 2001). Newman et al. (2016) suggested that the PDO is not an independent phenomenon, but a combination of multiple processes, including ENSO.

Presettlement Disturbance Regimes

Multiple agents of natural disturbance operated at different spatial and temporal scales and drove stand and landscape dynamics over the past several centuries (Spies and Franklin 1989). Disturbance agents can be characterized as biotic (e.g., pathogens, insects) or abiotic (e.g., fire, wind, volcanoes) and differ considerably in terms of their prevalence and severity (i.e., tree mortality) among vegetation zones in the assessment area (Reilly and Spies 2016). Biotic disturbances include several species of pathogens and insects (table 5.2) that are native to the area. Abiotic disturbances, including fire and wind, played a more variable role, occasionally affecting large areas in synoptic events. Fire was most frequent on the drier northeastern side of MTH and the eastern side of CRGNSA (fig. 5.5). On the west side of the Cascade crest, the historical fire regime differed along a latitudinal gradient, with higher fire frequency to the south and a greater role of high-severity fire driven by dry east-wind events in the north and at higher elevations (fig. 5.5). Physical disturbances such as landslides, mass wasting events, and floods also provided habitat heterogeneity in topographically complex landscapes.

Table 5.2—Primary insects and pathogens of dominant tree species in the Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest assessment area

Disturbance type	Insect or pathogen	Host species
Bark beetles	Douglas-fir beetle (*Dendroctonus pseudotsugae* Hopkins)	Douglas-fir
	Douglas-fir engraver beetles (*Scolytus unispinosis* LeConte, *Pseudohylesinus nebulosus* [LeConte])	Douglas-fir
	Fir engraver (*Scolytus ventralis* LeConte)	True firs
	Mountain pine beetle (*Dendroctonus ponderosae* Hopkins)	Pines
	Pine engraver beetles (*Ips* spp.)	Pines
	Spruce beetle (*Dendroctonus rufipennis* [Kirby])	Engelmann spruce
	Western pine beetle (*Dendroctonus brevicomis* LeConte)	Ponderosa pine
Insect defoliators	Douglas-fir tussock moth (*Orgyia pseudotsugata* McDunnough)	True firs, Douglas-fir
	Larch casebearer (*Coleophora laricella* Hübner)	Western larch
	Western spruce budworm (*Choristoneura freemani* Razowski)	True firs, Douglas-fir
	Black pineleaf scale (*Nuculaspis californica* Coleman)	Pines, Douglas-fir
Sucking insects	Balsam woolly adelgid (*Adelges piceae* Ratzeburg)	Subalpine fir, Pacific silver fir, grand fir
Root diseases	Laminated root rot (*Coniferiporia sulphurascens* [Pilat] L.W. Zhou & Y.C. Dai)	Douglas-fir, true firs, mountain hemlock
	Armillaria root disease (*Armillaria ostoyae* [Romagnesi] Herink)	Douglas-fir, true firs, hemlocks, pines, Engelmann spruce
	Heterobasidion root disease (*Heterobasidion occidentale* Otrosina & Garbel)	True firs, hemlocks, Engelmann spruce
	Black stain root disease (*Leptographium wageneri* var. *pseudotsugae* T.C. Harr. & F.W. Cobb)	Douglas-fir
Foliar diseases	Swiss needle cast (*Nothophaeocryptopus gaeumannii* [T. Rohde] Videira, C. Nakash., U. Braun & Crous)	Douglas-fir
	Rhabdocline needle cast (*Rhabdocline* spp.)	Douglas-fir
	Dothistroma needle blight (*Dothistroma septosporum* [Dorogin] M. Morelet syn. *Mycosphaerella pini*)	Ponderosa pine, western white pine, lodgepole pine
	Larch needle diseases (*Rhabdocline laricis* [Vuill.] J.K. Stone, *Hypodermella laricis* Tub.)	Western larch
Canker diseases	White pine blister rust (*Cronartium ribicola* A. Dietr.)	White pines
Heart rots	Brown trunk rot (*Fomitopsis officinalis* [Vill.] Kotl. & Pouzar)	Douglas fir, pines, western larch
	Red ring rot (*Porodaedalea pini* [Brot.] Bondartsev & Singer)	Douglas-fir, grand fir, white fir, mountain hemlock, pines
	Rust-red stringy rot (*Echinodontium tinctorium* [Ellis & Everh.] Ellis & Everh.)	True firs, hemlocks
	Schweinitzii root and butt rot (*Phaeolus schweinitzii* [Fr.] Pat.)	Douglas-fir, true firs, pines, western larch, spruce

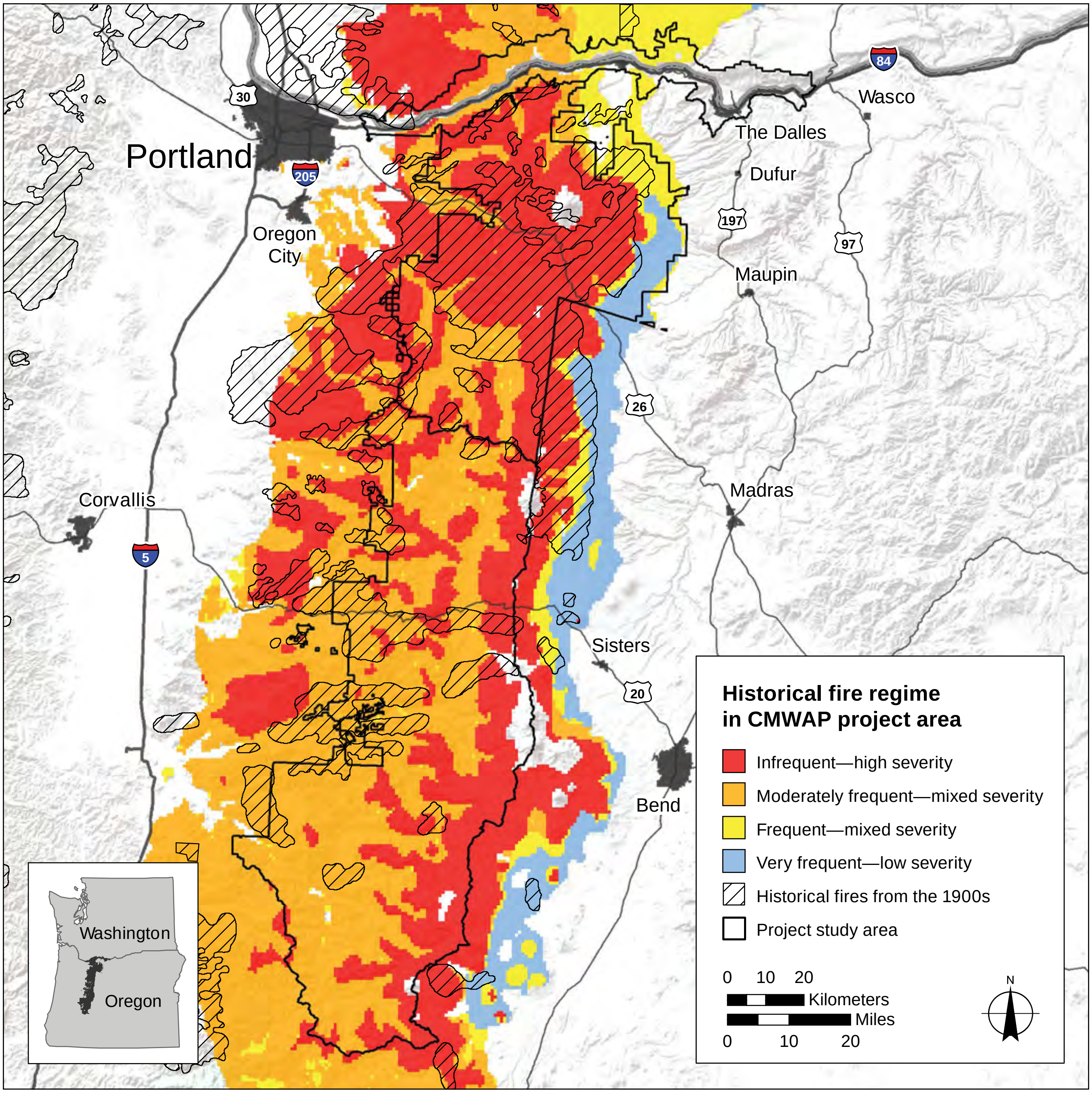

Figure 5.5—Historical fire regimes and perimeters of large fires from the 1900s for the Columbia River Gorge, Mount Hood, and Willamette National Forests adaptation partnership (CMWAP) assessment area. Fire regime map follows Spies et al. (2018).

Biotic Disturbance

Biotic disturbances (table 5.2) played a major role in forest development and landscape dynamics across the assessment area, contributing to “background mortality rates,” which are also associated with competition and stand development. However, insects and pathogens can also erupt into epidemic outbreaks that result in high levels of tree mortality (e.g., Raffa et al. 2008). Insect and pathogen activity does not always result in immediate tree mortality. However, the resulting decline in tree growth and vigor (Hansen and Goheen 2000, Marias et al. 2014) may initiate a long process of mortality (Franklin et al. 1987, Manion 1981). Pathogens may also make trees less resistant and increase sensitivity to wind disturbance by predisposing them to stem breakage (Larson and Franklin 2010). Native insects and pathogens play a prominent role in the disturbance regimes of both moist and dry vegetation zones of the assessment area (Hansen and Goheen 2000, Shaw et al. 2009).

Although some biotic disturbance agents are specific to a single host, many have the potential to affect multiple tree species (table 5.2). Tree mortality rates associated with insects are generally much lower than those associated with fire in the Pacific Northwest (Reilly and Spies 2016), but insects can cause greater loss of live carbon and canopy mortality than fire at large spatial scales (Berner et al. 2017, Hicke et al. 2016). Most native pathogens affect small, localized areas but are persistent and generally widespread across the region (Reilly and Spies 2016), killing more volume than fire or insects in a year at large spatial scales (Lockman and Kearns 2016). Hansen and Goheen (2000) estimated that over 8 percent of Douglas-fir forests in western Oregon are occupied by the fungus that causes laminated root rot (*Coniferiporia sulphurascens* [Pilat] L.W. Zhou & Y.C. Dai) (formerly *Phellinus weirii, P. sulphurascens*) (where at least half of the Douglas-firs in locations with root rot are dead). Pathogens operate at decadel time scales and often initiate forest canopy gaps that may expand over time from wind. They can also increase stand heterogeneity and accelerate successional dynamics.

Mountain pine beetle (*Dendroctonus ponderosae* Hopkins) can cause extensive mortality in lodgepole pine and affects other species of pines, including ponderosa pine, sugar pine (*Pinus lambertiana* Douglas), western white pine, and whitebark pine. Western pine beetle (*D. brevicomis* LeConte) and several species of pine *Ips* beetles (*Ips* spp.) attack and kill ponderosa pine, especially during drought periods and following fires. Douglas-fir beetle (*D. pseudotsugae* Hopkins) preferentially attacks larger Douglas-fir trees and typically causes outbreaks on relatively small patches of trees, particularly after blowdown from wind events (Powers et al. 1999). The fir engraver (*Scolytus ventralis* LeConte) infests true firs, and fir engraver activity is positively associated with drought and root disease. Defoliating insects are also common. Although it rarely causes mortality, insect defoliation may reduce growth and make trees more sensitive to other insect infestations and root disease (i.e., *Armillaria*). Western spruce budworm (*Choristoneura freemani* Razowski) feeds on the foliage of true firs and Douglas-fir and is a major concern east of the Cascades. Periodic outbreaks in this region during the past 40 years resulted in extensive tree mortality (Meigs et al. 2015).

Pathogens, particularly root diseases, are prevalent in all vegetation zones. Laminated root rot primarily affects Douglas-fir, true firs, and mountain hemlock. Armillaria root disease (caused by *A. ostoyae* [Romagnesi] Herink) affects Douglas-fir, true firs, hemlocks (*Tsuga* spp.), pines, and Engelmann spruce. Heterobasidion root disease (caused by *Heterobasidion occidentale* Otrosina & Garbel, formerly *H. annosum* S-type) affects true firs and hemlocks. Heartwood decays, such as those caused by the velvet top fungus (*Phaeolus schweinitzii* [Fr.] Pat.) and the ring-scale fungus (*Porodaedalea pini* [Brot.] Bondartsev & Singer), cause decay in the butts and stems of mature trees. These decay organisms reduce tree vigor but do not directly kill trees; however, heartwood decay in the butt or stem can increase sensitivity to tree failure or breakage and subsequent mortality. Black stain root disease (caused by *Leptographium wageneri* var. *pseudotsugae* T.C. Harr. & F.W. Cobb) affects Douglas-fir. Several other types of pathogens are also present, including stem rusts (caused by *Cronartium* spp.) and dwarf mistletoes (*Arceuthobium* spp.).

Other biotic disturbance agents include foliar diseases, which are a serious concern when planting trees that do not typically occur locally. These pathogens rarely result in the mortality of trees but may decrease individual tree growth and stand productivity over time and predispose trees to attack by insects and other pathogens.

Several nonnative pathogens and insects are of particular concern in the CMWAP assessment area. White pine blister rust, caused by *C. ribicola* A. Dietr., is a major threat to five-needled pines, including whitebark pine (Goheen et al. 2002, Ward et al. 2006), western white pine, and sugar pine (Goheen and Goheen 2014). Decline of Pacific madrone related to multiple fungal diseases has been reported over the past 30 years, with larger, older trees experiencing the most mortality (Elliott et al. 2002). Balsam woolly adelgid (*Adelges piceae* Ratzeburg) has affected subalpine fir, Pacific silver fir, and especially grand fir growing at lower elevations west of the Cascade Range (Mitchell and Buffam 2001).

Abiotic Disturbances

Abiotic agents of disturbance in the assessment area include windstorms, volcanic eruptions, landslides, avalanches, and fire. Most abiotic disturbances operate at intermediate levels of mortality, leaving substantial live legacies and altering pathways of structural and successional development (Reilly and Spies 2016).

Abiotic disturbances can create forest gaps and patches of mortality that range in size depending on the disturbance agent (Spies and Franklin 1989). Smaller gaps created by abiotic disturbances may increase stand and landscape heterogeneity, whereas large, infrequent disturbances may also have effects on landscape composition and structure that are qualitatively different from smaller disturbances (Romme et al. 1998) and often persist for centuries (Foster et al. 1998).

Windstorms arising from extratropical cyclones off the Pacific Ocean have the potential to produce hurricane-force winds and extensive damage to forested ecosystems. Multiple large storms affected parts of the assessment area several times in recorded history (Mass and Dotson 2010). These events are generally characterized by southwesterly winds and occur during winter when soils are saturated, but east-wind events may also occur in winter in the Columbia River Gorge (Sharp and Mass 2004).

Several notable synoptic wind events occurred during the 20th century and caused substantial tree mortality in portions of the western Cascades, particularly near the Columbia River Gorge (Sinton and Jones 2002). The most intense of these events, the Columbus Day Storm of 1962 (Lynott and Cramer 1966), killed trees containing 11 million board-feet of timber in Oregon and Washington (Teensma et al. 1991). High-wind events are positively associated with neutral to warm PDO conditions, and their influence shifted northward over the past 120 years (Knapp and Hadley 2012). Synoptic east winds may also occur during the dry season and are a particular concern for driving large fire events during early fall (Brewer et al. 2012).

Mass wasting events, floods, landslides, avalanches, earthflows, and volcanic eruptions may cause damage or mortality through physical damage (e.g., abrasion, snapping, uprooting) but are generally limited to specific landforms in steep or mountainous terrain (Miles and Swanson 1986). Floods are a chronic agent of mortality in floodplains and riparian areas and occasionally cause higher levels of mortality in large events where trees are tipped up or swept away (Acker et al. 2003). Mass wasting events are most associated with intense rain and storm events and can cause significant erosion. Swanson and Dyrness (1975) found that landslide area was 2.8 times greater in clearcuts and 30 times greater along road right-of-ways than in forested areas in unstable zones below 1000 m in the central western Cascades. Snow avalanches are common in mountainous terrain, especially on slopes between 35 and 45 degrees following large snowfall events. Dry-slab avalanches are fast, powerful slides of cold, consolidated snow. Wet slides occur during warm spring and summer conditions or during rain-on-snow events and are slow moving but capable of causing significant physical damage. Volcanic eruptions are infrequent but may damage forests within the blast zone or in close vicinity to lahars, which are fast-moving landslides associated with glacial melting.

Fire is one of the primary drivers of historical landscape dynamics across the assessment area, though its role differs geographically (Agee 1993) (fig. 5.5, table 5.3). American Indian populations played a role in fire ignition along the valley margins and along major rivers (Boyd 1999), and the importance of lightning as an ignition source relative to human ignitions was likely higher in more remote, mountainous areas. Regional drought driven by teleconnections with sea-surface temperature anomalies (e.g., PDO, ENSO) resulted in synchronous occurrence of fires in the assessment area (Hessl et al. 2004, Trouet et al. 2006, Weisberg and Swanson 2003, Wright and Agee 2004), as well as elsewhere in the Pacific Northwest and other regions of the Western United States (Heyerdahl et al. 2008, Kitzberger et al. 2007, Schoennagel et al. 2005). Major periods of wildfire occurred from 1400 to 1650, and from 1800 to 1900 (Weisburg and Swanson 2003). A period of lower fire activity from 1650 to 1800 was likely related to cool climatic conditions during the LIA and declines in American Indian populations from disease epidemics following European contact.

Historical fire regimes have been well documented in the assessment area using age structure and fire scars (table 5.3). The limited scarring potential of Douglas-fir makes estimates of historical fire frequency difficult compared to forest dominated by ponderosa pine. There are fewer fire-history studies in higher elevation forests of the assessment area where reconstructions are based on age structure rather than fire scars.

There is a distinct geographic pattern of increasing fire frequency toward the southern part of the assessment area and at lower elevations (fig. 5.5). Agee (1993) attributes geographic variation in historical fire regimes to decreased summer precipitation and increased lightning frequency, beginning approximately at the McKenzie River in central Oregon. This geographic trend is supported by numerous fire history studies (table 5.3), as well as the geographic occurrence of charred bark on old-growth trees (Spies et al. 2018).

The historical fire regime of cooler and wetter forests at higher elevations and in the northern part of the assessment area is characterized primarily as high severity and low frequency. Fire was generally infrequent in most moist vegetation zones, but frequency ranged from about 125 years to >200 years, with synchronous regional fire episodes occurring across the assessment area from the 1400s to the mid-1600s, and again from the early 1800s to about 1925 (Weisberg and Swanson 2003). Extremely large (>40 000 ha) stand-replacing fires in the early and mid 20th century (fig. 5.5) were driven by the occurrence of dry east-wind events (Agee 1993) that occur in early fall (Cramer 1957). Although fire-return intervals were generally long under this regime, short-interval reburns were common following early 20th century fires. Examples in the Washington western Cascades include the

Yacolt Burn which partially reburned several times (Gray and Franklin 1997), and the Tillamook Burn which reburned three times at 6-year intervals.

A moderately frequent, mixed-severity fire regime characterized much of the assessment area toward the south and at lower elevations and played an important role in driving pathways of successional development in the western hemlock zone (Spies et al. 2018). Complex mosaics of low-, moderate-, and high-severity fire characterized postfire landscapes (Morrison and Swanson 1990), though fire perimeters from the early 20th century indicate that large, east-wind driven fires were also part of the disturbance regime (fig. 5.5). Multiple studies show that non-stand-replacing fire was common (Weisberg 2004), and some studies document fire frequencies of less than 100 years in western hemlock forests of the central Oregon western Cascades (table 5.3). Tepley et al. (2013) found that 73 percent of old-growth stands in the Blue River and Fall Creek watersheds in central Oregon experienced at least one non-stand-replacing fire during their development. Results from this study also found that infrequent stand-replacing fire occurred in 27 percent of stands and was characterized by a single postfire cohort of Douglas-fir, followed by continuous establishment of shade-tolerant species.

Fire was far more frequent in dry vegetation zones, where return intervals were shorter and generally varied from 10 to 50 years until the late 19th and early 20th centuries (table 5.3). Large, fire-resistant ponderosa pine woodlands characterized much of the dry-forest landscape until the early 20th century when fire exclusion began (Hagmann et al. 2014). These landscapes now have higher tree densities, with a greater component of shade-tolerant conifers, and are sensitive to high-severity fire (Reilly et al. 2017) and insect infestations (Meigs et al. 2015).

Contemporary Forest Dynamics

Tree Mortality and Disturbance

Warming temperatures and increased water stress raise significant concern regarding increased rates of tree mortality and consequent forest decline in the Western United States. Forest decline (mortality and canopy cover loss) detected with remote sensing peaked in the mid-2000s (Cohen et al. 2016) during the warmest decade in the past 100 years (Abatzoglou et al. 2014). Some have suggested that tree mortality rates in old-growth forests across the Western United States are related to regional warming and increasing water deficits (van Mantgem et al. 2009). There is less evidence of increased drought occurrence in the Pacific Northwest than in other regions of western North America (1960 to 2013) (Peters et al. 2014), and forests of the Pacific Northwest may be less vulnerable to future drought and wildfire than the rest of the Western United States (Buotte et al. 2018). However, field-based studies substantiate the occurrence of higher levels

Table 5.3—Fire history studies in the assessment area[a]

Vegetation zone	Study	Extent and time period	Method	Frequency or return interval (years)	Rotation (years)	Percentage low, moderate, and high severity	High-severity patch size
Western hemlock	Means 1982	Unknown	Scars	100	—	—	
	Stewart 1986	<1 ha ~1200–1982	Age, scars	50[b]	—	—	—
	Yamaguchi 1986	Unknown post-1480	Age, scars	40–150	—	—	—
	Teensma 1987	11 000 ha 1482–1952	Age, scars	114	78	—	—
	Agee et al. 1990	3500 ha 1573–1985	Age, scars	137	—	—	—
	Morrison and Swanson 1990	1940 ha 1150–1985	Age, scars	96	95	0–86/0–60/0–100	<110 ha
	Garza 1995	3540 ha pre-1910	Age, scars	93–158	134	24–41/9–23/25–54	
	Impara 1997	~140 000 ha 1478–1909	Age, scars	85	271	—	—
	Wetzl and Fonda 2000	2 500 ha 1400–1985	Age, growth release	21.3[c]	—	—	—
	Agee and Krusemark 2001	26 000 ha pre-1900	Age, live residual structure from air photos	—	369	7–9/[d]18–31/62–90	—
	Robbins 1995	~1 562 km^2 1700–1990	Age, scars	49 (2–191)	—	—	—
	Olsen and Agee 2005	~7 000 ha 1650–1900	Age, scars	2–167	—	—	—
	Weisberg 2009	14 504 ha 1550–1849	Age, scars	—	162	—	—
	Wendel and Zabowski 2010	1 873 ha 1568–2007	Age, scars	127	140	—	—
Pacific silver fir	Hemstrom and Franklin 1982	~53 000 ha 1200–1850	Age	—	465	—	—
	Fahnestock and Agee 1983	Western Washington pre-1934	Age class from historical survey records	—	834	—	—
	Agee et al. 1990	3 500 ha 1573–1985	Age, scars	108–137	—	—	—
	Morrison and Swanson 1990	1 940 ha 1150–1985	Age, scars	239	149	0–80/0–78/0–100	<50
	Garza 1995	3,540 ha pre-1910	Age, scars	154–246	—	24–57/ 20–22/ 45–50	—
	Agee and Krusemark 2001	26 000 ha pre-1900	Age, live residual structure from air photos	—	289	7–9/[d]18–31/62–90	—
Mountain hemlock	Dickman and Cook 1989	18 000 ha post-1400	Age	—	—	—	>3 200
	Fahnestock and Agee 1983	Western Washington pre-1934	Age class from historical survey records	—	598	—	—
	Agee et al. 1990	3 500 ha 1573–1985	Age, scars	137	—	—	—

Vegetation zone	Study	Extent and time period	Method	Frequency or return interval (years)	Rotation (years)	Percentage low, moderate, and high severity	High-severity patch size
Subalpine	Fahenstock and Agee 1983	Western Washington pre-1934	Age class from historical survey records	—	800	—	—
	Agee et al. 1990	3 500 ha 1573–1985	Age, scars	109	—	—	—
Douglas-fir and grand fir/ white fir	Weaver 1959	Unknown	Scars	47	—	—	—
	Agee et al. 1990	3 500 ha 1573–1985	Age, scars	52–93	—	—	—
	Agee 1991	197 ha 1760–1930	Age, scars	16	37–64	—	—
	Bork 1985	~100 ha pre-1900	Scars	8	—	—	~400
	Wills and Stuart 1994	~20 ha 1745–1849	Age, scars	10.3–17.3	—	—	—
	Taylor and Skinner 1998	1 570 ha 1627–1849	Age, scars	14.5	19	59/27/14	—
	Van Norman 1998	45 000 ha 1480–1996	Age, scars	123	—	—	—
	Brown et al. 1999	2000 ha 1820–1945	Age, scars	7.7–13	—	—	—
	Everett et al. 2000	3 240–12,757 ha ~1700–1860	Scars	6.6–7	11–12.2	—	2.4–40
	Stuart and Salazar 2000	~120 ha 1614–1944	Age, scars	27 (12–161)	—	—	—
	Taylor and Skinner 2003	2325 ha pre-1905	Age, scars	11.5–16.5	19	—	—
	Wright and Agee 2004	~30 000 ha 1562–1995	Scars	19–24	—	—	10–100
	Hessburg et al. 2007	~72 000 ha~1930	Historic aerial photos	—	—	18/58/24	~10 000
	Baker 2012	140400 ha~1770–1880	Live structure from historical inventory	—	496c	18/59/23	—
Ponderosa pine	Weaver 1959	Unknown	Scars	11–16	—	—	—
	Soeriaatma-dja 1966	1500–5000 ha unknown	Scars	4–36	—	—	—
	West 1969	Unknown	Age	—	—	—	<0.26
	Bork 1985	~100 ha pre-1900	Scars	4–7	—	—	—
	Morrow 1985	2 ha pre-1900	Age	—	—	—	<0.35
	Hessburg et al. 2007	~106 000 ha 1930–1940	Live structure from historical aerial photos	—	—	30/58/12	—

— = no information available.

[a] Most fire history studies are based on fire scars or identification of cohorts of trees with similar establishment dates. Fire frequency or return interval are the most commonly reported metric of fire activity in fire history studies. Another metric related to fire frequency is fire rotation, or the time it takes to burn an area equal to the size of the area of interest. Relatively few studies report fire severity.

[b] Stewart noted 15 fires over a 750-year period.

[c] Estimated at a 200-ha scale.

[d] Estimates of percentage burned at different levels of fire severity include both the western hemlock and Pacific silver fir vegetation zones.

of mortality in old-growth forests associated with insects and pathogens than in previous decades, though mortality rates vary by vegetation zone and seral stage (Reilly and Spies 2016).

Mortality rates in old-growth forests in the Pacific Northwest have increased above most published rates (>1 percent/year) prior to 2000 (Reilly and Spies 2016, van Mantgem et al. 2009). A regional study on mortality rates on Forest Service lands in Oregon and Washington corroborated the occurrence of high mortality rates in old-growth forests across all vegetation zones from the mid-1990s to mid-2000s during regionwide drought (Reilly and Spies 2016). However, Acker et al. (2015) found that mortality rates were <1 percent per year in wet forests of four national park units in western Washington (Lewis and Clark National Historic Park, Olympic National Park, Mount Rainier National Park, and North Cascades National Park), suggesting that moister forests may be more buffered from drought. Except for old-growth forests, where increased mortality led to cumulative losses in basal area and density (van Mantgem et al. 2009), there is generally poor understanding of the effects of recent mortality on stand structure and composition. However, Bell and Gray (2016) found that biomass accumulation in old-growth forests dominated by Douglas-fir was greater in warm, moist environments than in dry environments during the same period.

Increasing tree mortality rates have been documented in young stands of other regions, and some studies suggest that young stands may be more sensitive to changes in climate than old-growth stands (Luo and Chen 2013). However, mortality rates in early- and mid-seral stages were lower than expected across the Pacific Northwest (Reilly and Spies 2016), although there are few published rates of mortality in young forests of the western hemlock and Pacific silver fir zones in the western Cascades (Larson et al. 2015, Lutz and Halpern 2006). Higher tree mortality rates in previously published studies are likely due to the inclusion of small trees (<2.54 cm diameter) that are more sensitive to density-dependent mortality and competitive exclusion during early-seral development. We are unaware of any published mortality rates in earlier developmental stages from cold and dry vegetation zones, but the relatively low rates observed in these zones by Reilly and Spies (2016) were consistent with protracted early developmental pathways in cold and dry environments of this region and suggest that younger forests in these vegetation zones are more resistant to drought than old-growth forests (Reilly and Spies 2015).

Insect damage is more prevalent in drier vegetation zones and affected large areas east of the Cascades in recent decades (Hicke et al. 2016, Meigs et al. 2015). In Oregon and Washington, recent mountain pine beetle outbreaks were positively associated with warmer winter temperatures and prior-year precipitation and

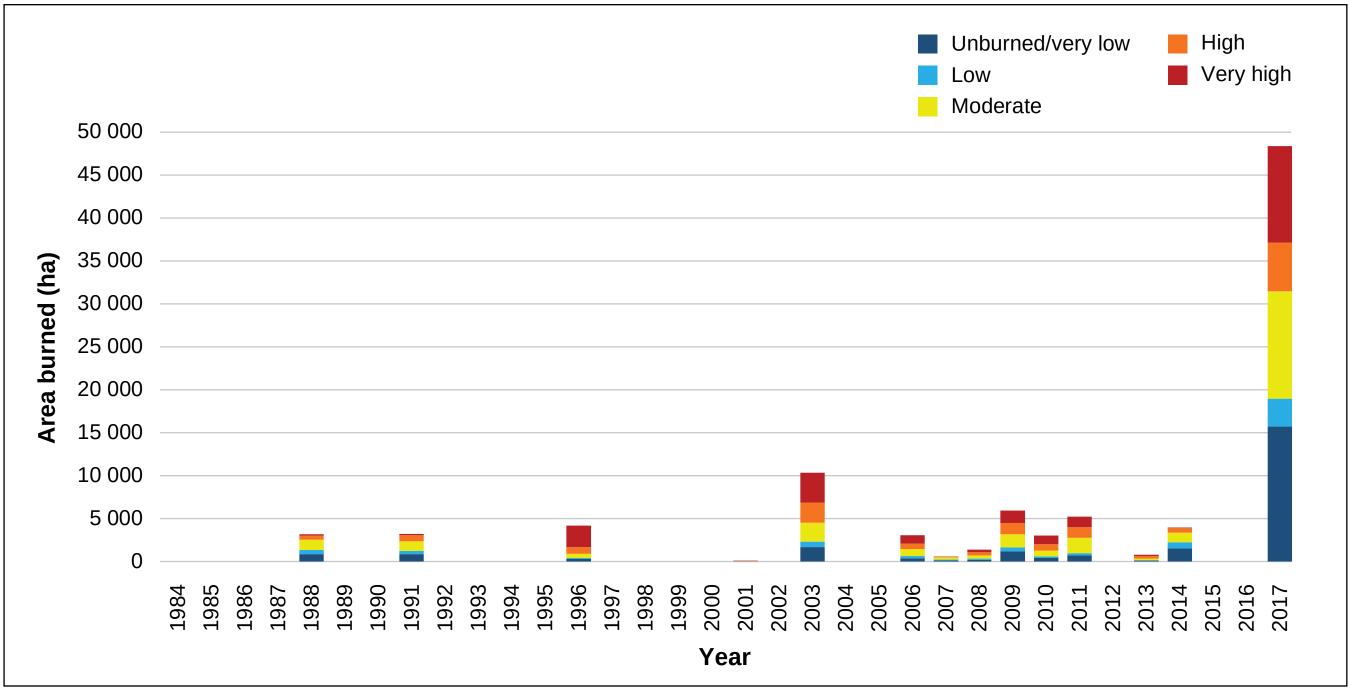

Figure 5.6—Contemporary trends in area burned and fire severity from 1984 to 2017 in the Columbia River Gorge, Mount Hood, and Willamette National Forests adaptation partnership assessment area. Fire severity classification follows Reilly et al. (2017) and is based on the percentage basal area mortality as follows: unburned/very low = <10 percent, low = 10 to 25 percent, moderate = 25 to 75 percent, high = 75 to 90 percent, very high = >90 percent.

negatively associated with the 2-year cumulative precipitation of the current and previous year (Preisler et al. 2012). Mountain pine beetles and western spruce budworms were particularly active on the eastern side of Mount Hood and other parts of the Cascade crest over the past decade (Meigs et al. 2015).

Although fire played an important role in the historical dynamics of the assessment area (Agee 1993), a long period of fire exclusion reduced fire activity during the relatively cool and moist mid-20th century (Littell et al. 2009). Between 1985 and 2010, the annual area burned increased in most vegetation zones in Oregon and Washington (Reilly et al. 2017). Likewise, fire activity has increased in the assessment area (fig. 5.6), with multiple large fires in the past 4 years including the 2017 Eagle Creek Fire (19 750 ha) and the Riverside (55 900 ha), Beachie Creek (78 300 ha), Lion's Head (82 800 ha), and Holiday Farm (70 107 ha) Fires of 2020 (fig. 5.7). The 2020 fires represent an unprecedented event in recent years (post 1950) and have yet to be incorporated into studies on contemporary fires in the region, though they will leave a long-lasting legacy.

Increased frequency and extent of fire across the Western United States since the mid-1980s have been attributed to drought (Littell et al. 2009), longer fire seasons associated with earlier snowmelt, warmer spring and summer temperatures (Jolly et al. 2015, Westerling et al. 2006), increasing fuel aridity (Abatzoglou and

Williams 2016), and declines in summer precipitation (Holden et al. 2018). Shifts in human populations are also important in increasing fire activity in some regions (Balch et al. 2017, Syphard et al. 2017). The Pacific Northwest has experienced recent increases in area burned, but recent fire activity differs substantially depending on spatial scale and geographic location across the region (Davis et al. 2015, Reilly et al. 2017).

Annual area burned increased since the mid-1980s (fig. 5.6) (Reilly et al. 2017), but there is growing consensus that the Pacific Northwest experienced less fire than would be expected under historical conditions (Haugo et al. 2019, Marlon et al. 2012, Parks et al. 2015, Reilly et al. 2017, Spies et al. 2018). Much of the area, particularly in lower elevation forests in the southwestern and northeastern part of the assessment area, has likely missed one or more fires that would likely have occurred historically, but 20th-century fire exclusion likely had less influence on fire activity toward the northern part of the western Cascades where historical fire intervals were longer.

With the exception of the western hemlock zone, cold and moist vegetation zones (Pacific silver fir, mountain hemlock, and subalpine zones) experienced the greatest proportions of high-severity fire across Oregon and Washington between 1985 and 2010 (Reilly et al. 2017). Most of the area burned in the western hemlock and dry vegetation zones was low and moderate severity (Reilly and Spies 2015, Reilly et al. 2017, Whittier and Gray 2016).

Although the area burned increased in all major vegetation zones during this time, there is little evidence that the proportion burning at high severity has increased across the Pacific Northwest (Law and Waring 2015, Reilly et al. 2017). Although they found no increase in the proportion of high-severity fire, Reilly et al. (2017) found that increases in high-severity patch size during this time were positively associated with more area burned during drought years in all major vegetation zones. At the stand scale, fire severity has also been related to several factors, including topography, stand structure, and fire weather (Dillon et al. 2011). Studies from the Klamath Mountains and southern part of the Oregon western Cascades indicate that dense young stands dominated by smaller trees (i.e., plantations) experience higher mortality than those dominated by multilayered old-growth forests (Thompson et al. 2007, Zald and Dunn 2018).

The large, high-intensity fires of 2020 (fig. 5.7) were driven by strong, dry winds out of the east. Very large patches of high-severity fire accounted for at least 40 to 50 percent of the area burned. Although the 2020 fires were unique in recent decades, the climatic conditions were not unprecedented in the past three decades, and there is little evidence to suggest that these fires were related to climate change or that prefire management played a major role in the resulting patterns of burn severity. Although unprecedented in recent years, all fires burned in areas that either experienced stand-replacing fire in 1902 or were adjacent to areas that did.

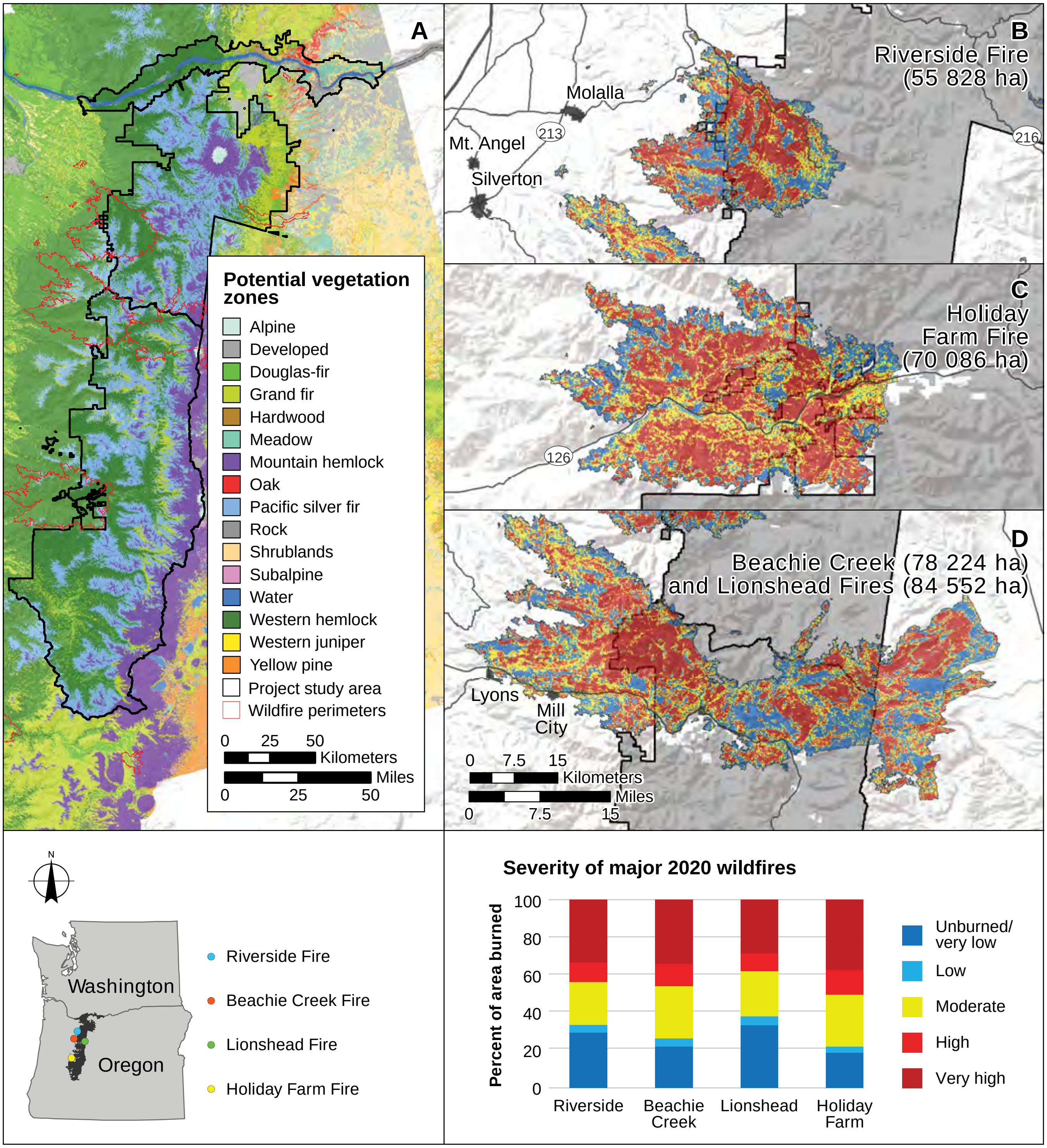

Figure 5.7—Locations and spatial patterns of burn severity in 2020 wildfires in the vicinity of the Columbia River Gorge, Mount Hood, and Willamette National Forests Adaptation Partnership assessment area. Burn severity maps were created using 15-m Landsat Sentinel-2 data and are based on the change in the relative difference in the normalized burn index. Prefire imagery is from summer 2020 and immediate postfire imagery from 29 September 2020. These methods differ from most published studies, including the results in figure 5.6, which are based on imagery from the years before and after the fire. These maps provide a preliminary look at immediate tree mortality which will likely continue in subsequent years. Fire severity classification follows Reilly et al. (2017) and is based on the percentage of basal area mortality: unburned/very low = <10 percent, low = 10 to 25 percent, moderate = 25 to 75 percent, high = 75 to 90 percent, very high = >90 percent.

Moist forests have been resilient to fire at all levels of burn severity, with seedling abundance and species richness peaking at moderate levels of severity (Dunn et al. 2020). Brown et al. (2013) found that Douglas-fir regeneration 14 years following the 1991 Warner Creek Fire was abundant, ranging from 1,500 to >300,000 seedlings per hectare. Regeneration occurred across several years despite the abundant growth of shrubs. In another study from the Warner Creek Fire, Larson and Franklin (2005) also found abundant regeneration of Douglas-fir, as well as western hemlock and western redcedar, in areas burned at low or moderate severity. Acker et al. (2017) found that conifer regeneration was sparse 2 years following high-severity fire in the 1996 Charlton Fire, but by 13 years postfire, the density of seedlings >10 cm in height ranged from 359 to >7,000 per hectare. Across all severity classes, 74 percent of seedlings were mountain hemlock, 22 percent were Pacific silver fir, and the remaining 4 percent were predominantly lodgepole pine.

Although the available studies indicate that moist and cold forests have been relatively resilient to recent fires during the 1990s, recent work from dry forests in other regions suggests regeneration and resilience to high-severity fire is decreasing (Stevens-Rumann et al. 2018, Tepley et al. 2017). Similar patterns have been documented in mixed-conifer forests and low-elevation ponderosa pine of the Oregon eastern Cascades following the B&B Complex Fire in 2003, where recruitment following high-severity fire is limited (Dodson and Root 2013, Meigs et al. 2009). Little is known about regeneration patterns in more recent fires (i.e., after 2003) or how postfire drought might influence future regeneration patterns.

Current Terrestrial Conditions and Forest Vulnerability to Drought

A national assessment of terrestrial condition class characterized most of the CMWAP assessment area as very good condition (fig. 5.8). This assessment was based on observed insect and pathogen mortality, critical loads of atmospheric nutrient deposition (e.g., nitrogen, sulphur) in soils, departures from long-term temperature and precipitation trends, road density, patterns of current fire, and departure from the natural range of variability (Cleland et al. 2017). The drier, northeastern part of MTH, which is dominated by moist grand fir and mountain hemlock, was rated either poor or very poor.

Mildrexler et al. (2016) calculated a forest vulnerability index (FVI) using drought and high temperatures across Oregon and Washington from 2003 to 2012. High temperatures and high drought stress were found to occur most often in August and September, but peak vulnerability occurred at different times for various forest types. Only a relatively small part of the CMWAP assessment area had positive FVI values (fig. 5.9), indicating high forest vulnerability to drought. Most positive FVI values occurred in moist forest zones at lower elevations in the southwestern part of

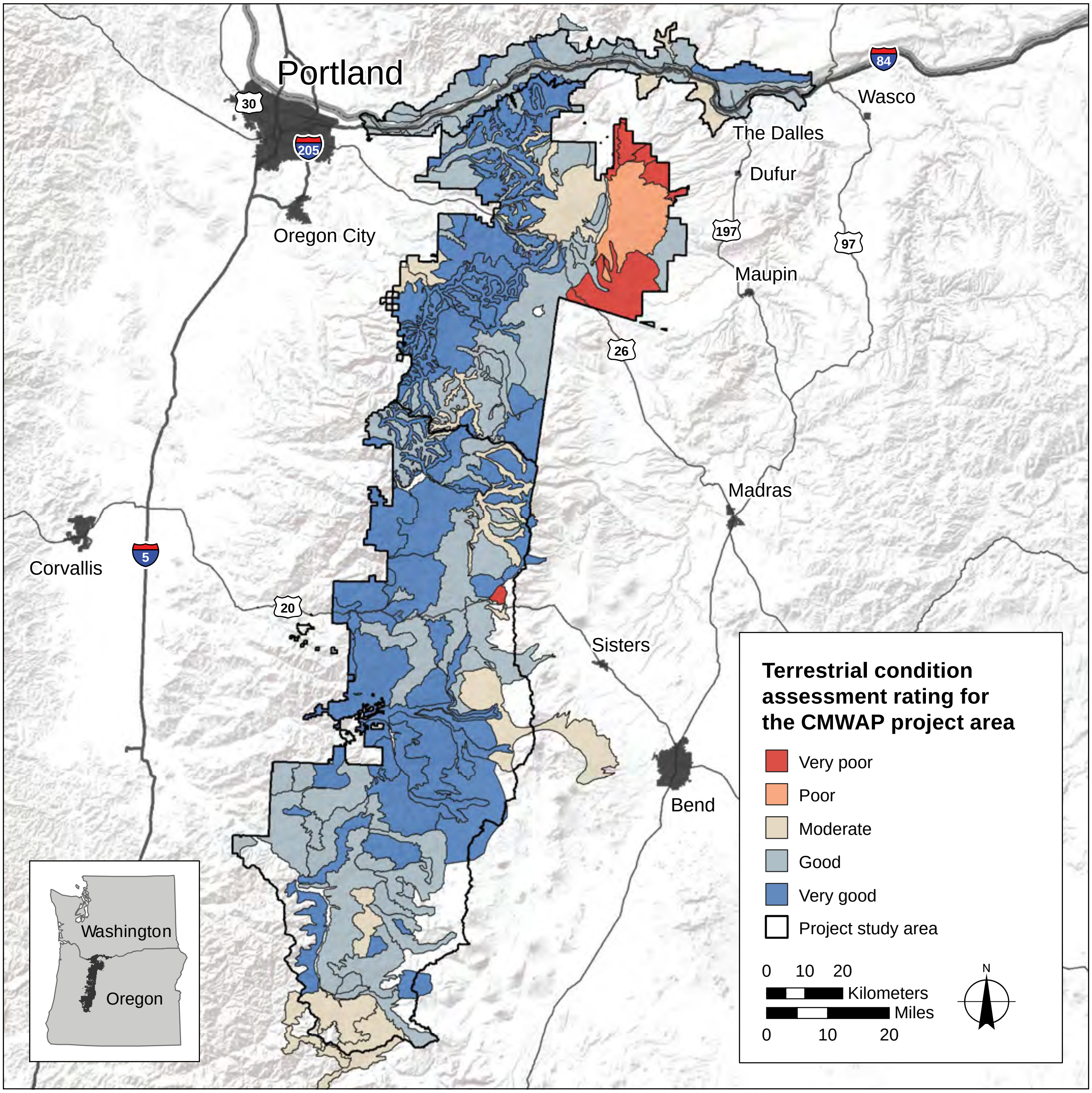

Figure 5.8—Terrestrial condition assessment rating for national forests in the Columbia River Gorge, Mount Hood, and Willamette National Forests Adaptation Partnership (CMWAP) assessment area. Data are from Cleland et al. (2017).

WIL, but a few small areas of moist forests toward the north also had positive FVI values. Positive FVI values in dry and cold vegetation zones were primarily limited to the northeastern portion of MTH.

Maps of potential soil drought stress (fig. 5.10) (Ringo et al. 2018) may help managers identify where drought effects will be most severe in the future. However, the existence of "droughty soils" does not automatically imply vulnerability. Nevertheless, the map may be useful for identifying where seedling survival and establishment will not be deterred by future drought. The highest soil drought

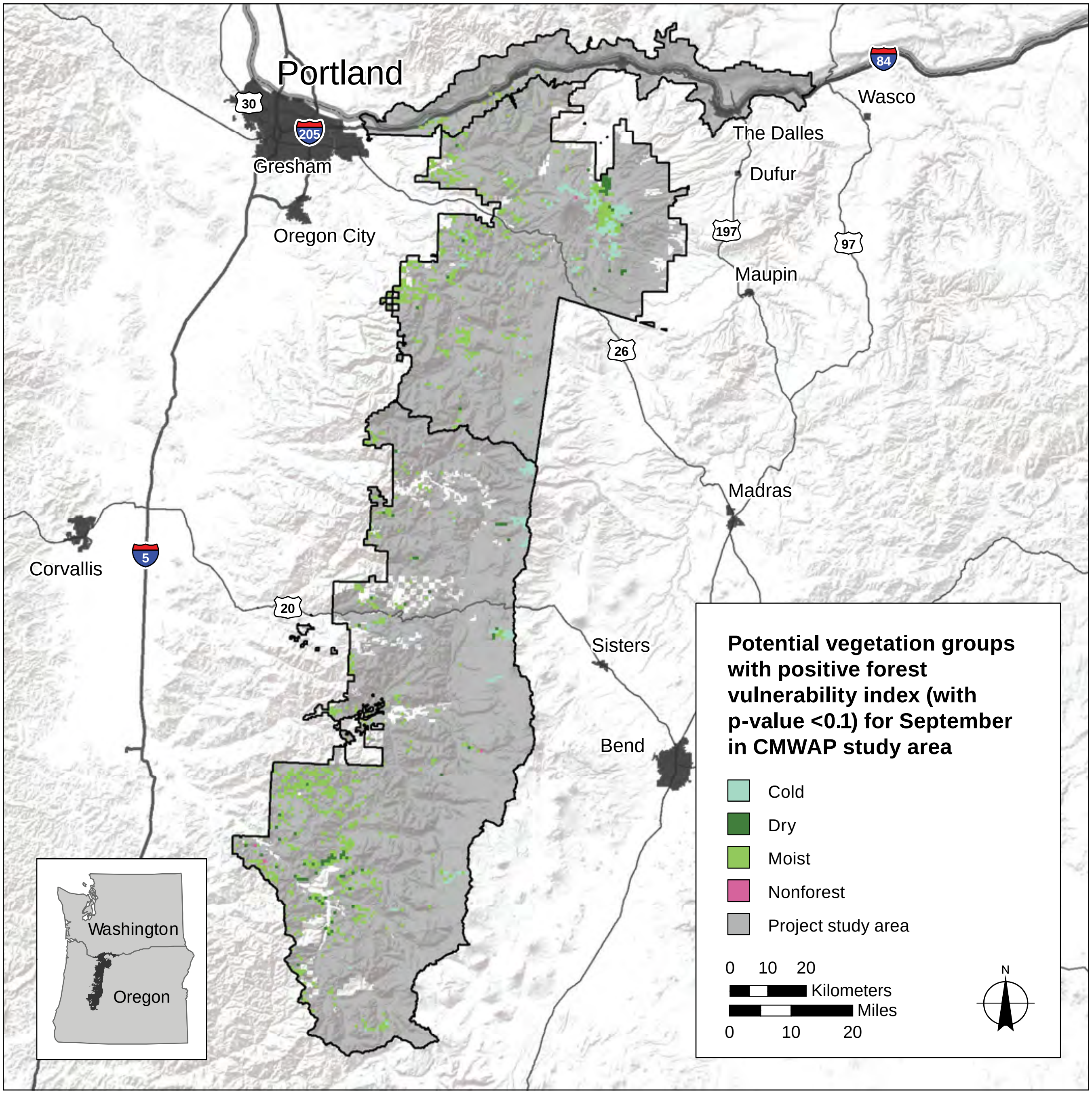

Figure 5.9—Positive forest vulnerability index (FVI) values (p-value <0.1) for September in the Columbia River Gorge, Mount Hood, and Willamette National Forests Adaptation Partnership (CMWAP) assessment area by potential vegetation type. Positive FVI values indicate forest areas that have experienced statistically significant trends in rising temperatures and increasing water deficits from 2003 to 2012. Based on these trends, we may expect higher forest vulnerability, although responses will differ by forest type. Only vegetation subzones with greater than 5 percent positive FVI values are shown. Data are from Mildrexler et al. (2016).

probabilities occur in middle and higher elevations along the Cascade crest in the central port of the assessment area, as well as along mid-elevation ridges, all of which are dominated by the Pacific silver fir and mountain hemlock vegetation zones.

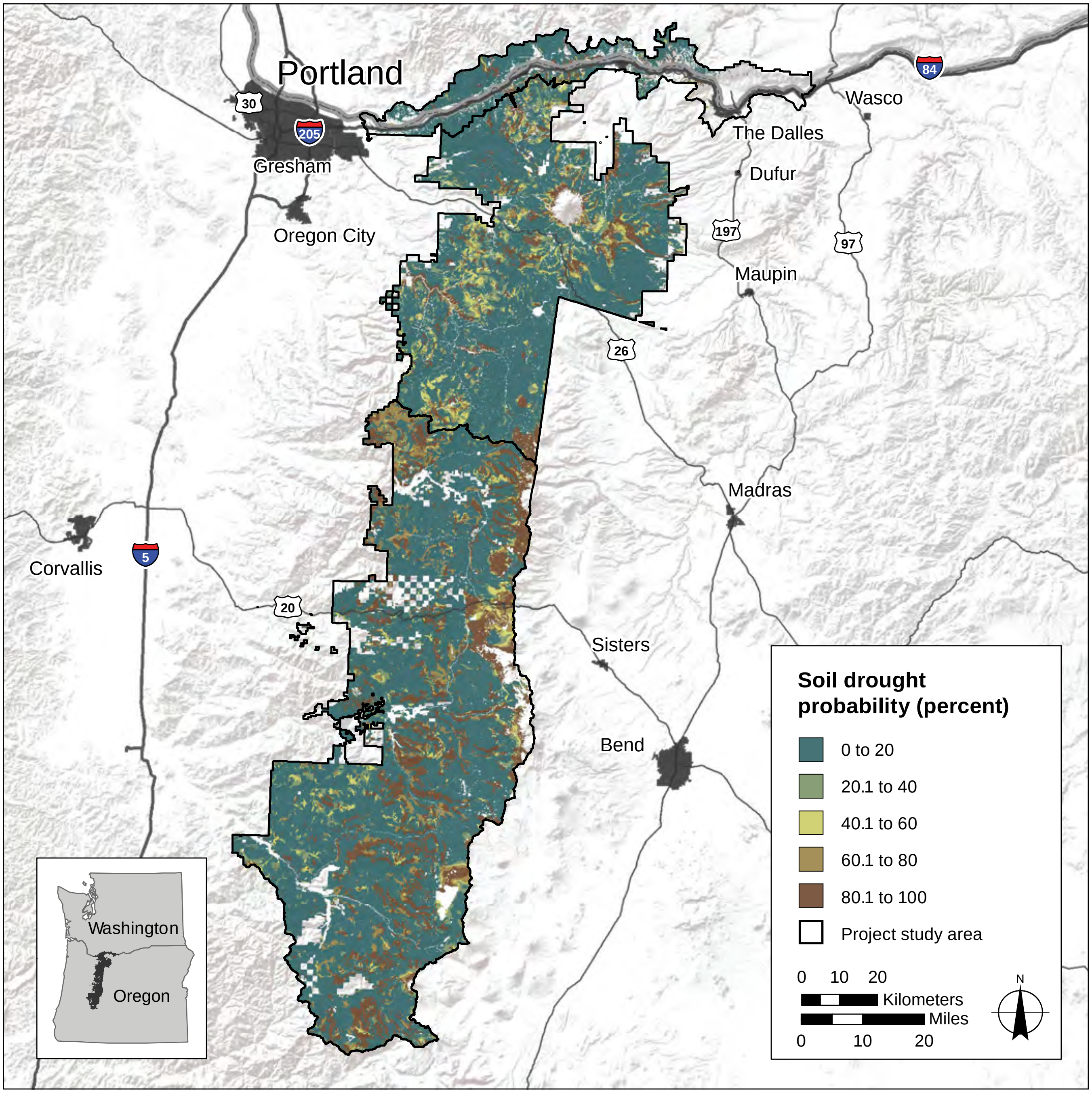

Figure 5.10—Potential soil drought stress in the western Cascades of Oregon (July through September). Data are from Ringo et al. (2018).

Potential Climate Change Effects on Vegetation

Climate change is expected to alter vegetation through a variety of mechanisms that may be characterized as **direct effects** (e.g., effects of carbon dioxide [CO_2] and climate on physiological processes) or **indirect effects** (e.g., disturbance processes). The direct effects of climate change and increasing CO_2 on vegetation are expected to be expressed through changes in mortality, growth, and reproductive processes (i.e., seed production, regeneration), all of which may be sensitive to altered phenology and biotic interactions within and among species (Peterson et al. 2014a, 2014b). The indirect effects of climate change are expected to be expressed through increases in the frequency and extent of disturbances, particularly fire, insects, and pathogens. These disturbances can cause rapid ecological change at broad spatial scales and are expected to be a greater driver of ecological change than direct effects (Dale et al. 2001, Littell et al. 2010). However, the relative importance of these drivers is likely to vary geographically and among species and seral stages.

Direct Effects of Climate Change: Demographic Responses

Tree mortality from higher temperatures and drought stress, typically interacting with insect outbreaks, has occurred in some forests of the Western United States in recent decades (Allen et al. 2010, 2015). Warmer temperatures and increased severity and duration of droughts projected for the assessment area are likely to increase exposure to climate-induced physiological stress on plants (Adams et al. 2009).

Drought-related stress can lead to hydraulic failure (irreversible desiccation and collapse of water transport structures) and carbon starvation (McDowell et al. 2008). Trees may survive within a range of conditions but may cross thresholds beyond which they cannot recover (Hartmann et al. 2018). However, interactions among risk factors are complex and limit our ability to predict where and when thresholds are likely to be crossed. Although there has been much recent work on the physiological mechanisms associated with tree mortality, a greater understanding of these mechanisms is needed to assess vulnerability among species and enhance our ability to predict mortality (Hartmann et al. 2015). Furthermore, a better understanding of the ecological consequences of mortality in terms of community-level change (i.e., structure and composition) and ecosystem function is needed (Anderegg et al. 2012).

The potential response of tree growth to climate change varies substantially among species and depends on the factors that affect growth, such as availability of water and length of growing season (Littell et al. 2010, Peterson and Peterson 2001). Growth in Douglas-fir is projected to decrease under climate change where it is currently water limited (Restaino et al. 2016), but growth may increase where the species is currently limited by growing season length or lower- than-optimal temperature (Albright and Peterson 2013; Creutzburg et al. 2017; Littell et al. 2008, 2010).

For species in higher elevation forests where growth is limited by temperature and growing season length (e.g., subalpine fir, mountain hemlock), growth increased during the 20th century with warmer winter temperatures and longer growing seasons (McKenzie et al. 2001, Nakawatase and Peterson 2006, Peterson et al. 2002). Warmer winters and earlier snowmelt may also increase potential for drought and water stress in higher elevation forests, especially toward the southern portion of their distribution. However, these effects are not well documented, and increased growth is expected to continue in the future (Albright and Peterson 2013).

The effects of projected climate change on ponderosa pine are uncertain, as wetter fall seasons may increase growth while drier summers may decrease growth (Kusnierczyk and Ettl 2002, McCullough et al. 2017). These effects may vary across the landscape, and ponderosa pine may be more sensitive to drought at lower elevations (Knutson and Pyke 2008). A century of fire exclusion also decreased ponderosa pine resistance to drought and potentially increased its susceptibility to biotic disturbances (Voelker et al. 2018).

Increased levels of CO_2 are also likely to have direct effects on vegetation change, especially for moist forests where growth is less limited by water availability. The general patterns that emerged from research on elevated CO_2 from 1984 to 2007 in moist forests and semiarid grassland systems suggest that elevated CO_2 reduces stress when it gets drier and enhances net annual productivity (McMurtrie et al. 2008). Seasonal variations in atmospheric CO_2 concentrations can substantially affect photosynthesis by increasing water use efficiency (WUE) at moist sites (Jiang et al. 2019). These results apply broadly to groundwater-dependent ecosystems that are distinct from the surrounding upland plant communities. In addition, forested and grassland systems usually have higher soil moisture under elevated CO_2, arising from effects such as greater litter production in conifer forests (see Schäfer et al. 2002) or through mechanisms such as increased WUE in both forests (Jiang et al. 2019, Keenan et al. 2013) and grasslands (Morgan et al. 2011).

Although notable increases in WUE have been reported within and across forest biomes over the past decades, equivalent increases in growth rates have not been consistently documented (Hararuk et al. 2019, Silva and Anand 2013). Distinct growth responses have been detected (positive and negative), but there is no clear evidence of a prevailing CO_2 stimulation based on changes in growth rates alone.

Silva and Anand (2013) identified net positive relationships between WUE and tree growth in boreal and Mediterranean forests located in latitudes greater than 40° N. However, this pattern was more negative in temperate, subtropical, and tropical forests. These results agree with the discussion above regarding limitations (i.e., water versus growing season length) on Douglas-fir growth. That is, when water is not limiting, the synergistic effects of warming and elevated CO_2 stimulate tree growth (Salzer et al. 2009, Silva et al. 2010). However, none of these effects are documented in more arid systems.

In dry forests, the response of ponderosa pine and western juniper to climate change may depend on the potential for elevated CO_2 to enhance growth by increasing WUE (Soulé and Knapp 2006). However, there is some evidence suggesting any benefits of CO_2 fertilization will be outweighed in the future as the climate warms and water becomes more limiting (Gedalof and Berg 2010, Restaino et al. 2016). Increased levels of CO_2 also can accelerate maturation and increase seed production (LaDeau and Clark 2001, 2006). Ultimately, the question is whether the CO_2 fertilization effect outpaces drought stress brought on by warming temperatures (Sperry et al. 2019). Climate change is likely to cause chronic hydraulic stress in forests of the assessment area, with possible increases in mortality in some locations.

The ability of a species to respond to changes in climate (e.g., earlier warming and drying) with shifts in phenology will be an important factor in determining species' responses to climate change. Altered seasonality may affect growth and reproduction in some plant species. A major concern in the assessment area associated with warmer winters and earlier springs is the requirement for many species (e.g., Douglas-fir, western hemlock, pine and fir species) to experience chilling for the emergence of new leaves or budburst (Harrington and Gould 2015). Douglas-fir may experience earlier budburst in some portions of its range owing to warming in early spring, but reduced chilling may cause later budburst in the southern portion of its range (Harrington and Gould 2015) and lead to delayed growth initiation (Ford et al. 2016).

Climate change may also affect interactions among and within species in complex ways. These effects are currently poorly understood; however, several recent studies from higher elevation moist forests in the Pacific silver fir vegetation zone of Washington provide some insights. For example, the negative effect of competition on growth is likely to be greater for saplings than for adults, and climate change may have less effect on closed-canopy forests at lower elevations than those at higher elevations (Ettinger and HilleRisLambers 2015). Consistent with theory (i.e., density-dependence), individual growth is likely to increase most in lower density stands, as trees may show little response to climate change at higher density where room for growth and expansion is more limited (Ford et al. 2017).

Little is known about the effects of climate change on positive species interactions (e.g., facilitation), which can be important in stressful environments (Callaway et al. 2002) and play a role in early stand development in dry and cold vegetation zones (e.g., ponderosa pine, subalpine, mountain hemlock) in the assessment area (Reilly and Spies 2015). However, facilitation is likely to become more important in the future, especially as climatic conditions necessary for establishment become less common (Brooker et al. 2008, Kitzberger et al. 2000). Resprouting broadleaf species and shrubs may grow more quickly and outcompete conifers for light and water following fire, but mycorrhizal connections formed between hardwoods, *Arctostaphylos* species, and conifer seedlings after disturbance may facilitate seedling establishment (Borchers and Perry 1990, Horton et al. 1999, Simard 2009). *Ceanothus* species fix nitrogen, which could facilitate forest recovery after fire (Busse 2000, Busse et al. 1996).

Indirect Effects of Climate Change: Disturbance

Increasing frequency and severity of disturbance are predicted to be the primary mechanisms of ecological change in the future (Dale et al. 2001, Littell et al. 2010). Disturbances include discrete events that alter the structure and function of ecosystems (Pickett and White 1985) but may also include multiyear episodes of pathogens and insects that have direct effects on tree growth. There is great concern that interactions among climate change, forests, and disturbance regimes may result in disturbance effects outside of the natural range of variation (Dale et al. 2000).

Biotic disturbances—

The effects of native insects and pathogens on mortality are expected to increase as trees are exposed to more stress associated with growing-season drought. However, the implications and magnitude of their effects are likely to differ geographically and among species (Agne et al. 2018, Chmura et al. 2011, Kolb et al. 2016, Sturrock et al. 2011). In addition to affecting host species, climate change will affect population dynamics and ranges of pathogens and insect populations.

Pathogen activity is likely to increase in areas with drought-stressed host species, whereas the effects of climate change on pathogens that cause greater infection under moist conditions may be more variable and difficult to predict (Sturrock et al. 2011). Increases in temperature may also allow some forest pathogens to expand their elevational and latitudinal ranges (Kliejunas et al. 2009).

Warmer winters and hotter droughts are expected to enable some species of insects (e.g., mountain pine beetle) to increase reproductive rates and move into previously unsuitable habitat (Bentz et al. 2010, 2016); many regions in western North America have experienced what are considered unprecedented outbreaks of insects in the last few decades (e.g., Raffa et al. 2008). Drought and insects may also interact to further increase sensitivity and exposure to mortality.

Nonnative plant species—

Invasions of nonnative plant species have the potential to alter vegetation dynamics, soil properties (Caldwell 2006, Slesak et al. 2016), and disturbance regimes (Brooks et al. 2004). Most nonnative plant species were initially introduced for horticultural uses, for erosion control, or in contaminated crop seed (Reichard and White 2001). Gray (2008) used a systematic inventory of forest health monitoring plots and found that over 50 percent of plots in almost all physiographic provinces in the assessment area had nonnative species present. Some of the more common species of concern can be found in table 5.4.

Many common nonnative plants are associated with disturbance and management (e.g., clearcuts, thinning), though some nonnative, shade-tolerant shrubs can spread in undisturbed forests (Gray 2005). Many nonnative plant species

Table 5.4—Major invasive plant species in the Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest

Species	Mechanism of invasion	Vegetation type[a]	Ecological implications
Cheatgrass (*Bromus tectorum* L.)	Fire, soil disturbance, overgrazing, recreational use (dispersal on clothing, fur, and in equipment or gear, dispersal in soil/rock products, dispersal in seed mixes, hay or straw)	PP, DF-D, GF-D	Increased fire frequency; early-season competition for moisture; conversion of bunchgrass/forb-dominated understory; reduction in forage value for wildlife/grazing
Medusahead rye (*Taeniatherum caput-medusae* [L.] Neski)	Fire, soil disturbance, overgrazing, recreational use (dispersal on clothing, fur, and in equipment or gear, dispersal in soil/rock products, dispersal in seed mixes, hay or straw)	PP, DF-D, GF-D	Increased fire frequency; early-season competition for moisture; conversion of bunchgrass/forb-dominated understory; reduction in forage value for wildlife/grazing
Ventenata grass (*Ventenata dubia* [Leers Coss.])	Not well documented, but potential mechanisms include fire, soil disturbance, overgrazing, recreational use (dispersal on clothing, fur, and in equipment or gear, dispersal in soil/rock products, dispersal in seed mixes, hay or straw)	PP, DF-D, GF-D	Increased fire frequency; early-season competition for moisture; conversion of bunchgrass/forb-dominated understory; reduction in forage value for wildlife/grazing
Houndstongue (*Cynoglossum oficionale* L.)	Mechanical disturbance activities, roads, wildlife, cattle, recreational use (dispersal on clothing, fur, and in equipment or gear)	PP, DF-D, GF-D	Reduced forage value for wildlife/grazing; reduction in understory diversity
Knapweed species (*Centaurea* spp.)	Roads, trails, mechanical disturbance, recreational use (windblown seed dispersal, dispersal through soil/rock material or on equipment)	PP, DF-D, GF-D, WH-D, WH-M	Reduced understory diversity; allelopathic effects on surrounding vegetation; reduced forage value
Thistle (*Cirsium* spp.)	Roads, trails, mechanical disturbance, recreational use (windblown seed dispersal, dispersal in soil/rock products, dispersal in seed mixes, hay or straw)	PP, DF-D, GF-D, WH-D, WH-M	Reduced understory diversity

persist in seed banks or are wind dispersed (Halpern et al. 1997, 1999), and thus are capable of rapid response and increase exposure to invasion following disturbance.

Increasing temperatures may favor nonnative species (Hellmann et al. 2008, Sandel and Dangremond 2012). Warm, dry sites with increased topographic exposure may be particularly sensitive to nonnative species, especially annual grasses following high-severity fire (Dodson and Root 2014). Roads and trails also facilitate the spread of nonnative plants (Parendes and Jones 2000, Rubenstein and Dechaine 2015). The abundance of nonnative plants increased with lower stand

Table 5.4—Major invasive plant species in the Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest (continued)

Species	Mechanism of invasion	Vegetation type[a]	Ecological implications
Himalayan blackberry (*Rubus bifrons* Vest), evergreen blackberry (*Rubus laciniatus* Willd.)	Roads, trails, mechanical disturbance (dispersal via wildlife or mechanical means)	PP, DF-D, GF-D, WH-D, WH-M	Reduced understory diversity; effects on native riparian vegetation; competition for growing space
Hawkweed (*Hieracium* spp.)	Roads, trails, recreational use, mechanical disturbance (windblown dispersal, dispersal in soil/rock products, or on equipment)	WH-D, WH-M	Reduced understory diversity; competition for growing space; high risk to meadow habitats
False brome (*Brachypodium sylvaticum* [Huds.] P. Beauv.)	Roads, trails, mechanical disturbance, recreational use (dispersal on clothing, fur, and in equipment or gear dispersal through soil/rock material or on equipment)	WH-D, WH-M	Reduced understory diversity; loss of native habitat
Scotch broom (*Cytisus scoparius* [L.] Link)	Roads, trails, mechanical disturbance, recreational use (dispersal through soil/rock material or on equipment)	PP, DF-D, GF-D, WH-D, WH-M	Long-lived seed bank; often forms a monoculture; increase in nitrogen availability; competition with tree establishment
Knotweed (*Fallopia* and *Pologonum* spp.)	Bank erosion, flooding, removal of native riparian shrubs, mechanical disturbance (dispersal via broken and floating plant fragments, rhizomes and seeds, dispersal in soil or rock products)	WH-M	Reduction in riparian plant diversity; increased bank erosion
Shiny and Robert's geranium (*Geranium lucidum* L. and *G. robertianum* L.)	Roads, trails, timber harvest areas, any disturbed area (dispersal through prolific seed production, moved in soil on equipment)	WH-M	Reduction in understory diversity; can create a monoculture
Tansy ragwort (*Jacobaea vulgaris* Gaertn)	Roadsides, meadows, timber harvest areas (windblown dispersal)	WH-M	Reduction in species diversity in meadows and open forest; toxic to wildlife and stock
St. Johnswort (*Hypericum perforatum* L.)	Roadsides, meadows, timber harvest areas(windblown dispersal and then once established expands through underground rhizomes)	WH-M	Reduction in species diversity in meadows and open forest

[a] PP = ponderosa pine, DF-D = Douglas-fir dry, GF-D = grand fir dry, WH-D = western hemlock dry, WH-M = western hemlock moist.

density from clearcutting or thinning (Gray 2005). Likewise, Bailey et al. (1998) found the species richness of nonnative species was higher in thinned stands than in undisturbed, old-growth stands.

Some existing nonnative species will likely expand with climate change because ecosystem disturbance and shifts in native species ranges will provide opportunities for establishment (Ayres et al. 2014). For example, nonnative species may exploit postfire conditions better than native species (Zouhar et al. 2008). Nonnative species, particularly annual grasses, may also alter fire regimes through changes in fire frequency or severity (Kerns et al. 2020). Gray et al. (2011) provide a field guide and prioritized list of nonnative plants along with range maps that cover the entire assessment area. More information on management of nonnative species is also available in Harrington and Reichard (2007).

Abiotic disturbances—

Most research on the effects of climate change on abiotic disturbances has focused on fire. Studies from other coastal regions of the world suggest an increase in tropical cyclones and hurricanes (Emmanuel et al. 2005, Webster et al 2005), but we are currently unaware of any published literature with future projections of the frequency or intensity of windstorms in the assessment area. However, if more precipitation falls and saturates soils during intense winter storms, exposure to large blowdown events will likely increase. Areas affected by pathogens that predispose trees to snapping or tip-up may be particularly sensitive to blowdown events.

Fire activity may respond to climate change through three major pathways: fuel conditions, fuel amount and structure, and ignition sources (Hessl 2011). Most studies to date have assumed that the major pathway to change will be through alteration of fuel conditions, as the relationships among weather, fuel moisture, and fire activity are well established. Fewer studies have focused on changes in the second pathway, though fuel amount and structure may be of particular concern given their relationship with fire severity. Changes in ignition sources are most uncertain, as they are affected by lightning frequency as well as changes in human ignitions and fire suppression efforts (Balch et al. 2017, Syphard et al. 2017). Although there is evidence suggesting lightning frequency will increase in the future as a result of warming at the continental scale (Romps et al. 2014), changes in lightning frequency are uncertain.

Several studies project increases in fire activity (i.e., increased area burned, increased fire size, shorter fire interval) during the 21st century (table 5.5). Although projections differ geographically and among studies, all suggest increased fire activity during the 21st century. While some of the projected increases may seem high, it is important to note that the recent extent of fire in moist forest is very low, and a tripling of area affected by fire events may still be a relatively small amount

Table 5.5—Studies that project the effects of climate change on wildfire that include the assessment area

Study	Method	Geographic extent	Emission scenario	Time period	Projected change from current	Suppression effects included	Variable
Stavros et al. 2014	Statistical	OR, WA	RCP 4.5, RCP 8.5	2031–2060	+	No	Very large fire occurrence[a]
McKenzie et al. 2004	Statistical	OR, WA	A2, B2	2070–2100	+	No	Area burned
Littell et al. 2010	Statistical	WA	A1B	2020–2080	+200 to 300%	No	Area burned
Turner et al. 2015	Process	Willamette Valley, OR	RCP 4.5, RCP 8.5	2100	+300 to 900%	No	Area burned
Krawchuk et al. 2009	Statistical	Global	A2, B1	2070–2090	+	No	Fire probability[b]
Spracklen et al. 2009	Statistical	OR, WA	A1B	2050	+78%	No	Area burned
Liu et al. 2012	Statistical	Continental US	A2	2041–2070	No change	No	Fire potential[c]
Rogers et al. 2011	Process	OR, WA	A2	2070–2099	+76 to 310%/ 29 to 41%	Yes	Area burned/ burn severity[c]
Sheehan et al. 2015	Process	OR, WA	RCP 4.5, RCP 8.5	2071–2099	-82 to +14%	Yes	Mean fire interval
Creutzburg et al. 2017	Statistical	OR	RCP 8.5	2100	Negligible	Yes	Area burned
Parks et al. 2016	Statistical	Western United States	RCP 8.5	2040–2069	No change to decrease	No	Fire severity[d]
Davis et al. 2017	Statistical	OR, WA	RCP 8.5	2071–2100	No change to increase	No	Suitability for large wildfires[e]
Littell et al. 2018	Statistical	OR, WA western Cascades	A1B	2080	+400 to 500%	No	Area burned

OR = Oregon, WA = Washington.

[a] Very large fires defined as those >20 000 ha.

[b] Burn severity is based on combustion of biomass.

[c] Fire potential is measured by the Keetch-Byram Drought Index.

[d] Burn severity is based on a postfire composite burn index based on changes in multiple strata including soil and rock, litter and surface fuels, low herbs and shrubs, tall shrubs, and trees.

[e] Large wildfires are defined in this study as >40 ha.

in absolute terms. Although the ecological effects may be local, even a doubling of area affected by fire events, such as the 2017 Eagle Creek Fire, would have significant social and economic impacts.

Davis et al. (2017) projected increases in suitability for large wildfires (>200 ha) during the 21st century (under Representative Concentration Pathways [RCPs] 4.5 and 8.5) for the western Cascades (fig. 5.11). Modeled fire suitability increases across the entire assessment area and is highest at the end of the century in the southern part of WIL and the northeastern part of MTH. Fire suitability increases but remains relatively low in higher elevation forests along the Cascade crest by the end of the century. Fire suitability is projected to remain low through the century in low-elevation forests of the northwestern part of MTH as well as in the western part of CRGNSA.

The wide range of projections of climate change effects on fire within the assessment area are caused by differences in emission scenarios, spatial and temporal scale, model structure (e.g., statistical versus process-based), and variability in how models project precipitation. In addition, McKenzie and Littell (2017) showed that differences in climate-fire relationships among physiographic provinces are likely to be substantial, and further analysis is required to put differences in methodological and regional projections of fire into context. At regional scales, dynamical and statistical approaches to projecting future fire activity may agree, but the mechanisms operating at more local scales require careful interpretation.

Projections of future fire severity are less common (Hessl 2011, Parks et al. 2016), potentially owing to the complexities of incorporating feedbacks from fire and climate on fuel structure and arrangement at different spatial scales. Previous fires can inhibit the spread of subsequent fires occurring within a limited time window (Parks et al. 2015), and increased area burned in the future may decrease fuel availability. Rogers et al. (2011) used the MC1 vegetation model to project that burn severity would increase by 29 to 41 percent because of increases in productivity and biomass during non-summer months. However, a recent study incorporating changes in vegetation type, fuel load, and fire frequency projected either no change or potential reductions in fire severity across the entire assessment area for 2040–2069 under the most extreme climate change scenario (RCP 8.5) (Parks et al. 2016). The authors attribute decreases in fire severity to greater water deficits, decreased productivity, and less available fuel.

Disturbance interactions—

Of particular concern are multiple, successive, or compound disturbances (McKenzie et al. 2009, Paine et al. 1998). The interaction of disturbances may result in multiplicative effects on the structure and function of ecosystems that differ from the cumulative effects of individual disturbances. The effects of compound disturbances are difficult to project but may amplify disturbance severity, cause transitions between ecological states (e.g., forest to nonforest), and decrease forest resilience (Buma 2015). However, despite growing recognition and interest in interactions among disturbances, the effects of compound disturbances remain poorly characterized and difficult to predict (Buma 2015, Seidl et al. 2017).

A major concern with increasing fire frequency is the potential for short-interval reburns. Young conifers with thin bark have low resistance to fire (Agee

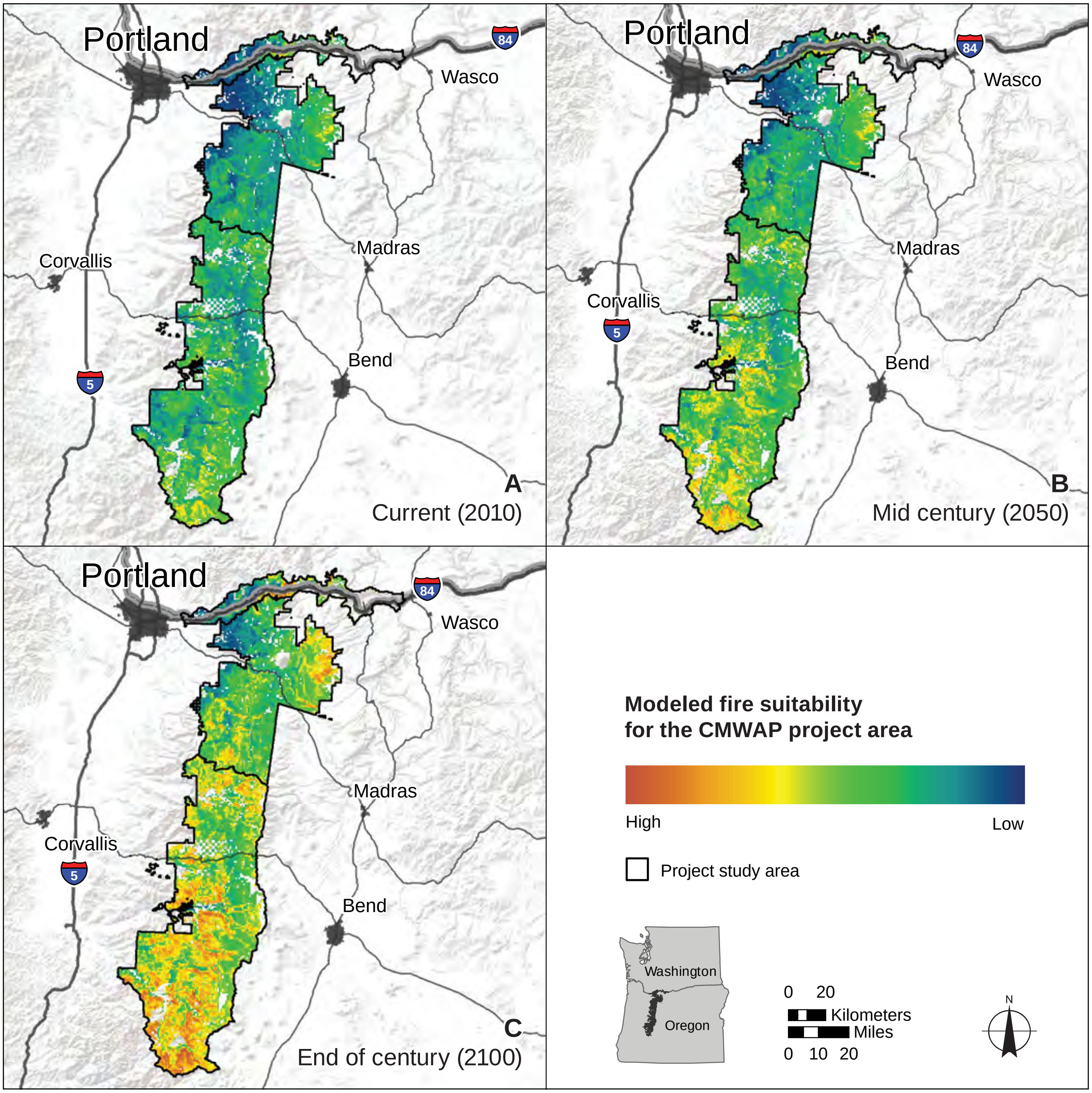

Figure 5.11—Modeled environmental suitability for large forest fires in the Columbia River Gorge, Mount Hood, and Willamette National Forests Adaptation Partnership (CMWAP assessment area) (A) under current climate and projected future climate, and (B) at the middle and (C) end of the century, both as projected under the Representative Concentrated Pathway 8.5 emission scenario. Modeling methods follow Davis et al. (2017).

1993), and if burned before reaching reproductive age, young forests may be subject to shifts from forest to nonforest states or long periods of arrested succession and development (Enright et al. 2015). Reproductive traits, such as early development in serotinous conifers (Reilly et al. 2019) and resprouting of hardwood tree species, enhance forest resilience to high-severity fire (McCord et al. 2020). Regeneration in large patches of high-severity reburns may depend on long-distance seed dispersal facilitated by wind or animals (Donato et al. 2009) and is likely to favor more drought-tolerant species (Davis et al. 2018). Conditions for regeneration may be too harsh for survival or establishment following short-interval fire, but some shrubs species may facilitate establishment by promoting mycorrhizal associations and providing shade and mitigating desiccation (Fuchs et al. 2000).

Interactions between wind disturbance and insect and pathogen infestations are well documented in the assessment area. Pathogens and disease may predispose trees to tip-up or snapping in windstorms (Larson and Franklin 2010). Tall, old-growth trees may be particularly sensitive to snapping if weakened by stem and butt decay fungi. Outbreaks of Douglas-fir beetle are common within the first few years following wind events and generally affect small patches of forest consisting of a few to several trees. Larger trees (>30 cm diameter at breast height) in dense stands with a large proportion of Douglas-fir are most sensitive (Shaw et al. 2009).

Despite concern that insect outbreaks may exacerbate fire effects by altering fuel structure, prefire insect activity (e.g., mountain pine beetle) typically do not contribute to increased area burned, tree mortality, or remotely sensed metrics of fire severity (Agne et al. 2016, Hicke et al. 2012, Meigs et al. 2016, Reilly and Spies 2016). These findings are consistent with other studies in the Western United States (Bond et al. 2009, Donato et al. 2013, Hart et al. 2015, Harvey et al. 2013, Simard et al. 2011). However, increased fuel loading may affect other components of fire severity and effects, especially on soils. For example, Metz et al. (2011) found that sudden oak death only affected overstory mortality in areas that had recently been invaded. However, substrate and soil burn severity increased in areas where dead trees had started falling and increased the volume of dead and downed wood.

Invasive plant species may also interact with abiotic disturbances, particularly fire. For example, Scotch broom facilitates fire spread, sprouts after fire, and creates seed banks that contribute to postfire germination. A similar species, gorse (*Ulex europaeus* L.) was implicated as a major driver of a fast-moving fire that burned the city of Bandon in the Oregon Coast Range in the 1930s (Isaac 1940). Invasive annual grasses (e.g. cheatgrass [*Bromus tectorum* L.]), ventenata (*Ventenata dubia* [Leers] Coss.) are potential threats to dry forest and nonforest vegetation types by posing a competitive threat to native vegetation for early-season soil moisture and increasing the frequency of fire (Kerns et al. 2020). False brome (*Brachypodium sylvaticum* [Huds.] P. Beauv.), another species of invasive grass, which is prominent in moist forests of the Pacific Northwest, may inhibit fire spread under moderate fire weather conditions (Poulos and Roy 2015). Poulos and Roy (2015) found that high-severity prescribed fire may help control false brome, but low-severity fire may increase its cover.

Simulated Vegetation Response to Future Climate Change

Several types of simulation models can be used to project vegetation responses to potential future climate scenarios, and each model has its own unique set of assumptions, strengths, and weaknesses (see Peterson et al. 2014b). A key utility of models is that they allow explorations of complex interactions among the many parts of an ecosystem. However, given the simplifying assumptions in models, the best use of models may be to understand variability in the magnitude of climate change effects, as opposed to predicting specific outcomes (Jackson et al. 2009, Littell et al. 2011). In essence, the model is calibrated to project a baseline of historical conditions against which future projected changes are compared.

The MC2 dynamic global vegetation model (Bachelet et al. 2001, Conklin et al. 2016, Daly et al. 2000) was run for the CMWAP assessment area. The MC2 model simulates biogeographic patterns of vegetation, biogeochemistry, and fire across broad spatial scales over long time periods. MC2 represents the landscape as a grid and runs on a monthly time step. The model is driven by long-term climate data output from global climate models (GCMs). MC2 outputs include vegetation distribution, fire effects, and ecosystem conditions, including various ecosystem carbon pools and water balance information.

MC2 does not simulate individual species growing in a particular region. Instead, vegetation is represented in terms of potential plant functional types (table 5.1), which are further grouped in major biomes. However, simulations are calibrated with region-specific data, and MC2 output of plant functional types can be crosswalked with vegetation zones and species distributions during analysis and interpretation.

MC2 output describes long-term patterns in the relationships among climate, potential natural vegetation, and fire. The model also includes links between climatic factors and particular aspects of plant functional types. Even where the simulated climate-vegetation-fire relationships may not necessarily hold under a future climate, the model still serves as a framework that identifies how climate is likely to change in ways that are most influential for vegetation. Because MC2 represents vegetation in terms of functional types, it may not project any change in some areas. However, that does not preclude climate change affecting vegetation, and we can use existing knowledge to assess which potential changes may occur.

Methods

MC2 was used to simulate potential changes in vegetation types in the CMWAP assessment area at a 30 arc-second spatial resolution (~800-m pixels) from 1895 to 2100. The historical portion of the simulation (1895–2012) was driven with parameter-elevation regressions on independent slopes model (PRISM) climate data (Daly et al. 2008), and an ensemble of future simulations was driven with the National Aeronautics and Space Administration's earth exchange downscaled climate projects (NEX-DCP30) dataset, as described further below. We synthesized soils data from the best available regional soil surveys and converted data to a format required by MC2.

For this assessment, we calibrated MC2 for Oregon and Washington. Simulating a spatial extent larger than the limits of the CMWAP assessment area allowed model calibration for a broader range of vegetation types than those that currently exist in the assessment area. MC2 was calibrated for the historical period (1895–2012) using a structured approach (Kim et al. 2018).

First, we created a calibration sample by sampling every fifth grid cell along latitude and longitude in the 30 arc-second spatial grid. We then calibrated the MC2 productivity algorithm by comparing the simulation output for the calibration sample with moderate resolution imaging spectroradiometer (MODIS) net primary production data (Zhao and Running 2010). We adjusted thresholds in its biogeography algorithm by comparing the simulation output for the calibration sample with a map of potential vegetation zones. We adjusted and calibrated the MC2 fire parameters by comparing the simulated fire patterns for the calibration sample with the fire-return interval and severity data from LANDFIRE (Rollins 2009). Fire suppression was not simulated. Once calibration was complete, we ran the simulation at full resolution for 1895–2012 using PRISM climate data.

MC2 simulations of future vegetation dynamics were driven with climate data from NASA's NEX-DCP30 dataset (Thrasher et al. 2013). The NEX-DCP30 dataset comprises outputs from 31 GCMs used in the coupled model intercomparison project phase 5 (CMIP5) (Taylor et al. 2012), downscaled from each GCM's coarse spatial resolution to 30 arc-second (~800 m) resolution for the conterminous United States. NEX-DCP30 includes climate projections for the future scenarios RCP 4.5 and RCP 8.5.

RCPs describe scenarios of emissions and land use, based on consistent scenarios representative of current literature (van Vuuren et al. 2011). For this study, we selected RCP 8.5, which represents a rapidly warming scenario without any effective climate change mitigation activities, leading to about 1,370 parts per million (ppm) CO_2 (Riahi et al. 2011) and a 3.7 °C increase in global mean surface temperature by the end of the 21^{st} century (Stocker et al. 2013). We selected RCP 8.5 because it represents a "business as usual" or "worst case" scenario, an important benchmark for decision making. The likelihood of a particular RCP being realized is unknown, and multiple plausible scenarios could give rise to any single endpoint. However, current global emissions are consistent with the RCP 8.5 trajectory.

MC2 simulations were run from 1950 to 2100 with 28 GCMs for which vapor pressure deficit data were available. The 28-member ensemble of simulations is useful for capturing the range of variability and uncertainty arising from GCMs and to obtain the most robust average values. We used the ensemble of simulations to quantify the degree of agreement in their future vegetation projections. To simplify display here, we selected simulations driven by five GCMs and focus on their outputs.

The five GCMs were selected to avoid the poorest performing models for the Pacific Northwest, as ranked by Rupp et al. (2013). We use the same five illustrative models as in chapter 2 to show a range of MC2 output for specific variables (table 2.2): “mean” CESM1(CAM5) (CESM1 hereafter); “hot-wet” CanESM2; “hot” BNU-ESM; “hot-dry” MIROC-ESM-CHEM (MIROC hereafter); and “warm” MRI-CGCM3 (MRI hereafter). BNU-ESM may overestimate winter precipitation because of data processing errors, although it is not a particularly “wet” outlier GCM in the 28-member ensemble, even with this error (see chapter 2).

MC2 Output

Vegetation—

MC2 consistently projected vegetation type changes (across all 28 climate projections) at higher elevations along the Cascade crest (fig. 5.12). The agreement among the 28 climate projections was similar at mid-century and the end of the century for changes in vegetation type. There was less agreement for changes in plant biomes (fig. 5.12). High agreement for biome changes occurred at only a few of the high-elevation areas along the Cascade crest, and in the eastern most portion of the CRGNSA at mid-century. Agreement for biome change was primarily low for the end of the century except for a few areas at the highest elevations of the Cascade crest. There was moderate to high agreement among models projecting forest expansion at high elevations along the Cascade crest, and especially on Mount Hood (fig. 5.13).

Except for low-elevation areas in the drier, eastern part of the CRGNSA, most of the assessment area was projected to have increased productivity by the end of the 21st century (fig. 5.14). Projections suggested the largest increases in productivity will occur at higher elevation along the Cascade crest. Cold temperatures, a short growing season, and late season snowpack currently limit productivity at high elevations. Thus, projected increases in productivity are likely driven by warming temperatures and a longer growing season. However, MC2 does not model the potential effects of summer drought well. In the model, although productivity shuts down when water is limited, complex plant responses (e.g., branch death, biomass loss, mortality, and vulnerability to insects and disease) are not modeled. Thus, summer drought and climatic water deficits may offset projected gains in productivity and exacerbate growth losses in some species. Overestimation of winter precipitation in the BNU-ESM scenario may lead to overestimation of vegetation productivity by MC2. Increases in productivity were lowest when the simulation was driven with the hot-dry MIROC climate projection.

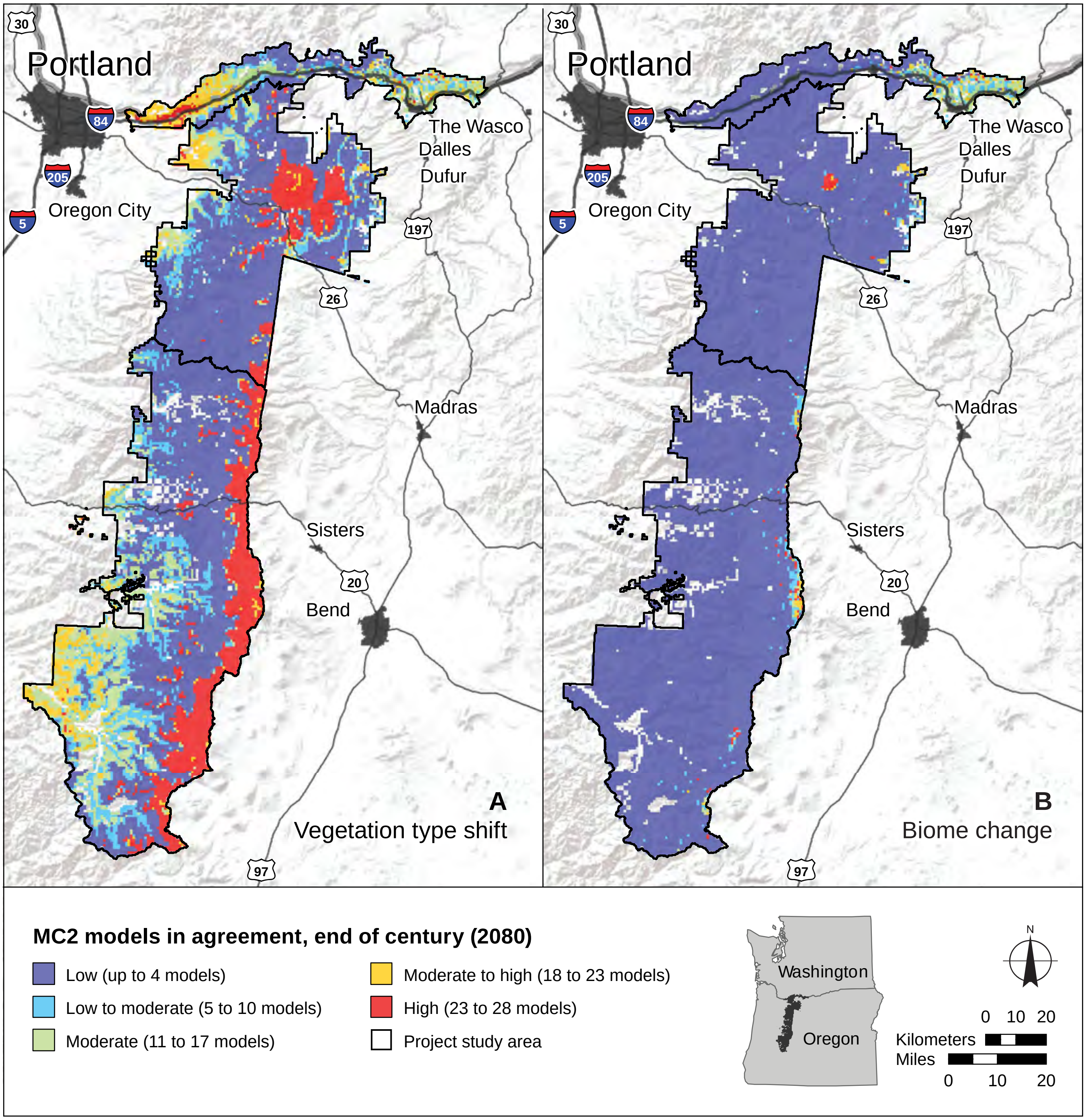

Figure 5.12—MC2 model agreement (among 28 climate scenarios) at the end of the century (2080) for (A) simulated change in vegetation type and (B) simulated change in biome (e.g., forest to woodland or shrubland to grassland).

Projected modal (most often occurring) vegetation types for the historical period, and middle and end of the 21st century are shown for five different future climate projections in figures 5.15 through 5.19, and the proportion of the landscape in different vegetation types for the historical period and end of the century are shown in figure 5.20. See table 5.1 for approximate crosswalks between potential

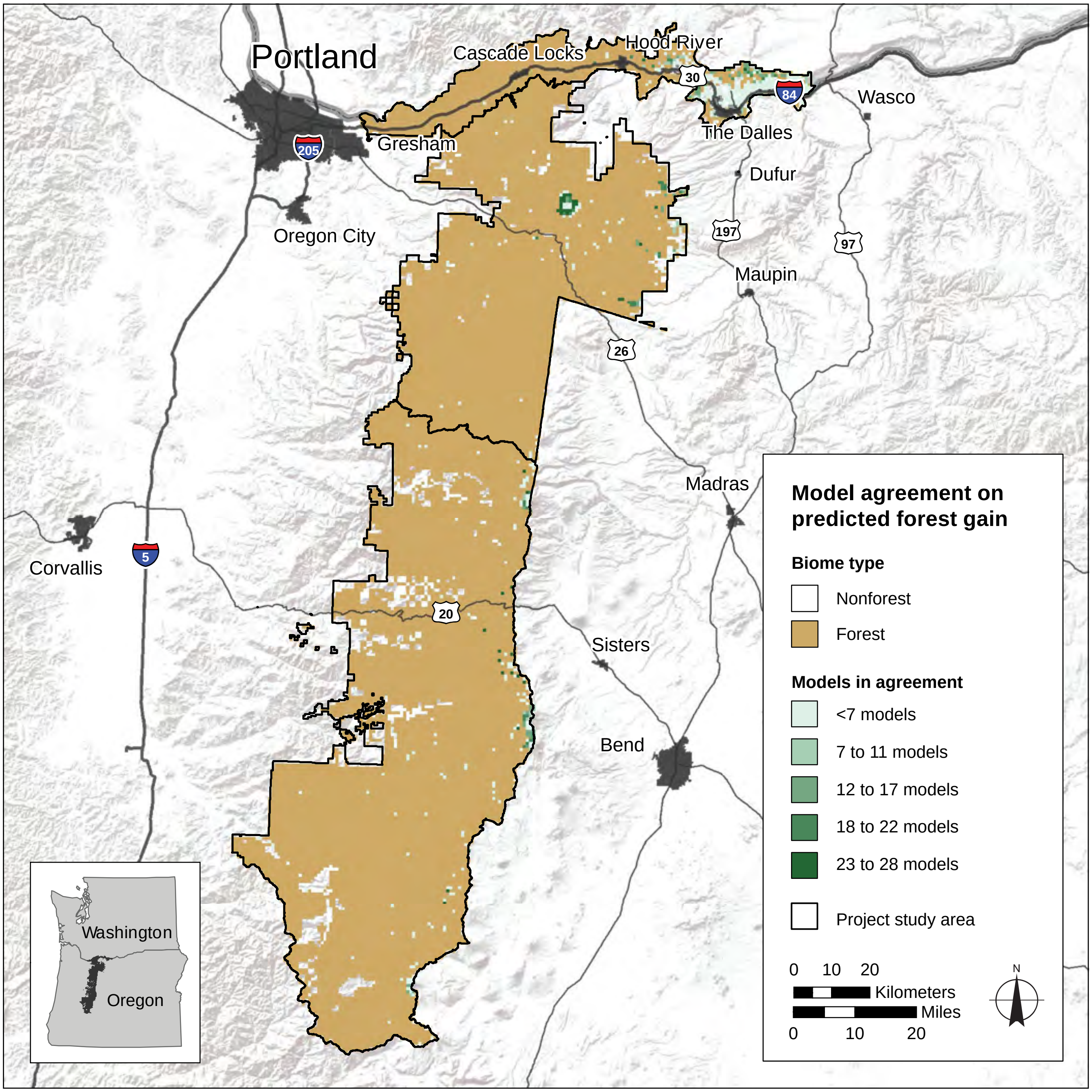

Figure 5.13—MC2 model agreement (among 28 climate scenarios) at the end of the century (2080) for projected forest gain.

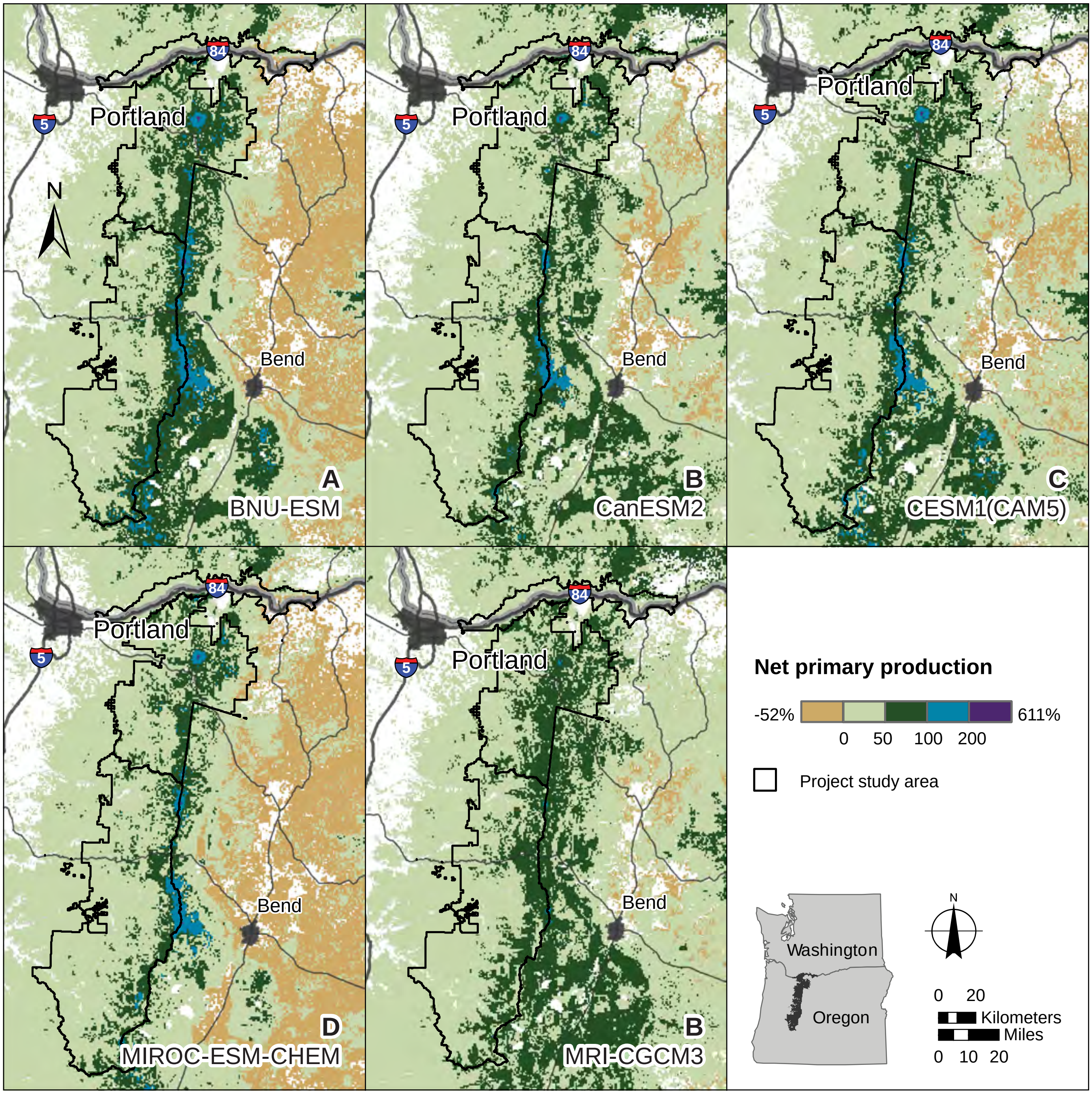

Figure 5.14—Percentage change in net primary production, as simulated by MC2 for the end of the century under five future climate scenarios (from five global climate models). The CESM1(CAM5) model is a top performer for the Pacific Northwest, with output similar to the model ensemble mean. CanESM2 represents the “hot-wet” extreme, BNU-ESM “hot,” MIROC-ESM-CHEM “hot-dry,” and MRI-CGCM3 “warm” (less warming than the hot extremes).

vegetation types (figs. 5.1 through 5.4) and MC2 vegetation types. Changes in MC2 vegetation types in figures 5.15 through 5.19 indicate that the climate will no longer be suitable for many current potential vegetation types and that shifts in species composition and abundance are likely. However, MC2 does not effectively simulate resilience of mature trees. Therefore, changes in species composition and abundance will likely be more gradual than suggested by simulations because of the longevity of many tree species and high tolerance of mature trees to climatic variation (Lloret et al. 2012), as well as the potential for acclimation of some species though phenotypic plasticity (Kozlowski and Pallardy 2002). Disturbances, such as fire, will likely be the main mechanisms that initiate large-scale compositional change.

Projections for moist coniferous forests, which historically made up about 80 percent of the assessment area, varied among the simulations driven with five selected GCMs. Only the warm climate projection (MRI) resulted in increases in moist coniferous forests, which occurred at higher elevations and replaced subalpine forests (fig. 5.20). Simulations under the other four climate projections suggested losses of moist coniferous forests, which primarily transitioned to warm mixed forest (fig. 5.20), particularly at lower elevations in the western portion of the assessment area (figs. 5.15 through 5.18). Under the hot-wet scenario (CanESM2), MC2 projected loss of almost half of the moist coniferous forest by the end of the century, whereas under the hot (BNU-ESM) and the hot-dry (MIROC) scenarios, MC2 projected about 25 percent loss of this vegetation type.

Under all five climate projections, MC2 projected large losses of climatically suitable habitat for subalpine forest along the Cascade crest. Some scenarios suggest the potential for small refugial areas of subalpine forest at the highest elevations, but all scenarios suggest that subalpine forests (currently 11 percent of the assessment area) will make up <1 percent of the assessment area by the end of the century (fig. 5.20). All projections suggest that areas of subalpine forest will shift to moist coniferous forest (fig. 5.20). This result suggests that species from mid-elevation moist forests, such as Pacific silver fir and noble fir, will likely become more competitive in high-elevation environments.

MC2 projected an expansion of warm mixed forest in the lower elevation, western portion of the assessment area under all but one future climate projection (MRI), with greater eastward expansion toward the Cascade crest between mid-century and the end of the century. Under historical climate, this type was not projected to occur in the assessment area but is currently found in a strip along the coast from southern Oregon to northern Washington that is currently dominated by the Sitka spruce and moist western hemlock vegetation zones. The expansion of the warm mixed forest type replaces the currently dominant moist coniferous forest.

Four of the five selected simulation results suggest that subtropical mixed forests will expand into the southwestern portion of the assessment area, as well as along the Columbia River in the CRGNSA by the end of the century. Subtropical mixed forests are projected for the historical period only along a small portion of the southern coast of Oregon that is currently dominated by the Sitka spruce and moist western hemlock vegetation zones. Under the hot (BNU) and the hot-dry (MIROC) scenarios, MC2 projected that 7 percent of the assessment area will transition from moist coniferous forest to subtropical mixed forest, whereas under the average (CESM) and the hot-wet (CAN) scenarios, the model projected that this vegetation type will make up less than 3 percent of the assessment area. The simulated shift to the subtropical mixed forest type is a response to increases in average monthly

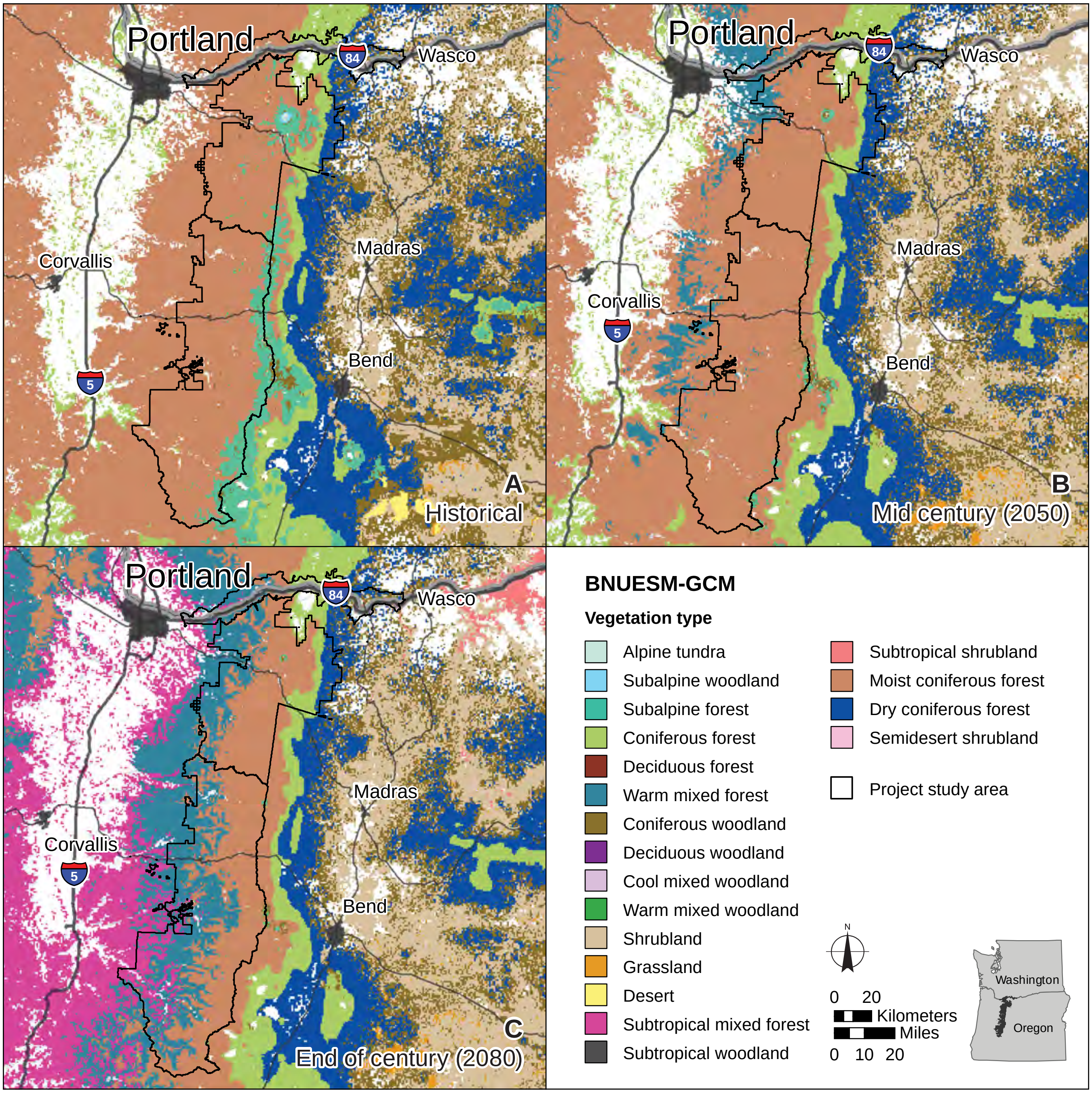

Figure 5.15—Vegetation types for the Columbia River Gorge, Mount Hood, and Willamette National Forests Adaptation Partnership assessment area for the historical period, mid century and end of century, as simulated by MC2 under the BNU-ESM global climate model (GCM) for the Representative Concentration Pathway 8.5 emission scenario. This model projects changes in temperature and precipitation that represent the “hot” extreme of higher performing models for the Pacific Northwest (Rupp et al. 2013).

temperatures and a loss of winter frosts. Thus, the expansion of this type was lowest under the GCM with the least warming (MRI) (fig. 5.19), and greatest for the GCMs with the most warming, including BNU-ESM (fig. 5.15), CanESM2 (fig. 5.16), and MIROC (fig. 5.18).

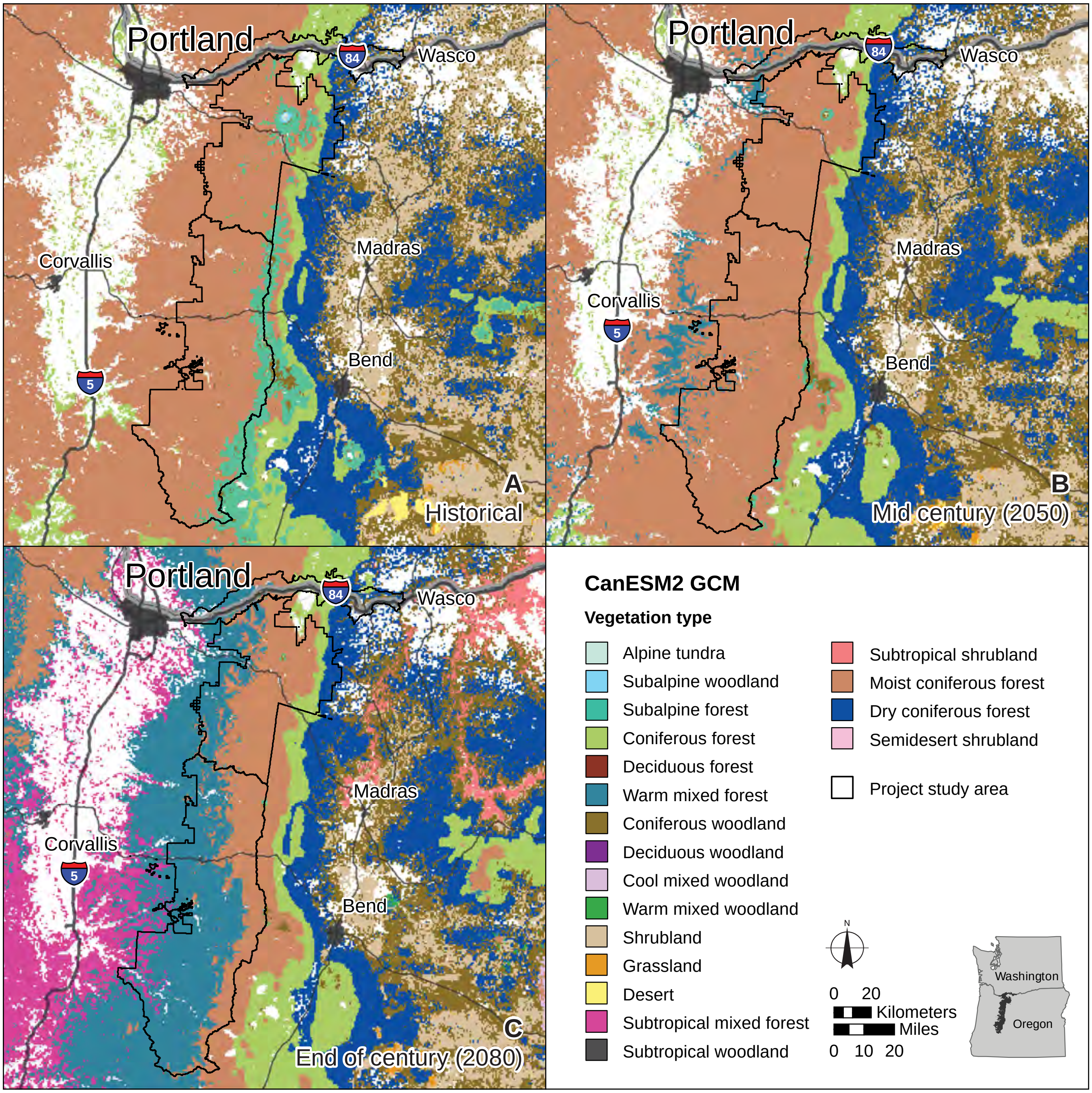

Figure 5.16—Vegetation types for the Columbia River Gorge, Mount Hood, and Willamette National Forests Adaptation Partnership assessment area for the (A) historical period, (B) mid century, and (C) end of century, as simulated by MC2 under the CanESM2 global climate model (GCM) for the Representative Concentration Pathway 8.5 emission scenario. This model projects changes in temperature and precipitation that represent the "hot-wet" extreme of higher performing models for the Pacific Northwest (Rupp et al. 2013).

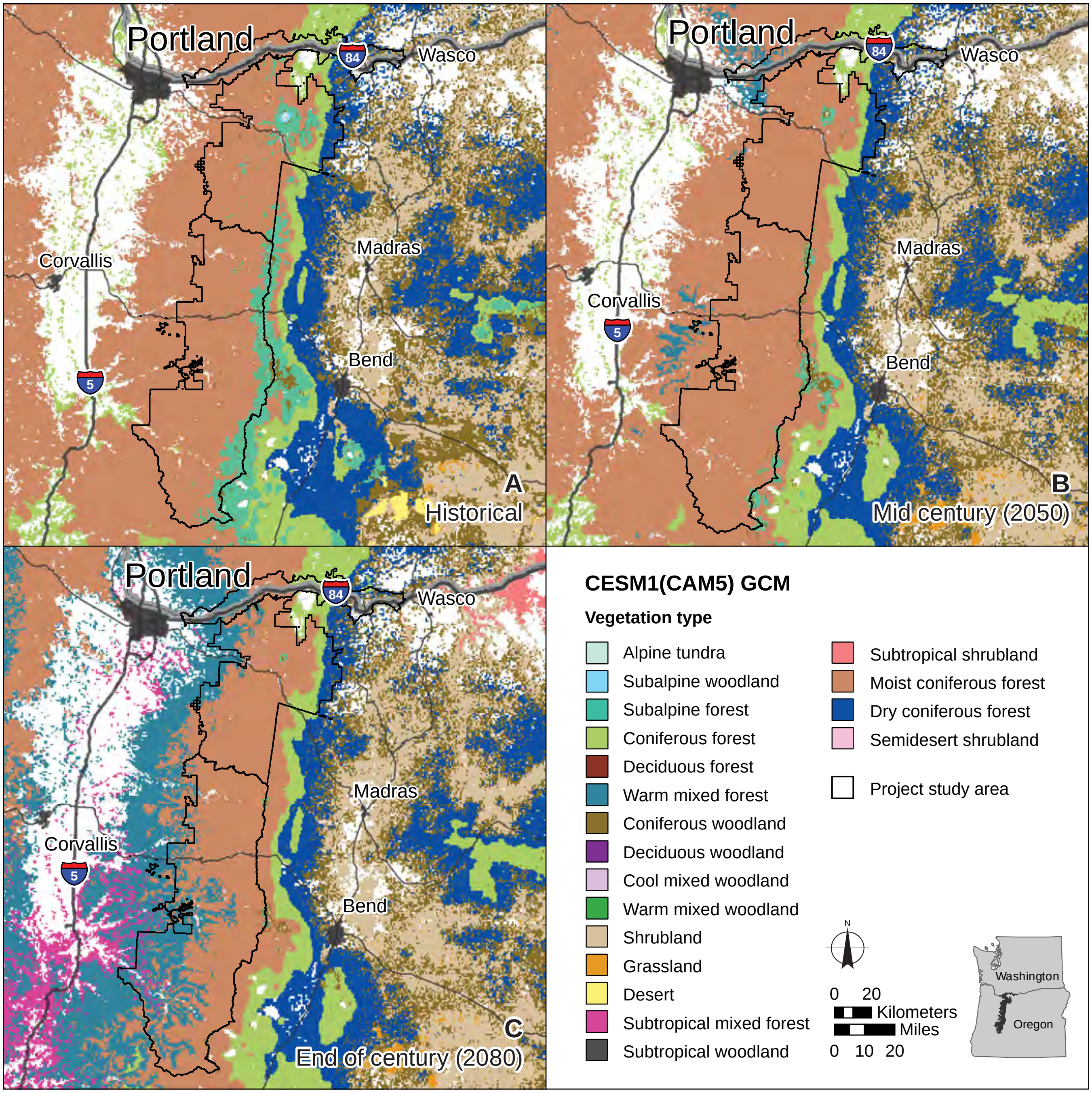

Figure 5.17—Vegetation types for the Columbia River Gorge, Mount Hood, and Willamette National Forests Adaptation Partnership assessment area for the (A) historical period, (B) mid century, and (C) end of century, as simulated by MC2 under the CESM1(CAM5) global climate model (GCM) for the Representative Concentration Pathway 8.5 emission scenario. This model is a highly ranked model for the Pacific Northwest (Rupp et al. 2013), with projected changes in temperature and precipitation similar to the ensemble mean (“average/best scenario”).

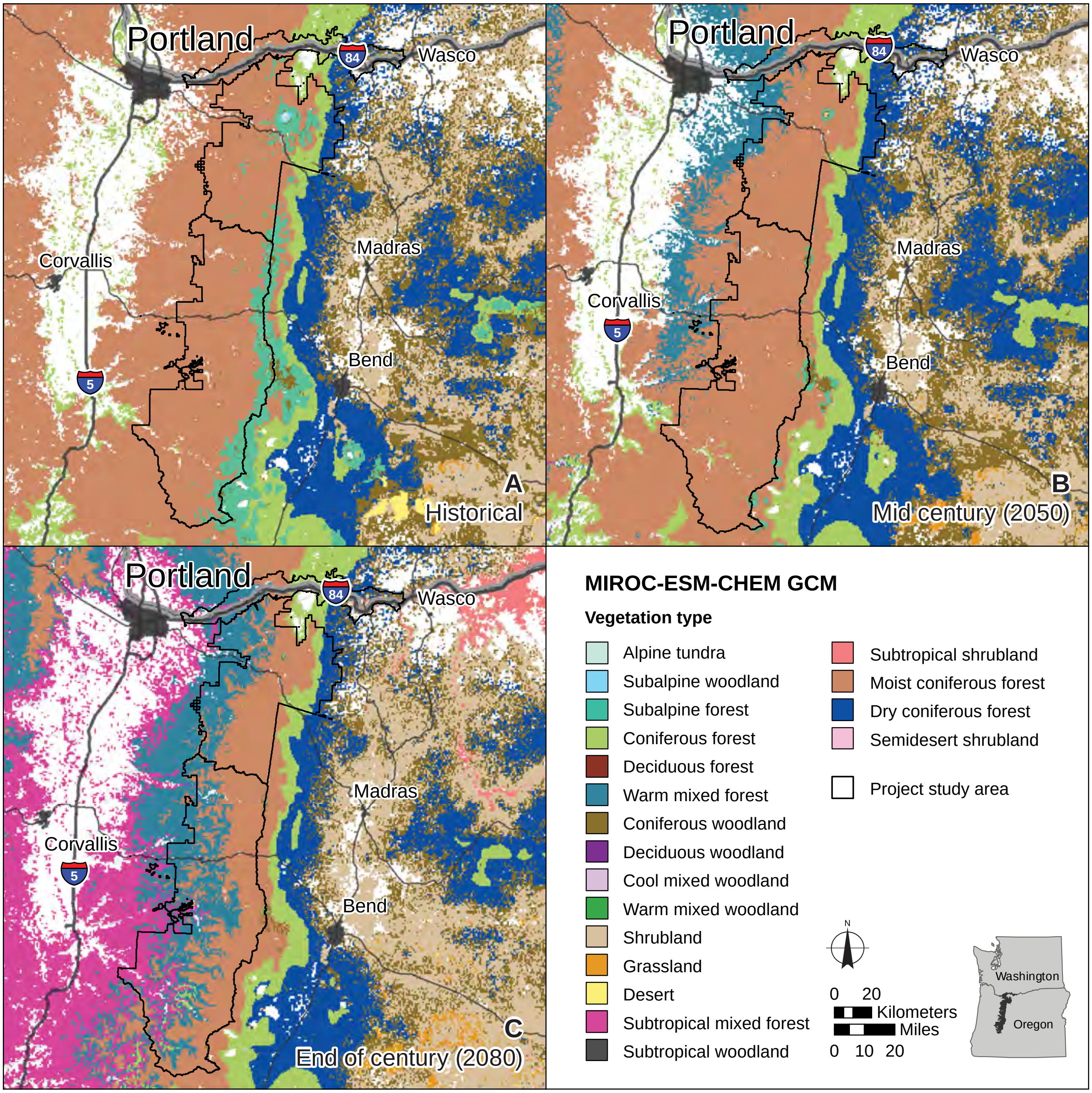

Figure 5.18—Vegetation types for the Columbia River Gorge, Mount Hood, and Willamette National Forests Adaptation Partnership assessment area for the (A) historical period, (B) mid century, and (C) end of century, as simulated by MC2 under the MIROC-EMS-CHEM global climate model (GCM) for the Representative Concentration Pathway 8.5 emission scenario. This model has projected changes in temperature and precipitation that represent the “hot-dry” extreme of higher performing models for the Pacific Northwest (Rupp et al. 2013).

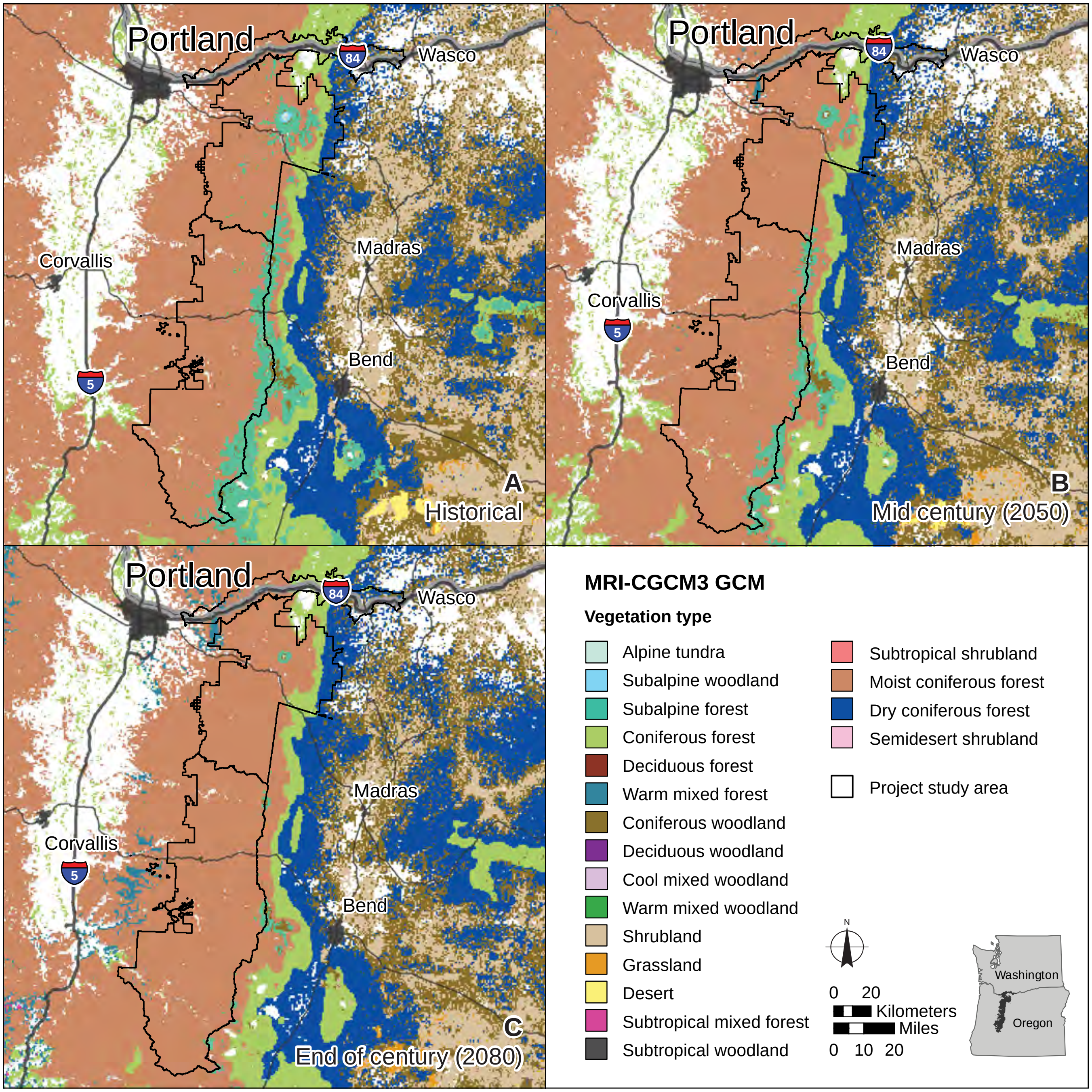

Figure 5.19—Vegetation types for the Columbia River Gorge, Mount Hood, and Willamette National Forests Adaptation Partnership assessment area for the (A) historical period, (B) mid century, and (C) end of century, as simulated by MC2 under the MRI-CGCM3 global climate model (GCM) for Representative Concentration Pathway 8.5 emission scenario. This model has projected changes in temperature and precipitation that represent the "warm" (less warming than hot) but not wet extreme of higher performing models for the Pacific Northwest (Rupp et al. 2013).

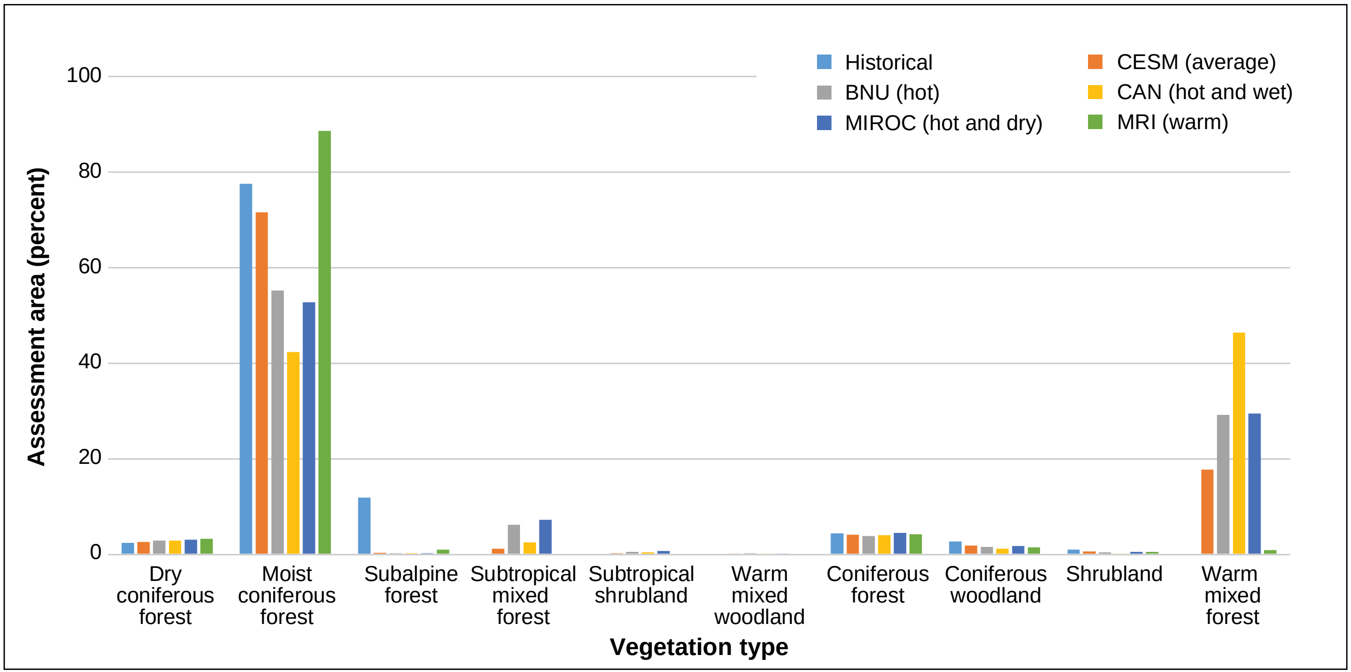

Figure 5.20—Proportion of different vegetation types for the Columbia River Gorge, Mount Hood, and Willamette National Forests Adaptation Partnership assessment area for the (A) historical period and (B) end of century, as simulated by MC2 under five global climate models for the Representative Concentration Pathway 8.5 emission scenario. Differences between the historical period and mid-century were minimal and thus are not shown.

Coniferous forests, which occur mostly in the northeastern part of the assessment area, are primarily projected to decrease slightly, transitioning to dry coniferous forests. Only under the hot-dry scenario (MIROC) did the model project a slight increase in coniferous forests, mainly in the northeastern part of the assessment area (where they may replace moist coniferous forest), and a small, isolated area in the southwestern part of the assessment area (fig. 5.18).

Dry coniferous forests are projected to expand under all scenarios but still generally make up <3 percent of the assessment area. This vegetation type occurs primarily in the northeastern part of the assessment area in MTH, where it appears mostly stable, and in CRGNSA, where it is projected to replace some coniferous woodland and shrublands. Both coniferous woodlands and shrublands are projected to decrease slightly and remain a very minor component of the assessment area across climate projections, existing primarily in the eastern portion of CRGNSA.

Wildfire—

We examined simulated fire occurrence by computing mean fire-return interval (MFRI) for the assessment area (fig. 5.21). MC2 simulates long-term fire regimes and their relationship to simulated potential natural vegetation. Specific historical fires are not simulated. Therefore, simulated historical MFRIs may not closely match empirical observations, and graphs should be interpreted in terms of relative changes.

Overall, MC2 simulated decreased MFRI for mid-century and the end of the century compared to the historical (1970–1999) time (fig. 5.21). Thus, fires are expected to be more frequent in the future, as increased vegetation productivity drives increases in fuels. In most cases, the greatest decreases in MFRI occur by mid-century. Simulated MFRIs for warm mixed forest were highly variable, likely

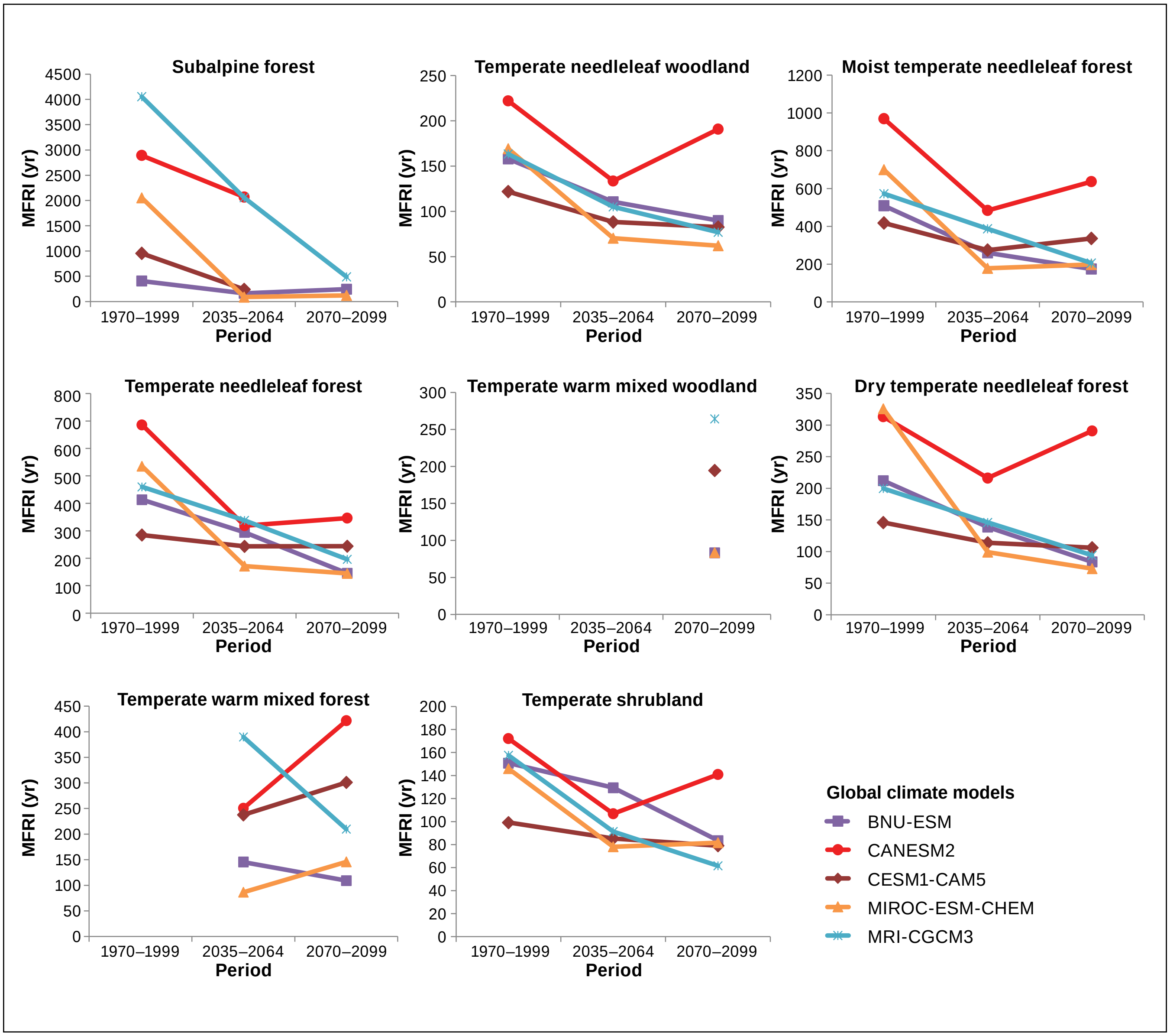

Figure 5.21—Projected mean fire-return interval (MRFI) in years for the historical (1970–1999), mid-century (2035–2064), and end-of-century (2070–2099) time periods for relevant MC2 vegetation types and global climate models (GCM) for the Representative Concentration Pathway 8.5 emission scenario. Note differences in scale for the y-axes.

owing to the limited extent of this vegetation type. In most cases, projections under the hot-wet CanESM2 GCM had longer MFRIs than the other GCMs, perhaps because small increases in summer precipitation may increase fuel biomass. Decreases in MFRI were greatest under the hot-dry MIROC and hot BNU-ESM GCMs, where increases in vegetation productivity in spring and fall resulted in more fuels, but fuels dried out more intensely in summer.

We assessed simulated fire severity by examining projections of mass of live carbon lost from fire from MC2 (fig. 5.22). Carbon lost from fire was generally

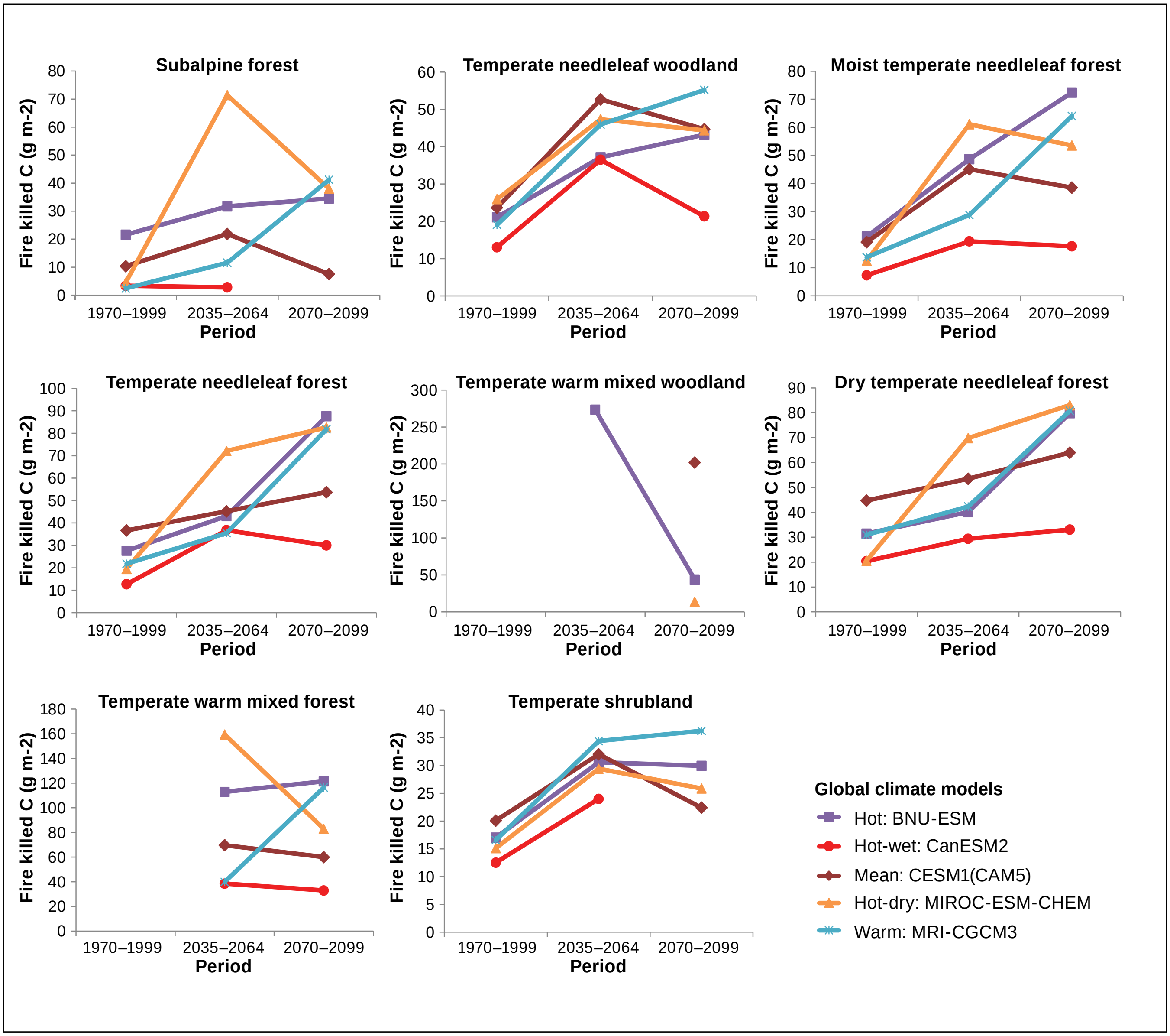

Figure 5.22—Projected fire severity (fire-killed carbon in g m^{-2}) for the historical (1970–1999), mid-century (2035–2064), and end-of-century (2070–2099) time periods for relevant MC2 vegetation types and global climate models (GCM) for the Representative Concentration Pathway 8.5 emission scenario. Note differences in scale for the y-axes.

projected to increase compared to the historical period, but it often leveled off or decreased by the end of the century as vegetation types converted to less productive types (fig. 5.22). Increases in fire severity were generally greatest under the hot BNU-ESM, hot-dry MIROC, and warm MRI-CGCM3 GCMs.

Changes in MFRI and fire severity projected by MC2 can be explained (1) by seasonal changes in temperature and precipitation projected by each of the GCMs, as these changes drive fuel moisture content, plant productivity, and aboveground biomass, and (2) by the model's complex interplay between these factors for each vegetation type and GCM. Fire occurrence is primarily a function of fuel moisture in MC2 (fuels must be dry enough to burn). Fire severity (live carbon killed by fire) is related to standing biomass or productivity. The amount of fuel or biomass may increase for some vegetation types in the future with increases in productivity (fig. 5.14). Given that MC2 does not model the effects of summer drought on productivity, increases in fire severity may be overestimated by MC2. However, more fuels could also lead to higher fire severity. In any case, more fuels under a hotter future climate resulted in MC2 simulating longer flame lengths and higher incidence of canopy fires.

Vulnerability Assessment for Vegetation Types

This section describes the potential effects of climate change on four broad vegetation groups in the CMWAP assessment area—low-elevation moist forests, high-elevation cold forests, dry forests, and special habitats (e.g., meadows, shrublands, woodlands). We discuss the geographic variability in potential vegetation responses and vulnerability to change within each of the vegetation groups to highlight how climate change effects may differ among units within the assessment area. We rely on multiple lines of evidence to assess vulnerability, including current knowledge of past vegetation response to climate change from paleoecological studies, recent sensitivity and ongoing vegetation response to climatic variability and disturbance, and climate projections as interpreted through simulations of future dynamics with MC2.

The cumulative effects of climate change will ultimately be manifest in shifts in species distributions and ranges. These effects will also depend on connectivity within populations where species in smaller, more isolated populations will likely be more vulnerable to local extirpation. Range expansion occurs through migration and colonization at the outer limits, or "leading edge," of a species distribution, where climate is becoming more favorable. Range expansion at the leading edge is controlled by fecundity and dispersal (Thuller et al. 2008). Species that produce more seeds or other propagules and have a greater ability to disperse will have greater potential to track climate change than those with poor dispersal ability.

At the lower limits or "trailing edge" of a species distribution, where climate is becoming less favorable, range contraction and progressive isolation will occur through local extirpation. Range contraction is related to the ability of a species to persist in locations that experience less change than the surrounding landscape. Individuals at the trailing edge may thus play an important role in the maintenance of genetic diversity for some species (Hampe and Petit 2005). Although local extirpation may occur throughout the range of species, small, isolated populations at the trailing edge may be particularly vulnerable if the climate changes rapidly (Davis and Shaw 2001).

Moist Forests

Moist forests in the CMWAP assessment area will likely continue to be dominated by Douglas-fir in a changing climate. Paleoecological evidence suggests that during warm and dry periods of the past, Douglas-fir was favored in moist forests, and western hemlock decreased in abundance (Long et al. 1998, Minckley and Long 2016). Fire- and drought-intolerant species, including western hemlock, Pacific silver fir, and western redcedar, are likely to decrease in abundance, which could reduce stand density, basal area, and the degree of canopy layering. These species may be more sensitive to insects and pathogens on drier sites because of drought stress (Chmura et al. 2011). These species may persist in the cooler portions of their range (Monleon et al. 2015), and they may become more restricted to climate change refugia (e.g., moist or cool landscape settings) (Morelli et al. 2016). Pacific yew (*Taxus brevifolia* Nutt.), one of the species in the assessment area that has experienced relatively high mortality (Monleon et al. 2015), may be particularly sensitive to climate change and dependent on refugia.

Hardwoods are likely to be favored by increasing fire frequency in lower elevation forests in the western part of the assessment area; these areas are projected to shift toward a mixed forest type with more hardwood species. The ability of hardwoods to resprout makes them resilient to fire, even at short intervals (McCord et al. 2020). However, several species of hardwoods may be increasingly sensitive and exposed to insects and pathogens in the future. At lower elevations, larger Oregon white oak trees are sensitive to western oak looper (*Lambdina fiscellaria somniaria* [Hulst]) and multiple species of root and butt rots (e.g., caused by *Armillaria* spp., *Inonotus dryadeus* [Pers.: Fr.] Murr.). Leafy mistletoes, including Pacific mistletoe (*Phoradendron villosum* [Nutt.] Nutt. ex Engelm.), usually have little impact on healthy trees. Decline in bigleaf maple (*Acer macrophyllum* Pursh) is being investigated, but a specific mechanism has yet to be identified. Pacific madrone is susceptible to multiple fungal foliage diseases, twig dieback, trunk cankers, and root diseases (Bennett and Shaw 2008, Maloney et al. 2004).

Although not currently present in the assessment area, sudden oak death (caused by *Phytophthora ramorum* Werres et al.) may be a threat to multiple species of trees and shrubs in the future. This invasive pathogen can spread through air, water, and infected plant material (Peterson et al. 2014b, Rizzo and Garbelloto 2003). Although it does not affect Oregon white oak, other hardwood species (e.g., madrone, bigleaf maple) and several species of shrubs (e.g., *Rhododendron* spp.) are susceptible. Warm, wet winters intensify risk of infection and increase exposure (Haas et al. 2015), and the area affected by sudden oak death is projected to increase tenfold by the 2030s under warmer and wetter conditions (Meentemeyer et al. 2011).

MC2 projected increased productivity in moist forest types in the assessment area with warming climate because of increased growing season length, adequate moisture levels, and increased atmospheric CO_2. These MC2 results agree with a study by Latta et al. (2010) that found annual growth increases of 2 to 7 percent in moist vegetation zones west of the Cascade Mountains. However, moisture may become limiting for tree establishment and growth on drier sites with increased evapotranspiration and summer water deficit (Restaino et al. 2016). Thus, growth of some moist forest sites at higher elevations may be sensitive to shifts from energy limitation (limited by temperature and length of the growing season) to water limitation (McKenzie et al. 2001). Warming may cause earlier budburst in some portions of the range of Douglas-fir, but reduced chilling may expose this species to later budburst in the southern portion of its range (Harrington and Gould 2015). Earlier growth in northern and higher elevation portions of the range of Douglas-fir may lead to earlier growth initiation, but reduced chilling in the southern and lower elevation portions of its range are likely to lead to delayed growth initiation (Ford et al. 2016).

Species that dominate middle elevations, such as noble fir and Pacific silver fir, may also be sensitive to replacement by species from lower elevations, primarily Douglas-fir. Fire will likely catalyze shifts of Douglas-fir toward higher elevations. Noble fir and Pacific silver fir, which currently occupy the higher elevation moist coniferous forests, may find suitable habitat in places where they can migrate to higher elevations (i.e., large continuous areas near the Cascade crest). However, these species may be especially sensitive to extirpation where they currently exist as small, isolated populations on upper elevation ridges and peaks toward the southern extent of their range.

Fire frequency is projected to increase in moist forests, and exposure to high-severity fire could increase as fuels become drier with greater summer moisture deficits. Although recent fires (1984–2019) have been relatively small, there is historical precedent for the large wildfires in 2020 from early 20th century forest surveys (fig. 5.5). It is estimated that the Silverton Fire in the 1850s burned almost

400 000 ha stretching from the southern slopes of MTH to the northern portions of WIL east of Salem and Silverton, Oregon. Such events are historically associated with dry east winds that occur in the early fall (Cramer 1957). An increase in the frequency of dry, east-wind events and drier fuels could increase exposure to extremely large wildfires, but it is unknown if the frequency of dry, east winds will change under climate change. Paleoecological studies from other moist forest types in the Pacific Northwest provide evidence that extremely large fires have the potential to be a catalyst for rapid and widespread vegetation change (Bartlein et al. 1998, Crausbay et al. 2017, Marlon et al. 2009, Walsh et al. 2015, Whitlock 1992, Whitlock et al. 2008).

Cold Forests

Cold forests at high elevation will be affected by climate change both directly by temperature and indirectly by disturbances. Subalpine fir, mountain hemlock, and Engelmann spruce range from treeline to the upper distribution of moist forests, and whitebark pine is primarily near treeline. At treeline, regeneration and growth of these species are typically energy limited because of many months of snow cover and low temperatures. At the lower end of their distribution, regeneration and growth are often limited more by soil moisture than by energy. The effects of a warmer climate on subalpine species will differ considerably, depending on elevation and aspect (e.g., south aspect [warm, dry] versus north aspect [cool, wet]).

Although MC2 results and other modeling studies project that a warmer climate will cause a large reduction in subalpine species, this inference is based primarily on the assumption that these species require a cold climate (e.g., Crookston et al. 2010, Rehfeldt et al. 2006, Shafer et al. 2015). In fact, subalpine species typically regenerate successfully and grow faster in warmer, snow-free locations (Peterson and Peterson 2001, Peterson et al. 2002, Woodward et al. 1995). Projections of climate change effects for whitebark pine, which exists mostly near treeline, are distinct from those of other subalpine species. It has been severely stressed for decades, with extensive mortality from white pine blister rust, and may now experience additional stress from mountain pine beetle, which is expanding its historical range to higher elevations as the climate gets warmer (Case and Lawler 2016).

Two related factors will be critical for long-term projections of climate change effects in cold forests. First, less snowpack at high elevation may, over decades to centuries, facilitate regeneration and establishment of species that are currently common in the upper elevations of moist forests (especially noble fir and Pacific silver fir) and may be more competitive than cold-forest species (Briles et al. 2008, Walther et al. 2005). Second, if fire frequency and extent increase at high elevations, mortality of cold-forest species would be high because they have low fire resistance, especially in areas of continuous forest (as opposed to subalpine parkland) where fire spread would be more pervasive and fire severity higher (Cansler and McKenzie 2014). Establishment of cold-forest species is slow (Little et al. 1994), and regeneration of moist-forest species might be more competitive in a postfire environment. Therefore, it is likely that cold-forest species will be more sensitive to warming at their lower limits of elevation, whereas moist-forest species at their upper limits of elevation may expand (HilleRisLambers et al. 2015).

Although much attention has been focused on the movement of treeline in mountains, it has rarely fluctuated more than 100 m during the Holocene throughout North America (Rochefort et al. 1994). In contrast, tree density and proportion of trees and herbaceous or grass species in the forest-meadow mosaic (parkland) are a more dynamic component of subalpine ecosystem function, fluctuating considerably in response to decadal- to centennial-scale climatic variation (Klasner and Fagre 2002, Woodward et al. 1995) and to disturbance (Little et al. 1994). In fact, cold-forest species at treeline may be able to establish at higher elevations as snowpack decreases, assuming that sufficient soil is available.

Mountain hemlock is limited by summer drought in the southern portion of its range (Kemp-Jennings et al. 2021, Parsons 1972, Peterson and Peterson 2001), suggesting that noble fir, Pacific silver fir, and perhaps Douglas-fir (in moist forests and on warmer sites in high-elevation forests) could increase in abundance in the future. Paleoecological studies suggest that pines, Douglas-fir, white fir, and western redcedar replaced subalpine parklands in the Siskiyou Mountains during warmer and drier periods in the past (Briles et al. 2008). In addition to the fire effects mentioned above, fire could limit establishment in reburns, resulting in younger age cohorts and smaller tree sizes in the long term (Kerns et al. 2017).

Fire activity over the past century has been limited in high-elevation forests of the assessment area (fig. 5.6), although the 2020 wildfires did burn some high-elevation forests (fig. 5.7). Consistent with historical fire regimes, much of the area burned in high-elevation forests has included large patches of high-severity fire (Reilly et al 2017). Mountain hemlock forests appeared to be resilient to high-severity fire that occurred in the early 1990s (Acker et al. 2017), but little is known about regeneration patterns of this species following more recent fires. Less late-season snow may facilitate seedling establishment in the near future, but exposure to drier summers could limit seedling survival on drier sites (e.g., south aspects and convexities). As fire activity increases, populations of lodgepole pine that are serotinous may be able to expand across some high-elevation forests, although regeneration will require low snowpack during the first few years after fire. Even-aged stands may develop where local seed sources are available, and mixed-age stands may develop if establishment occurs over many years through long-distance dispersal of seeds.

Increased summer drought will have different effects on different insect and pathogen species at the lower end of current cold-forest distribution. In general, soil moisture stress will reduce overall vigor and growth of subalpine tree species (Peterson and Peterson 2001, Peterson et al. 2002). Williams and Liebhold (1995) projected decreases in the area defoliated by spruce budworm with increased temperature alone, but the area increased with higher temperature and precipitation. Periodic episodes of mountain pine beetle will continue and potentially increase in whitebark pine (as noted above), low-vigor lodgepole pine stands, and possibly western white pine. Recent mountain pine beetle epidemics in the Rocky Mountains and western Canada have been partly attributed to increasing temperatures releasing the insects from climatic constraints (mainly lethal winter cold) (Bentz et al. 2013). However, temperatures in this assessment area are rarely cold enough to constrain beetle populations. In addition, there is some evidence that white pine blister rust infection increases sensitivity to attack by mountain pine beetle (Six and Adams 2007), but host trees can be attacked regardless of blister rust severity infection.

Dry Forests

MC2 projected that dry coniferous forest and woodlands will maintain their current geographic distribution in the future. However, dry forests in the CMWAP assessment area are likely to experience increased exposure to fire and shifts in composition and structure. Halofsky et al. (2014) used MC2 to project future changes for the central eastern Cascades of Oregon and found that the area of dry mixed-conifer forest is expected to increase, whereas the area of moist mixed-conifer forest is expected to decrease. Given its tolerance to drought, ponderosa pine is likely to shift toward higher elevations and become more dominant at the expense of Douglas-fir, which is more sensitive to drought.

Tree growth will likely be reduced for dry forest species (Restaino et al 2016). Tree mortality may also increase in some locations because of the interacting effects of drought, wildfire, and insects. High stem density in fire-excluded stands decreases resistance of ponderosa pine to drought (Voelker et al. 2019). Spruce budworm may increase in response to higher temperature and precipitation and negatively affect Douglas-fir and grand fir (Williams and Liebhold 1995), thus favoring ponderosa pine.

Dry forests will likely experience more area burned and be affected by large patches of high-severity fire. Shifts from dry forest to woodlands or shrublands may occur in the driest portions of the current dry forest range, which may experience lower conifer regeneration or longer periods of establishment. Drought stress and large, high-severity fire patches may impede forest development by limiting establishment in some locations, especially at lower elevations (Dodson and Root 2013). Conversion to shrubland could occur with increasing frequency of short-interval, high-severity reburns; these events will likely kill more regenerating conifers and potential seed trees with each successive fire. Invasive annual grasses may facilitate higher fire frequency and outcompete native species for soil moisture.

Special Habitats

The CMWAP assessment area contains multiple special habitats that are geographically restricted but represent an important component of biodiversity. Many of these may include threatened, rare, and endangered species of plants (app. 5A).

Woodlands in the assessment area were historically dominated by either ponderosa pine or Oregon white oak and were maintained by relatively frequent fire; fire frequency of less than 10 years is required to prevent the development of shade-tolerant conifers (Agee 1993). Oregon white oak woodlands are found along the margins of the Willamette Valley and in CRGNSA, as well as on the east side of MTH, where they may also mix with ponderosa pine. Ponderosa pine woodlands are on the east side of MTH but also occur in the southern part of WIL on dry southwest aspects.

Many woodlands in the assessment area are currently declining and at risk of being lost because of encroachment of shade-tolerant conifers. Douglas-fir encroachment occurred in many white oak woodlands over the past 50 years with fire exclusion (Gilligan and Muir 2011). With more frequent fire in a warming climate, conifer encroachment could be reduced, favoring development of relatively open oak woodlands. However, conifer encroachment may increase sensitivity of mature oak trees to drought.

Nonnative annual grass species are a major component of understory vegetation in some woodlands. Establishment of nonnative species is often facilitated by wildfire and thinning treatments in areas where conifers have encroached in shrub-dominated oak systems (Perchemlides et al. 2008, Riegel et al. 1992). Thus, effects of fire exclusion and nonnative species may limit the capacity of oak woodlands to adapt to changing climate and disturbance regimes. Furthermore, loss of mature oaks with conifer encroachment in the absence of fire will reduce resilience to future fire and increase drought sensitivity because oak regenerates by seed.

Expansion of woodland types is likely with hotter and drier conditions in the future. MC2-projected expansion of woodland types in the CMWAP assessment area under several (mostly warmer and drier) climate scenarios; expansion of woodland types was most often at the expense of dry forest. Paleoecological studies suggest that Oregon white oak moved upslope in response to drought in the past in the Klamath Mountains (Mohr et al. 2000) and Trinity Mountains (Daniels et al. 2005) in northwest California. Oregon white oak expansion will likely depend on long-distance dispersal by vertebrates, although seed desiccation may limit germination on southern aspects (Fuchs et al. 2000). Long-distance dispersal and animal caching may be facilitated by shade provided by shrubs, which can reduce seed desiccation (Keyes et al. 2009).

Meadows—

Loss of meadows across high-elevation landscapes is consistent with the forest expansion projections from MC2. Warming, decreased snowpack, and increasing CO_2 may facilitate woody vegetation growth and increase sensitivity to meadow loss. Observed losses of subalpine meadows during the late 20th century are likely to continue and may be mediated through changes in snowpack (Zald et al. 2012).

The occurrence of large patches of high-severity fire may restore some aspects of meadow vegetation, depending on the persistence of native species following tree encroachment. However, Haugo and Halpern (2007) found that once trees move into meadows, they may alter soil properties and reduce the seed bank of native meadow species, thus impeding reversion to meadows. Fires may also increase exposure to invasions of nonnative plant species (e.g., *Hieracium* spp.). Meadow flora may persist in places where it can migrate upwards in elevation before establishment of colonizing woody species.

Riparian areas—

The primary effects of climate change on riparian areas in the assessment area will likely be mediated through disturbance. Increased flooding may occur in some riparian areas as a result of lower snowpack and increased intensity of winter precipitation events (Hamlet et al. 2013). Increased peak flows would affect erosion and sedimentation, which could, in turn, affect channel form and the fluvial dynamics of streams and their riparian zones (Capon et al. 2013). Fires are also likely to be a mechanism of change in riparian areas. Fires generally burn with lower severity in riparian areas of central Oregon (Halofsky and Hibbs 2008); thus, these areas may serve as sources of propagules for adjacent uplands following fire.

Riparian vegetation depends on the presence of flowing water. With climate change, summer streamflows may decrease because of earlier snowmelt and earlier runoff (Luce and Holden 2009, Safeeq et al. 2013, Stewart et al. 2005). Increasing temperature and evapotranspiration, as well as decreasing summer streamflows, may lead to drying and increased drought sensitivity in some riparian areas (Dwire and Mellmann-Brown 2017). Drying in riparian areas could decrease the extent of the riparian zone in some locations or result in shifts in riparian plant composition. Drier conditions and more frequent fire in riparian areas may favor upland-associated species (e.g., conifers) over those typically associated with riparian areas (e.g., deciduous hardwoods). However, riparian areas may serve as refugia for species dependent on high soil moisture, especially in topographically complex landscapes where cold air drainage may mitigate increases in temperature and reductions in soil moisture (Morelli et al. 2016). Changes in riparian plant species composition and reduced riparian extent could result in direct losses to the quantity and quality of ecological contributions of riparian vegetation, such as wildlife habitat, shade over streams, and buffer capacity for maintenance of water quality (Capon et al. 2013, Dwire and Mellmann-Brown 2017).

Nonnative species may also become more competitive in riparian areas with increased opportunities for invasion after disturbance (Catford et al. 2013). Riparian areas in the assessment area are particularly sensitive to invasion from Japanese knotweed (*Fallopia japonica* [Houtt.] Ronse Decr.). This species can grow and expand rapidly once established, forming dense, clonal patches that can produce copious amounts of seed that may then be transported downstream in floods. Japanese knotweed displaces regenerating trees and may have long-term effects on the composition and structure of riparian forests (Urgenson et al. 2009).

Wetlands and groundwater-dependent ecosystems—

Increased exposure to higher temperatures, reduced snowpack, increased evapotranspiration, and nonnative species may have significant effects on wetlands and groundwater-dependent ecosystems in the assessment area. Less water during summer would alter local hydrology, potentially reducing the duration and depth of standing water, and increasing water temperature in wetlands and groundwater-dependent systems (Lee et al. 2015). This could affect local distribution and abundance of plant species associated with these ecosystems (Dwire and Mellmann-Brown 2017) as well as aquatic fauna (especially amphibians).

Many wetlands are groundwater dependent, and snowpack is the main source of groundwater recharge in montane areas (Winograd et al. 1998). Reduced snowpack with climate change will likely decrease the length of time aquifer recharge can occur, potentially leading to faster runoff, less groundwater recharge, and less groundwater to support springs and groundwater-dependent wetlands (Dwire and Mellmann-Brown 2017). Some groundwater-dependent wetlands may decrease in size or completely dry out in summer. However, effects will vary depending on hydrogeologic setting (Drexler et al. 2013). Some groundwater resources may be less sensitive to climate change than surface water, depending on local and regional geology, and surrounding land and water use (Tague and Grant 2009). Slowly infiltrating precipitation that includes both rain and snow could recharge groundwater aquifers as effectively as rapid, seasonal snowmelt runoff (Dwire and Mellmann-Brown 2017).

Ephemeral wetlands at higher elevations are expected to be highly sensitive to a warmer climate; some ephemeral montane wetlands may disappear, and intermediate montane wetlands may become ephemeral (Lee et al. 2015). Some wetlands, especially those connected to deep groundwater sources (as opposed to surface water-fed wetlands), may experience earlier drawdown and reach their minimum water level earlier but without drying out (Lee et al. 2015). Wetlands at lower elevations will be vulnerable to increasing water demands, pressure for increased diversion or water development, and other land use activities that require water (Dwire and Mellmann-Brown 2017).

Chapter Summary and Conclusions

Increased temperatures, soil moisture deficits, and wildfire will affect species composition and structure of vegetation across the CMWAP assessment area, but effects are expected to differ geographically, and considerable uncertainty exists about the ecological implications and timing of change. Other stressors, including nonnative species, may drive vegetation shifts by altering disturbance regimes or competitively excluding native species. Moist coniferous forest is expected to persist across much of the assessment area, but subalpine forests will likely experience significant reductions in area, and low-elevation forest in the western Cascades may experience decreased conifer dominance and increased hardwood abundance. Dry forests are projected to be relatively stable, but these forests will likely experience shifts in species composition and structure mediated by fire.

Moist coniferous forests are likely to be dominated by Douglas-fir with increasing temperature and disturbance rates. Fire- and drought-intolerant species, including western hemlock, Pacific silver fir, and western redcedar, are likely to decrease in abundance in moist forests, and grand fir may decrease in mesic forests. Hardwood species, particularly Oregon white oak, may expand into drier sites in lower elevation forests currently dominated by Douglas-fir. Hardwood species, such as bigleaf maple and alder, may expand under the warmer, wetter conditions in more topographically sheltered settings (where summer droughts may be less intense). Large, high-severity fires, such as the 2020 wildfires that occurred in the assessment area, will be a major catalyst of rapid change across large landscapes if they increase in frequency.

With increased temperatures and reduced snowpack, high-elevation tree species may experience increased competition from species that are currently dominant at lower elevations, including noble fir, Pacific silver fir, and Douglas-fir. Earlier snowmelt and longer growing seasons are likely to increase tree growth but will also lengthen the summer dry period. Increased frequency and extent of wildfire in the subalpine zone could be a catalyst for vegetation change.

Climate change is expected to have profound effects on the vegetation of the CWMAP assessment area over the next century. However, the rate and magnitude of change will differ geographically. Disturbance (e.g., fire, insect outbreaks) is expected to increase in a warmer climate and will drive changes in species distributions, tree age, and forest structure. Simulation results from MC2 suggest some parts of the assessment area may experience changes similar to those that occurred during warmer periods in the past during the Holocene. Such consistency among different lines of evidence provides confidence about potential changes. Improved knowledge about the diversity of responses by vegetation across different landscapes will inform development of effective adaptation strategies.

Literature Cited

Abatzoglou, J.T.; Rupp, D.E.; Mote, P.W. 2014. Seasonal climate variability and change in the Pacific Northwest of the United States. Journal of Climate. 27: 2125–2142.

Abatzoglou, J.T.; Williams, A.P. 2016. Impact of anthropogenic climate change on wildfire across Western U.S. forests. Proceedings of the National Academy of Sciences, USA. 113: 11770–11775.

Acker, S.A.; Boetsch, J.R.; Bivin, M. [et al.]. 2015. Recent tree mortality and recruitment in mature and old-growth forests in western Washington. Forest Ecology and Management. 336: 109–118.

Acker, S.A.; Gregory, S.V.; Lienkaemper, G. [et al.]. 2003. Composition, complexity, and tree mortality in riparian forests in the central Western Cascades of Oregon. Forest Ecology and Management. 173: 293–308.

Acker, S.A.; Kertis, J.A.; Pabst, R.J. 2017. Tree regeneration, understory development, and biomass dynamics following wildfire in a mountain hemlock (*Tsuga mertensiana*) forest. Forest Ecology and Management. 384: 72–82.

Adams, H.D.; Guardiola-Claramonte, M.; Barron-Gafford, G.A. [et al.]. 2009. Temperature sensitivity of drought-induced tree mortality portends increased regional die-off under global-change-type drought. Proceedings of the National Academy of Sciences, USA. 106: 7063–7066.

Agee, J.K. 1993. Fire ecology of Pacific Northwest forests. Washington, DC: Island Press. 493 p.

Agne, M.C.; Beedlow, P.A.; Shaw, D.C. [et al.]. 2018. Interactions of predominant insects and diseases with climate change in Douglas-fir forests of western Oregon and Washington, U.S.A. Forest Ecology and Management. 409: 317–332.

Agne, M.C.; Woolley, T.; Fitzgerald, S. 2016. Fire severity and cumulative disturbance effects in the post-mountain pine beetle lodgepole pine forests of the Pole Creek Fire. Forest Ecology and Management. 366: 73–86.

Albright, W.L.; Peterson, D.L. 2013. Tree growth and climate in the Pacific Northwest, North America: a broad-scale analysis of changing growth environments. Journal of Biogeography. 40: 2119–2133.

Allen, C.D.; Breshears, D.D.; McDowell, N.G. 2015. On underestimation of global vulnerability to tree mortality and forest die-off from hotter drought in the Anthropocene. Ecosphere. 6: 129.

Allen, C.D.; Macalady, A.K.; Chenchouni, H. [et al.]. 2010. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. Forest Ecology and Management. 259: 660–684.

Anderegg, W.R.L.; Kane, J.M.; Anderegg, L.D.L. 2012. Consequences of widespread tree mortality triggered by drought and temperature stress. Nature Climate Change. 3: 30–36.

Ayres, M.P.; Hicke, J.A.; Kerns, B.K. [et al.]. 2014. Disturbance regimes and stressors. In: Peterson, D.; Vose, J.; Patel-Weynand, T., eds. Climate change and United States forests. Cham, Switzerland: Springer Nature: 55–92. Advances in Global Change Research. Vol. 57.

Bachelet, D.; Lenihan, J.M.; Daly, C. [et al.]. 2001. MC1: dynamic vegetation model for estimating the distribution of vegetation and associated ecosystem fluxes of carbon, nutrients, and water—technical documentation. Version 1.0. Gen. Tech. Rep. PNW-GTR-508. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 95 p.

Bailey, J.D.; Mayrsohn, C.; Doescher, P.S. [et al.]. 1998. Understory vegetation in old and young Douglas-fir forests of western Oregon. Forest Ecology and Management. 112: 289–302.

Balch, J.K.; Bradley, B.A.; Abatzoglou, J.T. [et al.]. 2017. Human-started wildfires expand the fire niche across the United States. Proceedings of the National Academy of Sciences, USA. 114: 2946–2951.

Bartlein, P.K.; Anderson, K.; Anderson, P. [et al.]. 1998. Paleo-climate simulations for North America over the past 21,000 years: features of the simulated climate and comparisons with paleoenvironmental data. Quaternary Science Reviews. 17: 549–585.

Beechie, T.; Buhle, E.; Ruckelshaus, M. [et al.]. 2006. Hydrologic regime and the conservation of salmon life history diversity. Biological Conservation. 130: 560–572.

Bell, D.M.; Gray, A.N. 2016. Assessing intra- and inter-regional climate effects on Douglas-fir biomass dynamics in Oregon and Washington. Forest Ecology and Management. 379: 281–287.

Bennett, K.D.; Provan, J. 2008. What do we mean by "refugia"? Quaternary Science Reviews. 27: 2449–2455.

Bennett, M.; Shaw, D. 2008. Disease and insect pests of Pacific madrone. Forest Health Fact Sheet EC 1619-E. Corvallis, OR: Oregon State University Extension Services.

Bentz, B.J.; Duncan, J.P.; Powell, J.A. 2016. Elevational shifts in thermal suitability for mountain pine beetle population growth in a changing climate. Forestry. 89: 271–283.

Bentz, B.J.; Regniere, J.; Fettig, C.J. [et al.]. 2010. Climate change and bark beetles of the Western United States and Canada: direct and indirect effects. Bioscience. 60: 602–613.

Bentz, B.; Vandygriff, J.; Jensen, C. [et al.]. 2013. Mountain pine beetle voltinism and life history characteristics across latitudinal and elevational gradients in the Western United States. Forest Science. 60: 434–449.

Berner, L.T.; Law, B.E.; Meddens, A.J.H.; Hicke, J.A. 2017. Tree mortality from fires, bark beetles, and timber harvest during a hot, dry decade in the Western United States. Environmental Research Letters. 12: 065005

Bond, M.L.; Lee, D.E.; Bradley, C.M.; Hanson, C.T. 2009. Influence of pre-fire tree mortality on fire severity in conifer forests of the San Bernandino Mountains, California. Open Forest Science Journal. 2: 41–47.

Borchers, S.L.; Perry, D.A. 1990. Growth and ectomycorrhiza formation of Douglas-fir seedlings grown in soils collected at different distances from pioneering hardwoods in southwest Oregon clear-cuts. Canadian Journal of Forest Research. 20: 712–721.

Boyd, R. 1999. Indians, fire, and the land in the Pacific Northwest. Corvallis, OR: Oregon State University Press. 313 p.

Brewer, M.C.; Mass, C.F.; Potter, B.E. 2012. The west coast thermal trough: climatology and synoptic evolution. Monthly Weather Review. 140: 3820–3843.

Briles, C.E.; Whitlock, C.; Bartlein, P.J. 2005. Postglacial vegetation, fire, and climate history of the Siskiyou Mountains, Oregon, USA. Quaternary Research. 64: 44–56.

Briles, C.E.; Whitlock, C.; Bartlein, P.J.; Higuera, P. 2008. Regional and local controls on postglacial vegetation and fire in the Siskiyou Mountains, northern California, USA. Palaeogeography, Palaeoclimatology, Palaeoecology. 265: 159–169.

Brooker, R.W.; Maestre, F.T.; Callaway, R.M. [et al.]. 2008. Facilitation in plant communities: the past, the present, and the future. Journal of Ecology. 96: 18–34.

Brooks, M.L.; D'Antonio, C.M.; Richardson, D.M. [et al.]. 2004. Effects of invasive alien plants on fire regimes. Bioscience. 54: 677–688.

Brown, M.J.; Kertis, J.; Huff, M.H. 2013. Natural tree regeneration and coarse woody debris dynamics after a forest fire in the western Cascade Range. Res. Pap. PNW-RP-592. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 50 p.

Buma, B. 2015. Disturbance interactions: characterization, prediction, and the potential for cascading effects. Ecosphere. 6: 70.

Buotte, P.C.; Levis, S.; Law, B.E. [et al.]. 2018. Near-future forest vulnerability to drought and fire varies across the Western United States. Global Change Biology. 25: 290–303.

Busse, M.D. 2000. Ecological significance of nitrogen fixation by actinorhizal shrubs in interior forests of California and Oregon. In: Powers, R.F.; Hauxwell, D.; Nakamura, G., tech. eds. Proceedings of the California Forest Soils Council conference on forest soils biology and forest management. Gen. Tech. Rep. PSW-GTR-178. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station: 23–42.

Busse, M.D.; Cochran, P.H.; Barrett, J.W. 1996. Changes in ponderosa pine site productivity following removal of understory vegetation. Soil Science Society of America Journal. 60: 1614–1621.

Caldwell, B.A. 2006. Effects of invasive Scotch broom on soil properties in a Pacific coastal prairie soil. Applied Soil Ecology. 32: 149–152.

Callaway, R.M.; Brooker, R.W.; Choler, P. [et al.]. 2002. Positive interactions among alpine plants increase with stress. Nature. 417: 844–848.

Cansler, C.A.; McKenzie, D. 2014. Climate, fire size, and biophysical setting control fire severity and spatial pattern in the northern Cascade Range, USA. Ecological Applications. 24: 1037–1056.

Capon, S.J.; Chambers, L.E.; MacNally, R. [et al.]. 2013. Riparian ecosystems in the 21st century: hotspots for climate change adaptation? Ecosystems. 16: 359–381.

Case, M.J.; Lawler, J.J. 2016. Relative vulnerability to climate change of trees in western North America. Climatic Change. 136: 367–379.

Catford, J.A.; Naiman, R.J.; Chambers, L.E. 2013. Predicting novel riparian ecosystems in a changing climate. Ecosystems. 16: 382–400.

Chmura, D.J.; Anderson, P.D.; Howe, G.T. [et al.]. 2011. Forest responses to climate change in the northwestern United States: ecophysiological foundations for adaptive management. Forest Ecology and Management. 261: 1121–1142.

Clark, J.S.; Iverson, L.; Woodall, C.W. [et al.]. 2016. The impacts of increasing drought on forest dynamics, structure, and biodiversity in the United States. Global Change Biology. 22: 2329–2352.

Cleland, D.; Reynolds, K.; Vaughan, R. [et al.]. 2017. Terrestrial condition assessment for national forests of the USDA Forest Service in the continental US. Sustainability. 9: 21–44.

Cohen, W.B.; Yang, Z.; Stehman, S.V. [et al.]. 2016. Forest disturbance across the conterminous United States from 1985–2012: the emerging dominance of forest decline. Forest Ecology and Management. 360: 242–252.

Conklin, D.R.; Lenihan, J.M.; Bachelet, D. [et al.]. 2016. MCFire model technical description. Gen. Tech. Rep. PNW-GTR-926. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 75 p.

Cook, E.R.; Woodhouse, C.A.; Eakin, C.M. [et al.]. 2004. Long-term aridity changes in the Western United States. Science. 306: 1015–1018.

Cramer, O.P. 1957. Frequency of dry east winds over northwest Oregon and southwest Washington. Res. Pap. 24. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 19 p.

Crausbay, S.D.; Higuera, P.E.; Sprugel, D.G.; Brubaker, L.B. 2017. Fire catalyzed rapid ecological change in lowland coniferous forests of the Pacific Northwest over the past 14,000 years. Ecology. 98: 2356–2369.

Creutzburg, M.K.; Scheller, R.M.; Lucash, M.S. [et al.]. 2017. Forest management scenarios in a changing climate: trade-offs between carbon, timber, and old forest. Ecological Applications. 27: 503–518.

Crookston, N.L.; Rehfeldt, G.E.; Dixon, G.E.; Weiskittel, A.R. 2010. Addressing climate change in the Forest Vegetation Simulator to assess impacts on landscape forest dynamics. Forest Ecology and Management. 260: 1198–1211.

Cwynar, L.C. 1987. Fire and the forest history of the North Cascade Range. Ecology. 68: 791–802.

Dale, V.H.; Joyce, L.A.; McNulty, S.; Neilson, R.P. 2000. The interplay between climate change, forests, and disturbances. Science of the Total Environment. 262: 201–204.

Dale, V.H.; Joyce, L.A.; McNulty, S. [et al.]. 2001. Climate change and forest disturbances. Bioscience. 51: 723–734.

Daly, C.; Bachelet, D.; Lenihan, J.M. [et al.]. 2000. Dynamic simulation of tree–grass interactions for global change studies. Ecological Applications. 10: 449–469.

Daly, C.; Halbleib, M.; Smith, J.I. [et al.]. 2008. Physiologically sensitive mapping of climatological temperature and precipitation across the conterminous United States. International Journal of Climatology. 28: 2031–2064.

Daniels, M.L.; Anderson, R.S.; Whitlock, C. 2005. Vegetation and fire history since the Late Pleistocene from the Trinity Mountains, northwestern California. The Holocene. 15: 1062–1071

Davis, K.T.; Higuera, P.E.; Sala, A. 2018. Anticipating fire-mediated impacts of climate change using a demographic framework. Functional Ecology. 32: 1729–1745.

Davis, M.B.; Shaw, R.G. 2001. Range shifts and adaptive responses to quaternary climate change. Science. 292: 673–679.

Davis, R.J.; Ohmann, J.L.; Kennedy, R.E. [et al.]. 2015. Northwest Forest Plan—the first 20 years (1994–2013): status and trends of late-successional and old-growth forests. Gen. Tech. Rep. PNW-GTR-911. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 112 p.

Davis, R.J.; Yang, Z.; Yost, A. [et al.]. 2017. The normal fire environment—modeling environmental suitability for large forest fires using past, present, and future climate normal. Forest Ecology and Management. 390: 173–186.

Dawson, T.P.; Jackson, S.T.; House, J.I. [et al.]. 2011. Beyond predictions: biodiversity conservation in a changing climate. Science. 332: 53–58.

Dillon, G.K.; Holden, Z.A.; Morgan, P. [et al.]. 2011. Both topography and climate affected forest and woodland burn severity in two regions of the Western U.S., 1984 to 2006. Ecosphere. 2: 130.

Dodson, E.; Root, H.T. 2013. Conifer regeneration following stand-replacing fire varies along an elevation gradient in a ponderosa pine forest, Oregon, USA. Forest Ecology and Management. 302: 163–170.

Dodson, E.K.; Root, H.T. 2014. Native and exotic plant cover vary inversely along a climate gradient 11 years following stand-replacing wildfire in a dry coniferous forest, Oregon, USA. Global Change Biology. 21: 666–675.

Donato, D.C.; Fontaine, J.B.; Campbell, J.L. [et al.]. 2009. Conifer regeneration in stand-replacement portions of a large mixed-severity wildfire in the Klamath-Siskiyou Mountains. Canadian Journal of Forest Research. 39: 823–838.

Donato, D.; Harvey, B.J.; Romme, W.H. [et al.]. 2013. Bark beetle effects on fuel profiles across a range of stand structures in Douglas-fir forests of Greater Yellowstone. Ecological Applications. 23: 3–20.

Drexler, J.A.; Knifong, D.; Tuil, J. [et al.]. 2013. Fens as whole-ecosystem gauges of groundwater recharge under climate change. Journal of Hydrology. 481: 22–34.

Dunn, C.J.; Johnston, J.D.; Reilly, M.J. [et al.]. 2020. How does tree regeneration respond to moderate-severity fire in the western Oregon Cascades, USA? Ecosphere. 11: e03003.

Dwire, K.A.; Mellmann-Brown, S. 2017. Climate change and special habitats in the Blue Mountains: riparian areas, wetlands, and groundwater-dependent ecosystems. In: Halofsky, J.E.; Peterson, D.L., eds. Climate change vulnerability and adaptation in the Blue Mountains. PNW-GTR-939. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 251–323.

Elliott, M.; Edmonds, R.L.; Mayer, S. 2002. Role of fungal diseases in decline of Pacific madrone. Northwest Science. 76: 293–303.

Emmanuel, K. 2005. Increasing destructiveness of tropical cyclones over the past 30 years. Nature. 436: 686–688.

Enright, N.J.; Fontaine, J.B.; Bowman, D. [et al.]. 2015. Interval squeeze: altered fire regimes and demographic responses interact to threaten woody species persistence as climate changes. Frontiers in Ecology and the Environment. 13: 265–272.

Ettinger, A.K.; HilleRisLambers, J. 2013. Climate isn't everything: competitive interactions and variation by life stage will also affect range shifts in a warming world. American Journal of Botany. 100: 1344–1355.

Ford, K.R.; Breckheimer, I.K.; Franklin, J.F. [et al.]. 2017a. Competition alters tree growth responses to climate at individual and stand scales. Canadian Journal of Forest Research. 47: 53–62.

Ford, K.R.; Harrington, C.A.; Bansal, S. [et al.]. 2016. Will changes in phenology track climate change? A study of growth initiation timing in coast Douglas-fir. Global Change Biology. 22: 3712–3723.

Foster, D.R.; Knight, D.H.; Franklin, J.F. 1998. Landscape patterns and legacies resulting from large infrequent forest disturbances. Ecosystems. 1: 497–510.

Franklin, J.F.; Dyrness, C.T. 1988. Natural vegetation of Oregon and Washington. 2nd ed. Corvallis, OR. Oregon State University Press. 452 p.

Franklin, J.F.; Shugart, H.H.; Harmon, M.E. 1987. Tree death as an ecological process. BioScience. 37: 550–556.

Fuchs, M.A.; Krannitz, P.G.; Harestad, A.S. 2000. Factors affecting emergence and first-year survival of seedlings of Garry oaks (*Quercus garryana*) in British Columbia, Canada. Forest Ecology and Management. 137: 209–219.

Gavin, D.G.; Fitzpatrick, M.C.; Gugger, P.F. [et al.]. 2014. Climate refugia: joint inference from fossil records, species distribution models and phylogeography. New Phytologist. 204: 37–54.

Gavin, D.G.; McLachlan, J.S.; Brubaker, L.B.; Young, K.A. 2001. Postglacial history of subalpine forests, Olympic Peninsula, Washington, USA. The Holocene. 11: 177–188.

Gedalof, Z.E.; Berg, A.A. 2010. Tree ring evidence for limited direct CO_2 fertilization of forests over the 20th century. Global Biogeochemical Cycles. 24: 1–6.

Gedalof, Z.; Smith, D.J. 2001. Interdecadal climate variability and regime-scale shifts in Pacific North America. Geophysical Research Letters. 28: 1515–1518.

Gershunov, A.; Barnett, T.P.; Cayan, D.R. 1999. North Pacific Interdecadal Oscillation seen as actor in ENSO-related North American climate anomalies. Eos, Transactions, American Geophysical Union. 80: 25–30.

Gilligan, L.A.; Muir, P.S. 2011. Stand structure of Oregon white oak woodlands, regeneration, and their relationships to the environment in southwestern Oregon. Northwest Science. 85: 141–158.

Goheen, E.M.; Goheen, D.J. 2014. Status of sugar and western white pines on federal forest lands in southwest Oregon. Inventory query and natural stand survey results. Report no. SWWOFIDSC-14-01. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Region. 71 p.

Goheen, E.M.; Goheen, D.J.; Marshall, K. [et al.]. 2002. The status of whitebark pine along the Pacific Crest National Scenic Trail on the Umpqua National Forest. Gen. Tech. Rep. PNW-GTR-530. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 21 p.

Gray, A.N. 2005. Eight nonnative plants in western Oregon forests: associations with environment and management. Environmental Monitoring and Assessment. 100: 109–127.

Gray, A.N. 2008. Monitoring and assessment of regional impacts from nonnative invasive plants in forests of the Pacific coast, United States. In: Kohli, R.K.; Jose, S.; Singh, H.P.; Batish, D.R., eds. Invasive plants and forest ecosystems. Boca Raton, FL: CRC Press: 217–235.

Gray, A.N.; Barndt, K.; Reichard, S.H. 2011. Nonnative invasive plants of Pacific coast forests: a field guide for identification. Gen. Tech. Rep. PNW-GTR-817. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 91 p.

Gray, A.N.; Franklin J.F. 1997. Effects of multiple fires on the structure of southwestern Washington forests. Northwest Science. 71: 174–185.

Grigg, L.; Whitlock, C. 1998. Late-glacial vegetation and climate change in western Oregon. Quaternary Research. 49: 287–298.

Haas, S.E.; Cushman, J.H.; Dillon, W.W. [et al.]. 2015. Effects of individual, community, and landscape drivers on the dynamics of a wildland forest epidemic. Ecology. 97: 649–660.

Hagmann, R.K.; Franklin, J.F.; Johnson, K.N. 2014. Historical conditions in mixed-conifer forests on the eastern slopes of the northern Oregon Cascade Range, USA. Forest Ecology and Management. 330: 158–170.

Halofsky, J.E.; Hibbs, D.E. 2008. Determinants of riparian fire severity in two Oregon fires, USA. Canadian Journal of Forest Research. 38: 1959–1973.

Halofsky, J.S.; Halofsky, J.E.; Burcus, M.A.; Hemstrom, M.A. 2014. Dry forest resilience varies under simulated climate-management scenarios in a central Oregon USA landscape. Ecological Applications 24: 1908–1925.

Halpern, C.B.; Antos, J.A.; Geyer, M.A.; Olson, A.M. 1997. Species replacement during early secondary succession: the abrupt decline of a winter annual. Ecology. 78: 621–631.

Halpern, C.B.; Evans, S.A.; Nielson, S. 1999. Soil seed banks in young, closed-canopy forests of the Olympic Peninsula, Washington: potential contributions to understory reinitiation. Canadian Journal of Botany. 77: 922–935.

Hamlet, A.F.; Elsner, M.M.; Mauger, G.S. [et al.]. 2013. An overview of the Columbia Basin climate change scenarios project: approach, methods, and summary of key results. Atmosphere-Ocean. 51: 392–415.

Hampe, A.; Jump, A.S. 2011. Climate relicts: past, present, future. Annual Review of Ecology, Evolution, and Systematics. 42: 313–333.

Hampe, A.; Petit, R.J. 2005. Conserving biodiversity under climate change: the rear edge matters. Ecology Letters. 8: 461–467.

Hansen, E.M.; Goheen, E.M. 2000. *Phellinus weirii* and other native root pathogens as determinants of forest structure and process in western North America. Annual Review of Phytopathology. 38: 515–539.

Hararuk, O.; Campbell, E.M.; Antos, J.A.; Parish, R. 2019. Tree rings provide no evidence of a CO_2 fertilization effect in old-growth subalpine forests of western Canada. Global Change Biology. 25: 1222–1234.

Harrington, C.A.; Gould, P.J. 2015. Tradeoffs between chilling and forcing in satisfying dormancy requirements for Pacific Northwest tree species. Frontiers in Plant Science. 6: 1–12.

Harrington, T.B.; Reichard, S.H. 2007. Meeting the challenge: invasive plants in Pacific Northwest ecosystems. Gen. Tech. Rep. PNW-GTR-694. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 166 p.

Hart, S.J.; Schoennagel, T.; Veblen, T.T.; Chapman, T.B. 2015. Area burned in the western United States is unaffected by recent pine beetle outbreaks. Proceedings of the National Academy of Sciences, USA. 112: 4375–4380.

Hartmann, H.; Adams, H.D.; Anderegg, W.R.L. [et al.]. 2015. Research frontiers in drought-induced tree mortality: crossing scales and disciplines. New Phytologist. 205: 965–969.

Hartmann, H.; Moura, C.F.; Anderegg, W.R.L. [et al.]. 2018. Research frontiers for improving our understanding of drought-induced tree mortality. New Phytologist. 218: 15–28.

Harvey, B.J.; Donato, D.C.; Romme, W.H.; Turner, M.G. 2013. Influence of recent bark beetle outbreak on fire severity and postfire tree regeneration in montane Douglas-fir forests. Ecology. 94: 2475–2486.

Haugo, R.D.; Halpern, C.B. 2007. Vegetation responses to conifer encroachment in a western Cascade meadow: a chronosequence approach. Canadian Journal of Botany. 85: 285–298.

Haugo, R.D.; Kellogg, B.S.; Cansler, C.A. [et al.]. 2019. The missing fire: quantifying human exclusion of wildfire in Pacific Northwest forests. Ecosphere. 10: e02702.

Hellmann, J.J.; Byers, J.E.; Bierwagen, B.G.; Dukes, J.S. 2008. Five potential consequences of climate change for invasive species. Conservation Biology. 22: 534–543.

Hessl, A.E. 2011. Pathways for climate change effects on fire: models, data, and uncertainties. Progress in Physical Geography. 35: 393–407.

Hessl, A.E.; McKenzie, D.; Schellhaas, R. 2004. Drought and Pacific Decadal Oscillation linked to fire occurrence in the inland Pacific Northwest. Ecological Applications. 14: 425–442.

Heyerdahl, E.K.; McKenzie, D.; Daniels, L.D. [et al.]. 2008. Climate drivers of regionally synchronous fires in the inland Northwest (1651–1900). International Journal of Wildland Fire. 17: 40–49.

Hicke, J.A.; Johnson, M.C.; Hayes, J.L.; Preisler, H.K. 2012. Effects of bark beetle-caused tree mortality on wildfire. Forest Ecology and Management. 271: 81–90.

Hicke, J.A.; Meddens, A.J.H.; Kolden, C.A. 2016. Recent tree mortality in the western United States from bark beetles and forest fires. Journal of Forestry. 16: 141–153.

HilleRisLambers, J.; Anderegg, L.D.L.; Breckheimer, I. [et al.]. 2015. Implications of climate change for turnover in forest composition. Northwest Science. 89: 201–218.

Holden, Z.A.; Swanson, A.; Luce, C.H. [et al.]. 2018. Decreasing fire season precipitation increased recent western U.S. forest wildfire activity. Proceedings of the National Academy of Sciences, USA. 115: E8349–E8357.

Horton, T.R.; Bruns, T.D.; Parker, V.T. 1999. Ectomycorrhizal fungi associated with *Arctostaphylos* contribute to *Pseudotsuga menziesii* establishment. Canadian Journal of Botany. 77: 93–102.

Isaac, L.A. 1940. Vegetative succession following logging in the Douglas fir region with special reference to fire. Journal of Forestry. 38: 716–721.

Jackson, S.T.; Betancourt, J.L.; Booth, R.K.; Gray, S.T. 2009. Ecology and the ratchet of events: climate variability, niche dimensions, and species distributions. Proceedings of the National Academy of Sciences, USA. 106: 19685–19692.

Jiang, Y.; Still, C.; Rastogi, B. [et al.]. 2019. Trends and controls on water-use efficiency of an old-growth coniferous forest in the Pacific Northwest. Environmental Research Letters. 14: 074029.

Jolly, W.M.; Cochrane, M.A.; Freeborn, P.H. [et al.]. 2015. Climate-induced variations in global wildfire danger from 1979 to 2013. Nature Communications. 6: 7537.

Keenan, T.F.; Hollinger, D.Y.; Bohrer, G. [et al.]. 2013. Increase in forest water-use efficiency as atmospheric carbon dioxide concentrations rise. Nature. 499: 324–327.

Kemp-Jennings, S.; Peterson, D.L.; Bunn, A.G. 2021. Temporal variability in climate-growth response of mountain hemlock at treeline in Washington and Oregon. Northwest Science. 94: 286–301.

Kerns, B.K.; Powell, D.C.; Mellmann-Brown, S. [et al.]. 2017. Effects of climatic variability and change on upland vegetation in the Blue Mountains. In: Halofsky, J.E.; Peterson, D.L., eds. Climate change vulnerability and adaptation in the Blue Mountains. Gen. Tech. Rep. PNW-GTR-939. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 149–250. Chapter 6.

Kerns, B.K.; Tortorelli, C.; Day, M.A. [et al.]. 2020. Invasive grasses: a new perfect storm for forested ecosystems? Forest Ecology and Management. 463: 117985.

Keyes, C.R.; Maguire, D.A.; Tappeiner, J.C. 2009. Recruitment of ponderosa pine seedlings in the Cascade Range. Forest Ecology and Management. 257: 495–501.

Kim, J.B.; Kerns, B.K.; Drapek, R.J. [et al.]. 2018. Simulating vegetation response to climate change in the Blue Mountains with MC2 dynamic global vegetation model. Climate Services. 10: 20–32.

Kitzberger, T.; Brown, P.M.; Heyerdahl, E.K. [et al.]. 2007. Contingent Pacific-Atlantic Ocean influence on multicentury wildfire synchrony over western North America. Proceedings of the National Academy of Sciences, USA. 104: 543–548.

Kitzberger, T.; Steinaker, D.F.; Veblen, T.T. 2000. Effects of climatic variability on facilitation of tree establishment in northern Patagonia. Ecology. 81: 1914–1924.

Klasner, F.L.; Fagre, D.B. 2002. A half century of change in alpine treeline patters at Glacier National Park, Montana, U.S.A. Arctic, Antarctic, and Alpine Research. 34: 49–56.

Kliejunas, J.T.; Geils, B.W.; Glaeser, J.M. [et al.]. 2009. Review of literature on climate change and forest diseases of western North America. Gen. Tech. Rep. PSW-GTR-225. Albany, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. 54 p.

Knapp, P.A.; Hadley, K.S. 2012. A 300-year history of Pacific Northwest windstorms inferred from tree rings. Global and Planetary Change. 92–93: 257–266.

Knutson, K.C.; Pyke, D.A. 2008. Western juniper and ponderosa pine ecotonal climate-growth relationships across landscape gradients in southern Oregon. Canadian Journal of Forest Research. 38: 3012–3032.

Kolb, T.E.; Fettig, C.J.; Ayres, M.P. [et al.]. 2016. Observed and anticipated impacts of drought on forest insects and diseases in the United States. Forest Ecology and Management. 380: 321–334.

Kozlowski, T.T.; Pallardy, S.G. 2002. Acclimation and adaptive responses of woody plants to environmental stresses. The Botanical Review. 68: 270–334.

Krawchuk, M.A.; Moritz, M.A.; Parisien, M-A. [et al.]. 2009. Global pyrogeography: the current and future distribution of wildfire. PLoS ONE. 4: e5102.

Kusnierczyk, E.; Ettl, G.J. 2002. Growth response of ponderosa pine (*Pinus ponderosa*) to climate in the eastern Cascade Mountains, Washington, U.S.A.: implications for climatic change. Ecoscience. 9: 544–551.

LaDeau, S.L.; Clark, J.S. 2001. Rising CO_2 levels and the fecundity of forest trees. Science. 292: 95–98.

LaDeau, S.L.; Clark, J.S. 2006. Elevated CO_2 and tree fecundity: the role of tree size, interannual variability, and population heterogeneity. Global Change Biology. 12: 822–833.

Larson, A.J.; Franklin, J.F. 2005. Patterns of conifer tree regeneration following an autumn wildfire event in the western Oregon Cascade Range, USA. Forest Ecology and Management. 218: 25–36.

Larson, A.J.; Franklin, J.F. 2010. The tree mortality regime in temperate old-growth coniferous forests: the role of physical damage. Canadian Journal of Forest Research. 40: 2091–2103.

Larson, A.J.; Lutz, J.A.; Donato, D.C. [et al.]. 2015. Spatial aspects of tree mortality strongly differ between young and old-growth forests. Ecology. 96: 2855–2861.

Latta, G.; Temesgen, H.; Adams, D.; Barrett, T. 2010. Analysis of potential impacts of climate change on forests of the United States Pacific Northwest. Forest Ecology and Management. 259: 720–729.

Law, B.E.; Waring, R.H. 2015. Carbon implications of current and future effects of drought, fire and management on Pacific Northwest forests. Forest Ecology and Management. 355: 4–14.

Lee, S.; Ryan, M.E.; Hamlet, A.F. [et al.]. 2015. Projecting the hydrologic impacts of climate change on montane wetlands. PLoS ONE. 10: e0136385.

Littell, J.S.; McKenzie, D.; Kerns, B.K. [et al.]. 2011. Managing uncertainty in climate-driven ecological models to inform adaptation to climate change. Ecosphere. 2: 102.

Littell, J.S.; McKenzie, D.; Peterson, D.L.; Westerling, A.L. 2009. Climate and wildfire burned in the Western U.S. ecoprovinces, 1916–2003. Ecological Applications. 19: 1003–1021.

Littell, J.S.; Oneil, E.E.; McKenzie, D. [et al.]. 2010. Forest ecosystems, disturbance, and climatic change in Washington state, USA. Climatic Change. 102: 129–158.

Littell, J.S.; Peterson, D.L.; Tjoelker, M. 2008. Water limits tree growth from stand to region: Douglas-fir growth-climate relationships in Northwestern ecosystems. Ecological Monographs. 78: 349–368.

Little, R.L.; Peterson, D.L.; Conquest, L.L. 1994. Regeneration of subalpine fir (*Abies lasiocarpa*) following fire: effects of climate and other factors. Canadian Journal of Forest Research. 24: 934–944.

Liu, Y.; Stanturf, J.; Goodrick, S. 2012. Trends in global wildfire potential in a changing climate. Forest Ecology and Management. 259: 685–697.

Lloret, F.; Escudero, A.; Iriondo, J.M. [et al.]. 2012. Extreme climatic events and vegetation: the role of stabilizing processes. Global Change Biology. 18: 797–805.

Lockman, I.B.; Kearns, H.S.J., eds. 2016. Forest root diseases across the United States. Gen. Tech. Rep. RMRS-GTR-342. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 55 p.

Long, C.J.; Whitlock, C.; Bartlein, P.J.; Millspaugh, S.H. 1998. A 9000-year fire history from the Oregon Coast Range, based on a high-resolution charcoal study. Canadian Journal of Forest Research. 28: 774–787.

Luce, C.H.; Holden, Z.A. 2009. Declining annual streamflow distributions in the Pacific Northwest United States, 1948–2006. Geophysical Research Letters. 36: L16401.

Luo, Y.; Chen, H.Y.H. 2013. Observations from old forests underestimate climate change effects on tree mortality. Nature Communications. 4: 1655.

Lutz, J.A.; Halpern, C.B. 2006. Tree mortality during early forest development: a long-term study of rates, causes, and consequences. Ecological Monographs. 76: 257–275.

Lynott, R.E.; Cramer, O.P. 1966. Detailed analysis of the 1962 Columbus Day windstorm in Oregon and Washington. Monthly Weather Review. 94: 105–117.

Maloney, P.E.; Lynch, S.C.; Kane, S.F.; Rizzo, D.M. 2004. Disease progression of *Phytophthora ramorum* and *Botryosphaeria dothidea* on Pacific madrone. Plant Disease. 88: 852–857.

Manion, P.D. 1981. Tree disease concepts. Englewood Cliffs, NJ: Prentice-Hall. 399 p.

Mantua, N.J.; Hare, S.R.; Zhang, Y. [et al.]. 1997. A Pacific Interdecadal Climate Oscillation with impacts on salmon production. Bulletin of the American Meteorological Society. 78: 1069–1079.

Marias, D.; Meinzer, F.C.; Woodruff, D.R. [et al.]. 2014. Impacts of dwarf mistletoe on the physiology of host *Tsuga heterophylla* trees as recorded in tree-ring C and O stable isotopes. Tree Physiology. 34: 595–607.

Marlon, J.R.; Bartlein, P.J.; Gavin, D.G. [et al.]. 2012. Long-term perspectives on wildfires in the western USA. Proceedings of the National Academy of Sciences, USA. 109: E535–E543.

Marlon, J.R.; Bartlein, P.J.; Walsh, M.K. [et al.]. 2009. Wildfire responses to abrupt climate change in North America. Proceedings of the National Academy of Sciences, USA. 106: 2519–2524.

Mass, C.; Dotson, B. 2010. Major extratropical cyclones of the Northwest United States: historical review, climatology, and synoptic environment. Monthly Weather Review. 138: 2499–2527.

McAfee, S.A. 2014. Consistency and the lack thereof in Pacific Decadal Oscillation impacts on North American winter climate. Journal of Climate. 27: 7410–7431.

McCabe, G.L.; Dettinger, M.D. 1999. Decadal variability in the strength of ENSO teleconnections with precipitation in the Western United States. International Journal of Climatology. 19: 1399–1410.

McCord, M.; Reilly, M.J.; Butz, R.J.; Jules, E.S. 2020. Early seral pathways of vegetation change following repeated short-interval, high-severity wildfire in a low elevation mixed conifer-hardwood forest landscape of the Klamath Mountains, northern California. Canadian Journal of Forest Research 50: 13–23.

McCullough, I.M.; Davis, F.W.; Williams, A.P. 2017. A range of possibilities: assessing geographic variation in climate sensitivity of ponderosa pine using tree rings. Forest Ecology and Management. 402: 223–233.

McDowell, N.; Pockman, W.T.; Allen, C.D. [et al.]. 2008. Mechanisms of plant survival and mortality during drought: Why do some plants survive while other succumb to drought? New Phytologist. 178: 719–739.

McKenzie, D.; Gedalof, Z.; Peterson, D.L.; Mote, P. 2004. Climatic change, wildfire, and conservation. Conservation Biology. 18: 890–902.

McKenzie, D.; Hessl, A.E.; Peterson, D.L. 2001. Recent growth in conifer species of western North America: assessing the spatial patterns of radial growth trends. Canadian Journal of Forest Research. 31: 526–538.

McKenzie, D.; Littell, J.S. 2017. Climate change and the eco-hydrology of fire: Will area burned increase in a warming western USA? Ecological Applications. 27: 26–36.

McKenzie, D.; Peterson, D.L.; Littell, J.S. 2009. Global warming and stress complexes in forests of western North America. In: Bytnerowicz, A.; Arbaugh, M.J.; Riebau, A.R.; Andersen, C., eds. Wildland fires and air pollution. The Hague, The Netherlands: Elsevier Publishers: 317–337.

McMurtrie, R.E.; Norby, R.J.; Medlyn, B.E. [et al.]. 2008. Why is plant-growth response to elevated CO_2 amplified when water is limiting, but reduced when nitrogen is limiting? A growth-optimization hypothesis. Functional Plant Biology. 35: 521–534.

Meentemeyer, R.K.; Cunniffe, N.J.; Cook, A.R. [et al.]. 2011. Epidemiological modeling of invasion in heterogeneous landscapes: spread of sudden oak death in California (1990–2030). Ecosphere. 2: 17.

Meigs, G.W.; Donato, D.C.; Campbell, J.L. [et al.]. 2009. Forest fire impacts on carbon uptake, storage, and emission: the role of burn severity in the eastern Cascades, Oregon. Ecosystems. 12: 1246–1267.

Meigs, G.W.; Kennedy, R.E.; Gray, A.N.; Gregory, M.J. 2015. Spatiotemporal dynamics of recent mountain pine beetle and western spruce budworm out breaks across the Pacific Northwest. Forest Ecology and Management. 339: 71–86.

Meigs, G.W.; Zald, H.S.J.; Campbell, J.L. [et al.]. 2016. Do insect outbreaks reduce the severity of subsequent forest fires? Environmental Research Letters. 11: 045008.

Metz, M.R.; Frangioso, K.M.; Meentemeyer, R.K.; Rizzo, D.M. 2011. Interacting disturbances: wildfire severity affected by stage of forest disease invasion. Ecological Applications. 21: 313–320.

Mildrexler, D.; Yang, Z.; Cohen, W.B.; Bell, D.M. 2016. A forest vulnerability index based on drought and high temperatures. Remote Sensing of the Environment. 173: 314–325.

Miles, D.W.R.; Swanson, F.J. 1986. Vegetation composition on recent landslides in the Cascade Mountains of western Oregon. Canadian Journal of Forest Research. 16: 739– 744.

Minckley, T.A.; Long, C.J. 2016. Paleofire severity and vegetation change in the Cascade Range, Oregon, USA. Quaternary Research. 85: 211–217.

Mitchell, R.G.; Buffam, P.E. 2001. Patterns of long-term Balsam woolly adelgid infestations and effects in Oregon and Washington. Western Journal of Applied Forestry. 16: 121–126.

Mohr, J.A.; Whitlock, C.; Skinner, C.N. 2000. Postglacial vegetation and fire history, eastern Klamath Mountains, California, USA. The Holocene. 10: 587–601.

Monleon, V.J.; Lintz, H.E.; Sylvain, D. 2015. Evidence of tree species' range shifts in a complex landscape. PLoS ONE. 10: e0118069. 17 p.

Morelli, T.L.; Daly, C.; Dobrowski, S.Z. [et al.]. 2016. Managing climate change refugia for climate adaptation. PLoS ONE. 11: e0159909.

Morgan, J.A.; LeCain, D.R.; Pendall, E. [et al.]. 2011. C_4 grasses prosper as carbon dioxide eliminates desiccation in warmed semi-arid grassland. Nature. 476: 202–205.

Morrison, P.H.; Swanson, F.J. 1990. Fire history and pattern in a Cascade Range landscape. Gen. Tech. Rep. PNW-GTR-254. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 77 p.

Nakawatase, J.M.; Peterson, D.L. 2006. Spatial variability in forest growth-climate relationships in the Olympic Mountains, Washington. Canadian Journal of Forest Research. 36: 77–91.

Nelson, D.B.; Abbott, M.B.; Steinman, B. [et al.]. 2011. Drought variability in the Pacific Northwest from a 6,000-yr lake sediment record. Proceedings of the National Academy of Science, USA. 108: 3870–3875.

Newman, M.; Alexander, M.A.; Ault, T.R. [et al.]. 2016. The Pacific Decadal Oscillation, revisited. Journal of Climate. 29: 4399–4427.

Paine, R.T.; Tegner, M.J.; Johnson, E.A. 1998. Compounded perturbations yield ecological surprises. Ecosystems. 1: 535–545.

Parendes, L.A.; Jones, J.A. 2000. Role of light availability and dispersal in exotic plant invasion along roads and streams in the H.J. Andrews Experimental Forest, Oregon. Conservation Biology. 14: 64–75.

Parks, S.A.; Holsinger, L.M.; Miller, C.; Nelson, C.R. 2015. Wildland fire as a self-regulating mechanism: the role of previous burns and weather in limiting fire progression. Ecological Applications. 25: 1478–1492.

Parks, S.A.; Miller, C.; Parisien, M-A. [et al.]. 2016. How will climate change affect wildland fire severity in the Western U.S.? Environmental Research Letters. 11: 035002

Parsons, D.J. 1972. The southern extensions of *Tsuga mertensiana* (mountain hemlock) in the Sierra Nevada. Madroño. 21: 536–539.

Perchemlides, K.A.; Muir, P.S.; Hosten, P.E. 2008. Responses of chaparral and oak woodland plant communities to fuel reduction thinning in southwestern Oregon. Rangeland Ecology and Management. 61: 98–109.

Peters, M.P.; Iverson, L.R.; Matthews, S.N. 2014. Spatio-temporal trends of drought by forest type in the conterminous United States, 1960–2013 [1:12,000,000]. Res. Map NRS-7. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station.

Peterson, D.L.; Vose, J.M.; Patel-Weynand, T. 2014a. Climate change and United States forests. Dordrecht, The Netherlands: Springer.

Peterson, D.W.; Kerns, B.K.; Dodson, E.K., eds. 2014b. Climate change effects on vegetation in the Pacific Northwest: a review and synthesis of the scientific literature and simulation model projections. Gen. Tech. Rep. PNW-GTR-900. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 183 p.

Peterson, D.W.; Peterson, D.L. 2001. Mountain hemlock growth responds to climatic variability at annual and decadal time scales. Ecology. 82: 3330–3345.

Peterson, D.W.; Peterson, D.L.; Ettl, G.J. 2002. Growth responses of subalpine fir to climatic variability in the Pacific Northwest. Canadian Journal of Forest Research. 32: 1503–1517.

Peterson, E.; Hansen, E.; Hurlbert, J. 2014b. Source or sink? The role of soil and water borne inoculum in the dispersal of *Phytophthora ramorum* in Oregon tanoak forests. Forest Ecology and Management. 322: 48–57.

Pickett, S.T.A.; White, P.S. 1985. The ecology of natural disturbance and patch dynamics. New York, NY: Academic Press. 472 p.

Poulos, L.P.; Roy, B.A. 2015. Fire and false brome: How do prescribed fire and invasive *Brachypodium sylvaticum* affect each other? Invasive Plant Science and Management. 8: 122–130.

Powers, J.S.; Sollins, P.; Harmon, M.E.; Jones, J.A. 1999. Plant-pest interactions in time and space: a Douglas-fir bark beetle outbreak as a case study. Landscape Ecology. 14: 105–120.

Preisler, H.K.; Hicke, J.A.; Ager, A.; Hayes, J.L. 2012. Climate and weather influences on spatial temporal patterns of mountain pine beetle populations in Washington and Oregon. Ecology. 93: 2421–2434.

Prichard, S.J.; Gedalof, Z.; Oswald, W.W. 2009. Holocene fire and vegetation dynamics in a montane forest, North Cascade Range, Washington, USA. Quaternary Research. 72: 57– 67.

Raffa, K.F.; Aukema, B.H.; Bentz, B.J. [et al.]. 2008. Cross-scale drivers of natural disturbances prone to anthropogenic amplification: the dynamics of bark beetle eruptions. Bioscience. 58: 501–517.

Rehfeldt, G.E.; Crookston, N.L.; Warwell, M.V.; Evans, J.S. 2006. Empirical analyses of plant-climate relationships for the western United States. International Journal of Plant Sciences. 167: 1123–1150.

Reichard, S.H.; White, P.S. 2001. Horticulture as a pathway of invasive plant introductions in the United States. Bioscience. 51: 103–113.

Reilly, M.J.; Dunn, C.J.; Meigs, G.W. [et al.]. 2017. Contemporary patterns of fire extent and severity in forests of the Pacific Northwest, USA (1985–2010). Ecosphere. 8: e01695.

Reilly, M.J.; Monleon, V.; Jules, E.S.; Butz, R.J. 2019. Biogeographic patterns of population structure and dynamics of a serotinous conifer, knobcone pine (*Pinus attenuata* L.). Forest Ecology and Management. 441: 182–191.

Reilly, M.J.; Spies, T.A. 2015. Regional variation in stand structure and development in forests of Oregon, Washington, and inland northern California. Ecosphere. 6: 192.

Reilly, M.J.; Spies, T.A. 2016. Disturbance, tree mortality, and implications for contemporary regional forest change in the Pacific Northwest. Forest Ecology and Management. 374: 102–110.

Restaino, C.M.; Peterson, D.L.; Littell, J.S. 2016. Increased water deficit decreases Douglas-fir growth throughout Western U.S. forests. Proceedings of the National Academy of Sciences, USA. 113: 9557–9562.

Riahi, K.; Rao, S.; Krey, V. [et al.]. 2011. RCP 8.5—a scenario of comparatively high greenhouse gas emissions. Climatic Change. 109: 33–57.

Riegel, G.M.; Smith, B.G.; Franklin, J.F. 1992. Foothill oak woodlands of the interior valleys of southwestern Oregon. Northwest Science. 66: 66–76.

Ringo, C.; Bennett, K.; Noller, J. [et al.]. 2018. Modeling droughty soils at regional scales in Pacific Northwest forests, USA. Forest Ecology and Management. 424: 121–135.

Rizzo, D.M.; Garbelotto, M. 2003. Sudden oak death: endangering California and Oregon forest ecosystems. Frontiers in Ecology and the Environment. 1: 197–204.

Rochefort, R.M.; Little, R.M.; Woodward, A.; Peterson, D.L. 1994. Changes in subalpine tree distribution in Western North America: a review of climatic and other causal factors. The Holocene. 4: 89–100.

Rogers, B.M.; Neilson, R.P.; Drapek, R. [et al.]. 2011. Impacts of climate change on fire regimes and carbon stocks of the U.S. Pacific Northwest. Journal of Geophysical Research–Biogeography. 116: G03037.

Rollins, M.G. 2009. LANDFIRE: a nationally consistent vegetation, wildland fire, and fuel assessment. International Journal of Wildland Fire. 18: 235–249.

Romme, W.H.; Everham, E.H.; Frelich, L.F. [et al.]. 1998. Are large, infrequent disturbances qualitatively different from small, frequent disturbances? Ecosystems. 1: 524–534.

Romps, D.M.; Seeley, J.T.; Vollaro, D.; Molinari, J. 2014. Projected increase in lighting strikes in the United States due to global warming. Science. 346: 851–854.

Rubenstein, S.M.; Dechaine, J.M. 2015. Native-nonnative seed dispersal and establishment along an interstate highway. Northwest Science. 89: 324–335.

Rupp, D.E.; Abatzoglou, J.T.; Hegewisch, K.C.; Mote, P.W. 2013. Evaluation of CMIP5 20th century climate simulations for the Pacific Northwest USA. Journal of Geophysical Research Atmospheres. 118: 884–906.

Safeeq, M.; Grant, G.E.; Lewis, S.L.; Tague, C.L. 2013. Coupling snowpack and groundwater dynamics to interpret historical streamflow trends in the Western United States. Hydrological Processes. 27: 655–668.

Salzer, M.; Hughes, M.; Bunn, A.; Kipfmueller, K. 2009. Recent unprecedented tree-ring growth in bristlecone pine at the highest elevations and possible causes. Proceedings of the National Academy of Sciences, USA. 106: 20348–20353.

Sandel, B.; Dangremond, E.M. 2012. Climate change and the invasion of California by grasses. Global Change Biology. 18: 277–289.

Schäfer, K.V.R.; Oren, R.; Lai, C-T.; Katul, G.G. 2002. Hydrologic balance in an intact temperate forest ecosystem under ambient and elevated atmospheric CO_2 concentration. Global Change Biology. 8: 895–911.

Schoennagel, T.; Veblen, T.T.; Romme, W.H. [et al.]. 2005. ENSO and PDO variability affect drought-induced fire occurrence in Rocky Mountain subalpine forests. Ecological Applications. 15: 2000–2014.

Sea, D.S.; Whitlock, C. 1995. Postglacial vegetation and climate of the Cascade Range, central Oregon. Quaternary Research. 43: 370–381.

Seidl, R.; Thom, D.; Kautz, M. [et al.]. 2017. Forest disturbances under climate change. Nature Climate Change. 7: 395–402.

Shafer, S.L.; Bartlein, P.J.; Gray, E.M.; Pelltier, R.T. 2015. Projected future vegetation changes for the Northwest United States and southwest Canada at a fine spatial resolution using a dynamic global vegetation model. PLoS ONE. 10: e0138759.

Sharp, J.; Mass, C.F. 2004. Columbia Gorge gap winds: their climatological influence and synoptic evolution. Weather and Forecasting. 19: 970–992.

Shaw, D.C.; Oeaster, P.T.; Filip, G.M. 2009. Managing insects and disease of Oregon conifers. Publication no. EM 8980. Corvallis, OR: Oregon State University Extension Services.

Silva, L.C.R.; Anand, M. 2013. Probing for the influence of atmospheric CO_2 and climate change on forest ecosystems across biomes. Global Ecology and Biogeography. 22: 83–92.

Silva, L.C.R.; Anand, M.; Leithead, M. 2010. Recent wide-spread tree growth decline despite increasing atmospheric CO_2. PLoS ONE. 5: e11543.

Simard, S.W. 2009. The foundational role of mycorrhizal networks in self-organization of interior Douglas-fir forests. Forest Ecology and Management. 258: S95–S107.

Simard, M.; Romme, W.H.; Griffin, J.M.; Turner, M.G. 2011. Do mountain pine beetle outbreaks change the probability of active crown fire in lodgepole pine forests? Ecological Monographs. 81: 3–24.

Sinton, D.S.; Jones, J.A. 2002. Extreme winds and windthrow in the western Columbia River Gorge. Northwest Science. 76: 173–182.

Six, D.L.; Adams, J. 2007. White pine blister rust severity and selection of individual whitebark pine by mountain pine beetle (Coleoptera: Curculionidae: Scolytinae). Journal of Entomological Science. 42: 345–353.

Slesak, R.A.; Harrington, T.B.; D’Amato, A.W. 2016. Invasive scotch broom alters soil chemical properties in Douglas-fir forests of the Pacific Northwest, USA. Plant Soil. 398: 281–289.

Soulé, P.T.; Knapp, P.A. 2006. Radial growth rate increases in naturally occurring ponderosa pine trees: a late-20th century CO_2 fertilization effect? New Phytologist. 171: 379–390.

Sperry, J.S.; Venturas, M.D.; Todd, H.N. [et al.]. 2019. The impact of rising CO_2 and acclimation on the response of U.S. forests to global warming. Proceedings of the National Academy of Sciences, USA. 116: 25734–25744.

Spies, T.A.; Franklin, J.F. 1989. Gap characteristics and vegetation response in coniferous forests of the Pacific Northwest. Ecology. 70: 543–545.

Spies, T.A.; Hessburg, P.; Skinner, C. [et al.]. 2018. Old-growth, disturbance, forest succession, and management in the area of the Northwest Forest Plan. In: Spies, T.A.; Stine, P.A.; Gravenmier, R.; Long, J.W.; Reilly, M.J., tech. coords. Synthesis of science to inform land management within the Northwest Forest Plan area. Gen. Tech. Rep. PNW-GTR-966. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 95–243. Chapter 3.

Steinman, B.A.; Abbott, M.B.; Mann, M.E. [et al.]. 2014. Ocean-atmosphere forcing of centennial hydroclimate variability in the Pacific Northwest. Geophysical Research Letters. 41: 2553–2560.

Stevens-Rumann, C.S.; Kemp, K.B.; Higuera, P.E. [et al.]. 2018. Evidence for declining forest resilience to wildfires under climate change. Ecology Letters. 21: 243–252.

Stewart, I.T.; Cayan, D.R.; Dettinger, M.D. 2005. Changes toward earlier streamflow timing across western North America. Journal of Climate. 18: 1136–1155.

Stocker, T.F.; Qin, D.; Plattner, G.K. [et al.]. 2013. Climate change 2013: the physical science basis. Contribution of working group 1 to the fifth assessment report of the Intergovernmental Panel on Climate Change. New York. Cambridge University Press. 1535 p.

Sturrock, R.N.; Frankel, S.J.; Brown, A.V. [et al.]. 2011. Climate change and forest diseases. Plant Pathology. 60: 133–149.

Swanson, F.J.; Dyrness, C.T. 1975. Impact of clear-cutting and road construction on soil erosion by landslides in the western Cascade Range, Oregon. Geology. 3: 393–396.

Syphard, A.D.; Keeley, J.E.; Pfaff, A.H.; Ferschweiler, K. 2017. Human presence diminishes the importance of climate in driving fire activity across the United States. Proceedings of the National Academy of Sciences, USA. 114: 13750–13755.

Tague, C.; Grant, G.E. 2009. Groundwater dynamics mediate low-flow response to global warming in snow-dominated alpine regions. Water Resources Research. 45: W07421.

Taylor, K.E.; Stouffer, R.J.; Meehl, G.A. 2012. An overview of CMIP5 and the experimental design. Bulletin of the American Meteorological Society. 93: 485–498.

Teensma, P.D.A. 1987. Fire history and fire regimes of the central western Cascades of Oregon. Eugene, OR: University of Oregon. 188 p. Ph.D. dissertation.

Teensma, P.D.A.; Rienstra, J.T.; Yeiter, M.A. 1991. Preliminary reconstruction and analysis of change in forest stand age classes of the Oregon Coast Range from 1850 to 1940. Tech. Note OR-9. Portland, OR: U.S. Department of the Interior, Bureau of Land Management, Oregon State Office. 9 p.

Tepley, A.J.; Swanson, F.J.; Spies, T.A. 2013. Fire-mediated pathways of stand development in Douglas-fir/western hemlock forests of the Pacific Northwest, USA. Ecology. 94: 1729–1743.

Tepley, A.J.; Thompson, J.R.; Epstein, H.E.; Anderson-Teixeira, K.J. 2017. Vulnerability to forest loss through altered postfire recovery dynamics in a warming climate in the Klamath Mountains. Global Change Biology. 23: 4117–4132.

Thompson, J.R.; Spies, T.A.; Ganio, L.M. 2007. Reburn severity in managed and unmanaged vegetation in a large wildfire. Proceedings of the National Academy of Sciences, USA. 104: 10743–10748.

Thrasher, B.; Xiong J.; Wang, W. [et al.]. 2013. Downscaled climate projections suitable for resource management. Eos, Transactions, American Geophysical Union. 94: 321–323.

Thuller, W.; Albert, C.; Araujo, M.B. [et al.]. 2008. Predicting global change impacts on plant species’ distributions: future challenges. Perspectives in Plant Ecology, Evolution, and Systematics. 9: 137–152.

Topik, C.; Halverson, N.M.; High, T. 1988. Plant association and management guide for the ponderosa pine, Douglas-fir, and grand fir zones, Mount Hood National Forest. R6 Ecol. Tech. Pap. 004-88. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Region. 132 p.

Trouet, V.; Taylor, A.H.; Carleton, A.M.; Skinner, C.N. 2006. Fire-climate interactions in forests of the American Pacific coast. Geophysical Research Letters. 33: L18704.

Turner, D.P.; Conklin, D.R.; Bolte, J.P. 2015. Projected climate impacts on forest land cover and land use over the Willamette River Basin, Oregon, USA. Climatic Change. 133: 335–348.

Urgenson, L.S.; Reichard, S.H.; Halpern, C.B. 2009. Community and ecosystem consequences of giant knotweed (*Polygonum sachalinense*) invasion into riparian forests of western Washington, USA. Biological Conservation. 142: 1536–1541.

van Mantgem, P.J.; Stephenson, N.L.; Byrne, J.C. [et al.]. 2009. Widespread increase of tree mortality rates in the Western United States. Science. 323: 521–524.

van Vuuren, D.P.; Edmonds, J.; Kainuma, M. [et al.]. 2011. The representative concentration pathways: an overview. Climatic Change. 109: 5–31.

Voelker, S.L.; Merschel, A.G.; Meinzer, F.C. [et al.]. 2018. Fire deficits have increased drought sensitivity in dry conifer forests: fire frequency and tree-ring carbon isotope evidence from central Oregon. Global Change Biology. 25: 1247–1262.

Vose, J.M.; Peterson, D.L.; Patel-Wenard, T., eds. 2012. Effects of climatic variability and change on forest ecosystems: a comprehensive science synthesis for the U.S. forest sector. Gen. Tech. Rep. PNW-GTR-870. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 256 p.

Walsh, M.K.; Duke, H.J.; Haydon, K.C. 2018. Toward a better understanding of climate and human impacts on late Holocene fire regimes in the Pacific Northwest, USA. Progress in Physical Geography. 42: 478–512.

Walsh, M.K.; Lukens, M.L.; McCutcheon, P.T.; Burtchard, G.C. 2017. Fire-climate-human interactions during the postglacial period at Sunrise Ridge, Mount Rainier National Park, Washington (USA). Quaternary Science Reviews. 177: 246–264.

Walsh, M.K.; Marlon, J.R.; Goring, S.J. [et al.]. 2015. A regional perspective on Holocene fire-climate-human interactions in the Pacific Northwest of North America. Annals of the Association of American Geographers. 105: 1135–1157.

Walsh, M.K.; Whitlock, C.; Bartlein, P.J. 2008. A 14,300-year-long record of fire-vegetation-climate linkages at Battle Ground Lake, southwestern Washington. Quaternary Research. 70: 251–264.

Walther, G-R.; Beiβner, S.; Pott, R. 2005. Climate change and high mountain vegetation shifts. In: Broll, G.; Keplin, B., eds. Mountain ecosystems: studies in treeline ecology. New York. Springer: 75–96.

Ward, K.; Shoal, R.; Aubry, C. 2006. Whitebark pine in Washington and Oregon: a synthesis of current studies and historical data. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Region. 29 p.

Webster, P.J.; Holland, G.J.; Curry, J.A.; Chang, H-R. 2005. Changes in tropical cyclone number, duration, and intensity in a warming environment. Science. 309: 1844–1846.

Weisberg, P.J., 2009. Historical fire frequency on contrasting slope facets along the McKenzie River, Western Oregon Cascades. Western North American Naturalist. 69: 206–214.

Weisberg, P.J. 2004. Importance of non-stand-replacing fire for development of forest structure in the Pacific Northwest, USA. Forest Science. 50: 245–258.

Weisberg, P.J.; Swanson, F.J. 2003. Regional synchroneity in fire regimes of western Oregon and Washington, USA. Forest Ecology and Management. 172: 17–28.

Westerling, A.L.; Hidalgo, H.G.; Cayan, D.R.; Swetnam, T.W. 2006. Warming and earlier spring increase Western U.S. forest wildfire activity. Science. 313: 940–943.

Whitlock, C. 1992. Vegetational and climatic history of the Pacific Northwest during the last 20,000 years: implications for understanding present-day biodiversity. The Northwest Environmental Journal. 8: 5–28.

Whitlock, C.; Marlon, J.; Briles, C. [et al.]. 2008. Long-term relations among fire, fuel, and climate in the Northwestern U.S. based on lake sediment studies. International Journal of Wildland Fire. 17: 72–83.

Whitlock, C.; Shafer, S.L.; Marlon, J. 2003. The role of climate and vegetation change in shaping past and future fire regimes in the Northwestern U.S. and the implications for management. Forest Ecology and Management. 178: 5–21.

Whittier, T.R.; Gray, A.N. 2016. Tree mortality based fire severity classification for forest inventory surveys: a Pacific Northwest national forests example. Forest Ecology and Management. 359: 199–209.

Williams, D.W.; Liebhold, A.M. 1995. Forest defoliators and climatic change: potential changes in spatial distribution of outbreaks of western spruce budworm (Lepidoptera: tortricidae and gypsy moth (Lepidoptera: lymantriidae). Environmental Entomology. 24: 1–9.

Winograd, I.J.; Riggs, A.C.; Coplen, T.B. 1998. The relative contributions of summer and cool-season precipitation to groundwater recharge, Spring Mountains, Nevada. Hydrogeology Journal. 6: 77–93.

Winthers, E.; Fallon, D.; Haglund, J. [et al.]. 2005. Terrestrial ecological unit inventory technical guide: landscape and land unit scales. Gen. Tech. Rep. WO-68. Washington, DC: U.S. Department of Agriculture, Forest Service, Ecosystem Management Coordination Staff. 254 p.

Woodward, A.; Schreiner, E.G.; Silsbee, D.G. 1995. Climate, geography, and tree establishment in subalpine meadows of the Olympic Mountains, Washington, USA. Arctic and Alpine Research. 27: 217–225.

Wright, C.S.; Agee, J.K. 2004. Fire and vegetation history in the eastern Cascade Mountains, Washington. Ecological Application. 14: 443–459.

Zald, H.S.; Dunn, C.J. 2018. Severe fire weather and intensive forest management increase fire severity in a multi-ownership landscape. Ecological Applications. 28: 1068–1080.

Zald, H.S.; Spies, T.A.; Huso, M.; Gatziolis, D. 2012. Climatic, landform, and overstory canopy controls of tree invasion in a subalpine meadow landscape, Oregon Cascades, USA. Landscape Ecology. 27: 1197–1212.

Zhao, M.; Running, S.W. 2010. Drought-induced reduction in global terrestrial net primary production from 2000 through 2009. Science. 329: 940–943.

Zouhar, K.; Smith, J.K.; Sutherland, S.; Brooks, M.L. 2008. Wildland fire in ecosystems: fire and nonnative invasive plants. Gen. Tech. Rep. RMRS-GTR-42. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 355 p.

Chapter 5 Appendix

Table 5A.1—Rare habitats and threatened and endangered plant species in the Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest Adaptation Partnership assessment area

Habitat	Associated plants	National Forest System unit[a]
Cold moving water	Coldwater corydalis (*Corydalis aquae-gelidae* M. Peck & W.C. Wilson)	CRGNSA
Alpine talus	Whitebark pine	WIL, MTH
Lakes and ponds	Adder's tongue	WIL, MTH
High-elevation bogs, wetlands, fens	20 to 25 rare vascular and nonvascular plant species	WIL, MTH
Alpine meadows	Shorthair reedgrass (*Calamagrostis breweri* Thurb.)	WIL, MTH
Rock gardens (vernal annuals)	Thompson's mistmaiden (*Romanzoffia thompsonii* Marttala)	WIL
Wet, cool cliffs	Northern false coolwort (*Bolandra oregana*), Oregon daisy (*Erigeron speciosus* [Lindl.] DC.)	CRGNSA
Ridgetop flora	Hell's Canyon rockcress (*Boechera hastatula* [Greene] Al-Shehbaz)	WIL
Rocky cliffs, talus, grasslands	Broadleaf lupine *(Lupinus latifolius*), Barrett's beardtongue (*Penstemon barrettiae* A. Gray), and Suksdorf's desertparsley (*Lomatium suksdorfii* [S. Watson] J.M. Coult. & Rose) These species exist along a narrow zone from Hood River to The Dalles on both sides of the Columbia River. The general habitats are oak, grasslands, and combinations of the two in the dry areas within the rain shadow of the Cascade Mountains.	CRGNSA

[a] CRGNSA = Columbia River Gorge National Scenic Area, MTH = Mount Hood National Forest, WIL = Willamette National Forest.

Chapter 6: Climate Change Effects on Wildlife and Wildlife Habitats

Tristan Nuñez and Peter Singleton[1]

Introduction

Wildlife and Climate Change

The distribution and abundance of wildlife species in the Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest Adaptation Partnership (CMWAP) assessment area have always been dynamic, fluctuating in response to human, climatic, and biogeographical factors for millennia. However, climate change is causing rates of change that are unprecedented in the evolutionary history of contemporary species and exceed or strain many species' ability to keep pace (Clark et al. 2016b, Schloss et al. 2012).

Climate change is projected to alter the distribution and abundance of wildlife species globally and regionally by altering the availability and distribution of physiologically suitable temperatures and available moisture. Indirectly, climate change will alter the distribution of vegetation, food, shelter, and other resources on which animals rely, and the disease dynamics and interactions among species (Inkley et al. 2004). Depending on the species and place, suitable conditions may contract or disappear, shift in location, or expand (Lawler et al. 2009). Climate change in the CMWAP assessment area is acting on animals and ecosystems that are already affected by legacies of land use, including habitat loss and fragmentation.

Although almost all wildlife species will be affected by climate change, the nature of effects on individual species and their habitats is uncertain. In addition to uncertainty in projections from global climate models, for most species, quantitative models that project how habitat and resource components (e.g., vegetation structure and composition, plant and animal food sources, water) will be affected by climate change are incomplete or unavailable. Species distribution models, while useful for general insights, are coarse in spatial and temporal resolution, are usually correlative rather than mechanistic, and few focus on the CMWAP assessment area. Further, the ability of species to respond to changes in their habitats is poorly understood (Early and Sax 2011).

Trait-based, correlative, and mechanistic approaches are all used to project vulnerability to climate change (Pacifici 2015). Trait-based approaches rank species according to biological characteristics thought to affect vulnerability to

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[1] **Tristan Nuñez** is a wildlife biologist, Wyoming Cooperative Fish and Wildlife Research Unit, University of Wyoming, 1000 E University Avenue, Laramie, WY 82071-3166; **Peter Singleton** is a research wildlife biologist, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, 1133 N Western Avenue, Wenatchee, WA 98801.

climate change. Commonly used traits include degree of habitat specialization, movement ability, and physiological tolerances. Correlative approaches relate observed species distributions to their climatic niches, using those relationships to project distributions in response to altered distribution of climatic parameters (e.g., temperature). In contrast, mechanistic models use observations of physiology, energetics, population growth rates, dispersal abilities, and related measures, focusing on individual species. Each approach, combined with on-the-ground knowledge and expertise, can inform management actions.

Assessment Approach

This assessment synthesizes information on potential climate change effects on wildlife species in the CMWAP assessment area. We focus on all taxa of vertebrate fauna found in the region, except for fish, which are covered in chapter 4. Because of the lack of studies conducted in the assessment area, we relied heavily on studies from other locations, combined with general projections about climate, hydrology, and vegetation change elsewhere in this report. We also used literature on habitat requirements to make inferences about the vulnerability of species and habitats to climate change.

Vegetation communities as a habitat proxy—

This assessment is structured around the broad vegetation communities that provide habitat for wildlife species in the assessment area (fig. 6.1). These communities are an imperfect proxy for the habitat needs of specific species, and many species may rely on components found in more than one of the general groupings outlined here or may rely on additional habitat resources. Wildlife habitat includes not just one or more types of vegetation but also the availability of sufficient water, structures, and food, nesting, resting, thermal, and other resources that support different aspects of a species life history, including occupancy, survival, and reproduction (Morrison et al. 2006). In addition, these resources need to be arranged spatially in a way that allows for species persistence. A species habitat concept that incorporates the full combination of resources and conditions needed for persistence is critical to understanding climate change effects on spatial population dynamics. Thus, management of species of concern in a changing climate will require more detailed consideration of particular habitat requirements.

Vulnerability framework—

We adapted the approach of climate change vulnerability assessments, most frequently applied to individual species, to wildlife assemblages broadly associated with specific vegetation types (Case et al. 2015, Chapman et al. 2014, Halofsky et al. 2012). We assessed three components of vulnerability: exposure, sensitivity, and

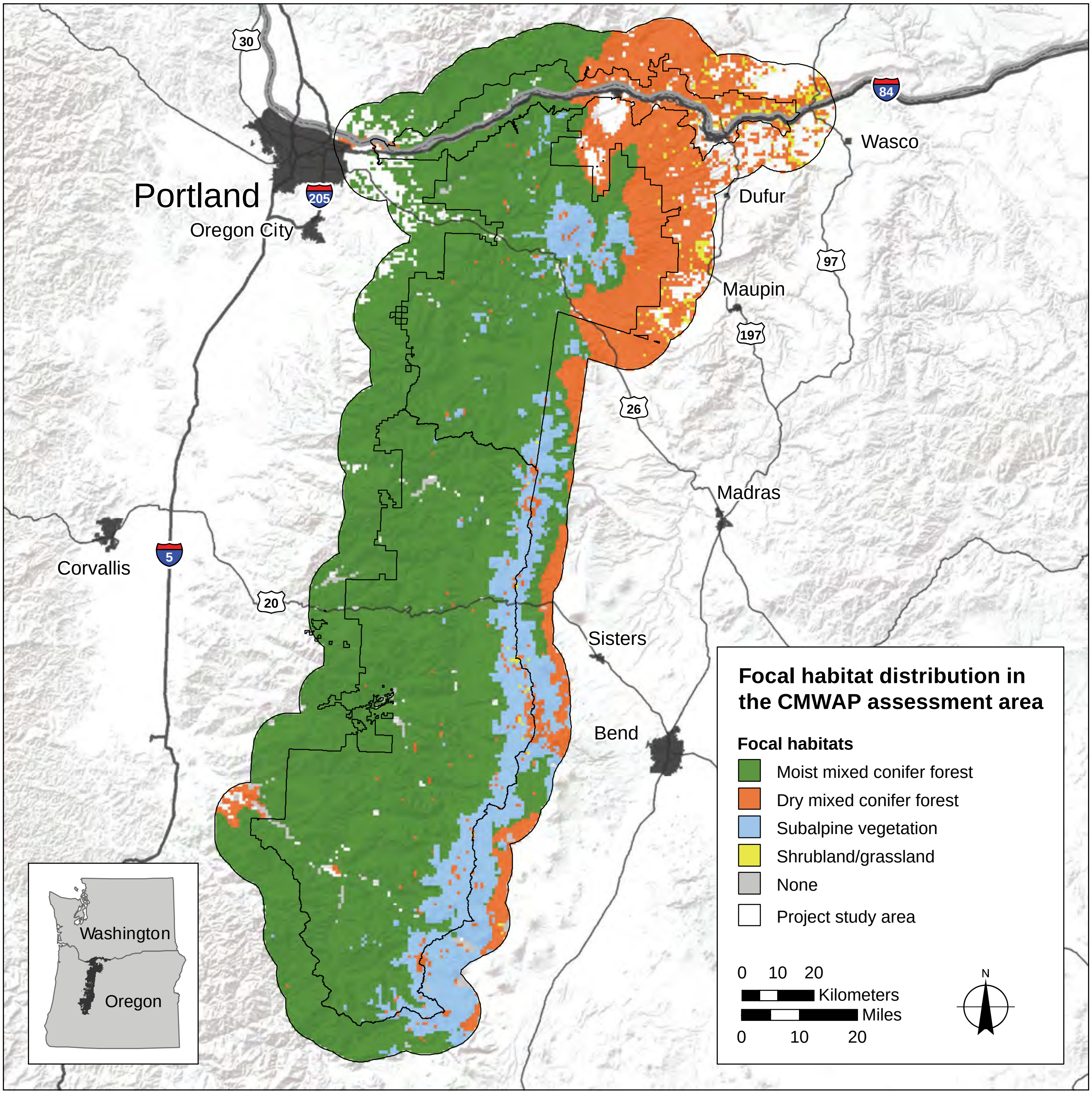

Figure 6.1—Distribution of some of the focal habitats in the Columbia River Gorge, Mount Hood, and Willamette National Forests Adaptation Partnership (CMWAP) assessment area. Other focal habitats occur at fine spatial scales and cannot be shown in a broad-scale map.

adaptive capacity (Turner et al. 2003, Williams et al. 2008). We defined the terms as follows:

- **Exposure**—The extent to which climate conditions or climate-driven processes will change in areas currently occupied by a given vegetation type.

- **Sensitivity**—The degree to which exposure will affect the persistence of wildlife species reliant on those vegetation types.
- **Adaptive capacity**—Opportunities for vegetation types or wildlife to change or move in ways that compensate for climate effects (e.g., behavioral changes, evolutionary adaptation, range shifts).

These terms and framework were directly adapted from the wildlife chapters of climate change vulnerability assessments conducted for southwest Oregon (Singleton et al. 2022) and south-central Oregon (Singleton et al. 2019). We augmented this framework, where possible, by referencing studies that use mechanistic or correlative approaches to evaluate the vulnerability of species in the assessment area.

Focal Habitats

We considered eight focal habitats found in the assessment area:

- Oak woodlands
- Coniferous forests
- Montane coniferous forests
- Subalpine forests
- East-side forests and mixed woodlands
- Shrub, grass, and rock
- Early-seral forests and brushfields
- Riparian, wetlands, and water

We considered the effects of climate change described in the climate (chapter 2), hydrology (chapter 3), fish (chapter 4), and vegetation (chapter 5) assessments and the implications for wildlife populations and their habitats. For each focal habitat, we described general characteristics (climate, vegetation communities, and structural or spatial characteristics and configurations significant to wildlife), and distribution. We then assessed exposure, sensitivity, and adaptive capacity of each habitat to climate change.

We relied heavily on the vegetation chapter (chapter 5) to describe vegetation-type exposure to climate change (figs. 6.2a, 6.2b, and 6.3). The MC2 vegetation model that underpins the vegetation chapter projects long-term changes in vegetation types, but because mature trees can withstand considerable climatic variability, changes in forests may take decades or centuries to occur in the absence of disturbance, such as wildfire (Parks et al. 2019). Thus, there is considerable uncertainty regarding the rate of vegetation and wildlife habitat change in the future.

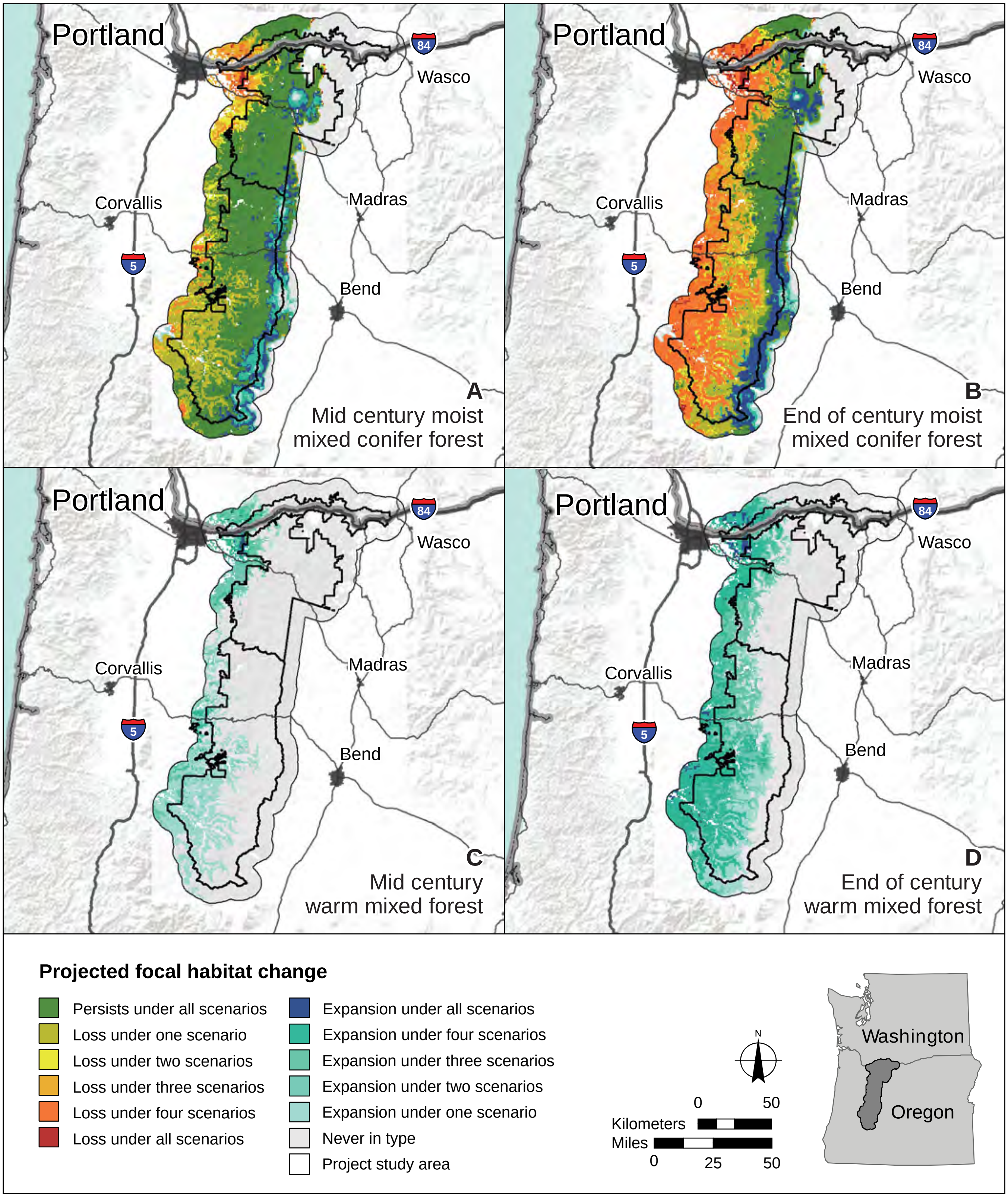

Figure 6.2a—Change in the proportion of the Columbia River Gorge, Mount Hood, and Willamette National Forests Adaptation Partnership assessment area capable of supporting moist mixed-conifer and warm mixed forests, based on MC2 projections using five global climate models (see fig. 6.3) representing a range of potential climate outcomes projected for mid century (2035–2064) and end of century (2070–2099) under Representative Concentration Pathway 8.5.

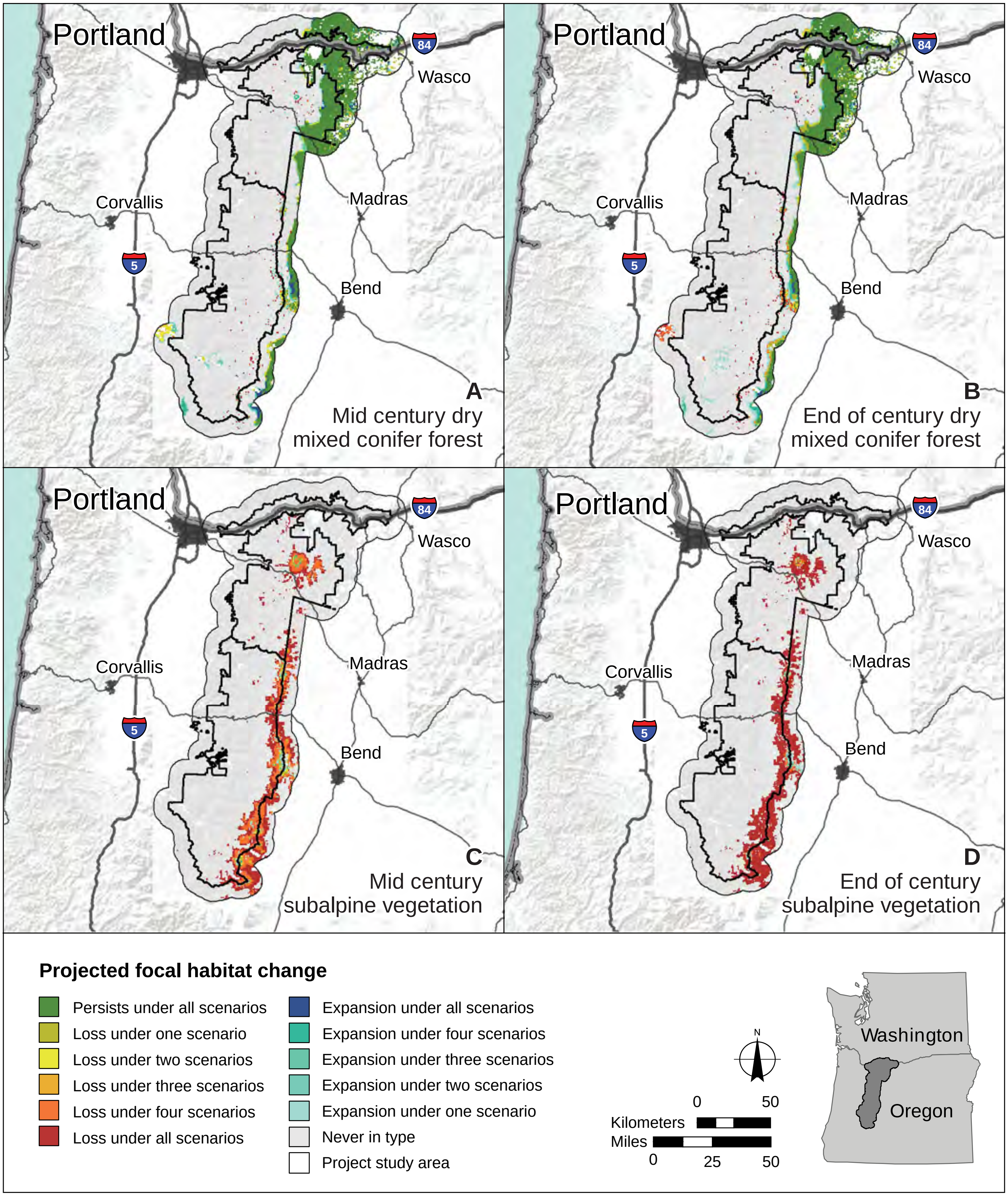

Figure 6.2b—Change in the proportion of the Columbia River Gorge, Mount Hood, and Willamette National Forests Adaptation Partnership assessment area capable of supporting dry mixed-conifer and subalpine vegetation, based on MC2 projections using five global climate models (see fig. 6.3) representing a range of potential climate outcomes projected for mid century (2035–2064) and end of century (2070–2099) under Representative Concentration Pathway 8.5.

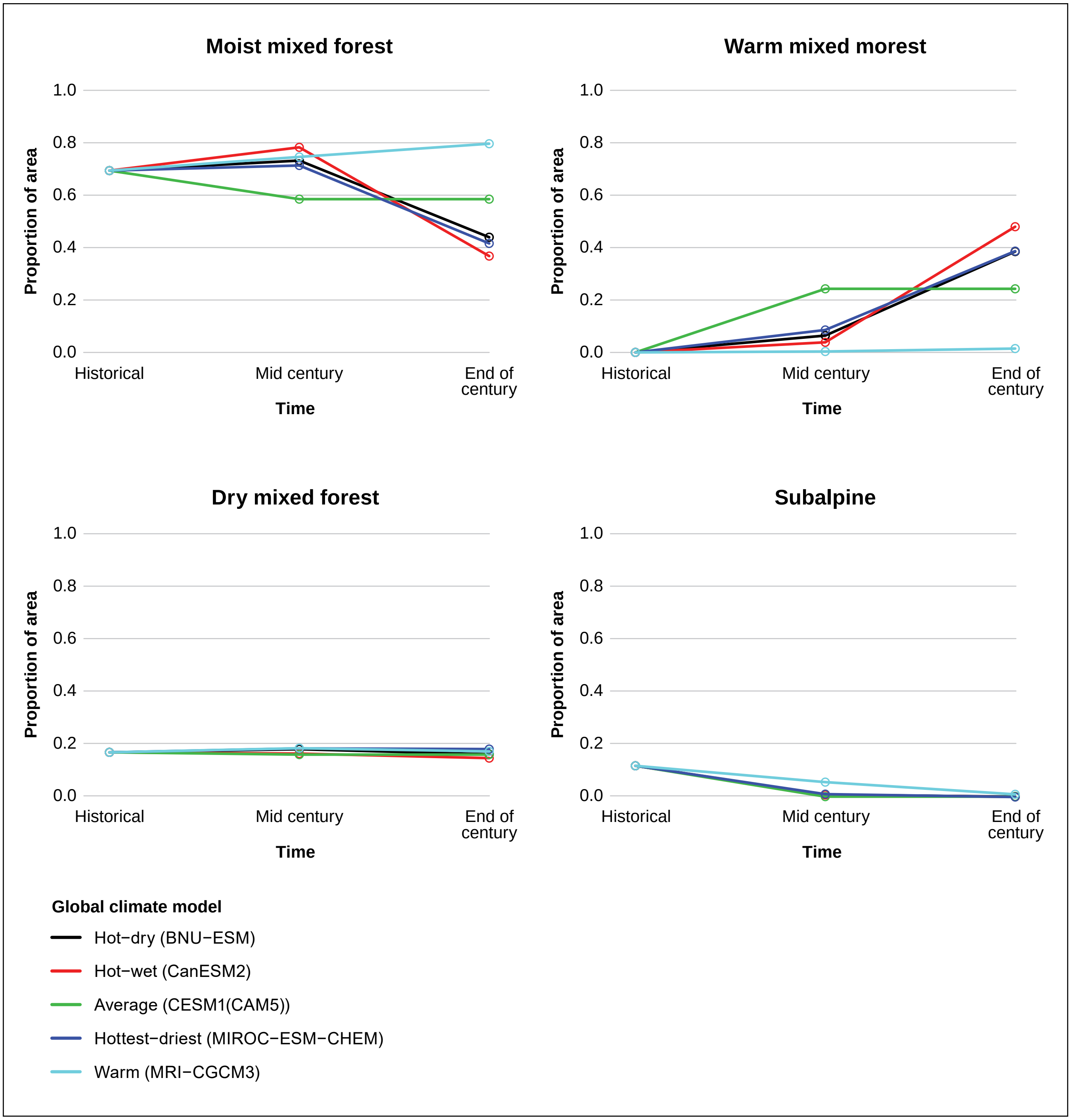

Figure 6.3—Change in the proportion of area in the CMWAP assessment area capable of supporting focal habitat types, based on MC2 projections using five global climate models representing a range of potential climate outcomes projected for mid century (2035–2064) and end of century (2070–2099) under Representative Concentration Pathway 8.5.

Regional Overview and History

The CMWAP assessment area comprises diverse landscapes characterized by different elevations, temperatures, moisture, soils, and vegetation. Over thousands of years, biogeographic diversity, along with both natural and human-caused disturbances, have shaped the region's habitats and the wildlife assemblages they support. The Cascade Range shapes the most prominent regional patterns, with relatively high rainfall, mild winters, and warm summers to the west; subalpine conditions at the crest; and arid conditions, cold winters, and hot summers to the east.

From west to east across the assessment area, oak woodlands and valleys of the Willamette Valley transition to coniferous forest and moist coniferous forest. Subalpine forests, woodlands, and meadows characterize the high elevations of the Cascade crest. On the east side of the Cascade crest, subalpine forest transitions to moist mixed coniferous forest, then to ponderosa pine forests (see table 6.1 for scientific names of species in this chapter) and oak woodlands, and to shrublands and grasslands at low elevations. To the north, the Columbia River Gorge creates steep climatic and biogeographic gradients, connecting wet forests in the west to arid grasslands to the east. Southern portions of the assessment area, particularly on dry, south-facing slopes in Willamette National Forest, support vegetation similar to dry coniferous forests of southwestern Oregon.

Fine-scale spatial heterogeneity in climate and soil contribute to a diversity of conditions, which differ with aspect, slope, and fine-scale hydrology. Complex elevation gradients created by river valleys in the Cascades result in heterogeneous vegetation communities. Throughout the assessment area, north-facing slopes are often markedly different in vegetative cover than south-facing slopes. Diverse landcover types and landforms, including riparian areas, seeps and springs, caves, talus slopes, and cliffs, all provide wildlife species with habitat resources. Different stages of forest development also contribute different resources; early-seral vegetation can provide important resources, biological legacies (e.g., snags and downed wood, remaining live trees), and young vegetation preferred by some animals; whereas late-seral habitats provide structures (big trees and snags, multistory canopies) needed by other animals.

Human activities have shaped the region's vegetation and wildlife assemblages. Historically, indigenous communities used burning to maintain open grasslands and oak woodlands at lower elevations (Aikens et al. 2011), particularly to maintain acorn, camas, and berry resources, and they continue to do so on the Warm Springs Indian Reservation adjacent to the assessment area. However, the intensity, frequency, and distribution of these activities is unknown. Euro-American exploration, settlement, and industrialization brought trapping of fur bearers; carnivore extermination campaigns; extensive logging, mining, grazing, road and urban development; and fire suppression. These activities altered vegetation and faunal assemblages and caused numerous wildlife species extirpations.

More recent land use affects the landscape in which wildlife species will respond to climate change. Forest management over the past century has altered the ecological characteristics and dynamics of the region. For example, logging across the assessment area and adjacent private lands has reduced the amount and connectivity of late-seral forest habitat. Extensive road networks have facilitated the dispersal of nonnative and invasive species and created barriers to wildlife species movement. Significant portions of the CMWAP assessment area are also used for recreation (chapter 7), and recreation use in sensitive habitats may constrain the ability of wildlife species to adapt to climate change.

Table 6.1—Common and scientific names for plant, animal, and fungal species discussed in this chapter

Common name	Scientific name
Acorn woodpecker	*Melanerpes formicivorus* Swainson
American beaver	*Castor canadensis* Kuhl
American marten	*Martes americana* Turton
American mink	*Mustela vison* Schreber
American peregrine falcon	*Falco peregrinus anatum* Bonaparte
American pika	*Ochotona princeps* Richardson
American pipit	*Anthus rubescens* Tunstall
Ash-throated flycatcher	*Myiarchus cinerascens* Lawrence
Bald eagle	*Haliaeetus leucocephalus* Linnaeus
Band-tailed pigeon	*Patagioenas fasciata* Say
Barred owl	*Strix varia* Barten
Barren juga	*Juga hemphilli* J. Henderson
Beller's ground beetle	*Agonum belleri* Hatch
Big sagebrush	*Artemisia tridentata* Nutt.
Bigleaf maple	*Acer macrophyllum* Pursh
Black bear	*Ursus americanus* Pallas
Black swift	*Cypseloides niger* Gmelin
Blue-gray taildropper	*Prophysaon coeruleum* Cockerell
Black-backed woodpecker	*Picoides arcticus* Swainson
Black-tailed deer	*Odocoileus hemionus hemionus* Rafinesque
Bobcat	*Lynx rufus* Schreber
Brewer's sparrow	*Spizella breweri* Cassin
Broadwhorl tightcoil	*Pristiloma johnsoni* Dall
Brown creeper	*Certhia americana* Bonaparte
Bufflehead	*Bucephala albeola* L.
California black oak	*Quercus kelloggii* Newberry
California floater	*Anodonta californiensis* Lea
California mountain kingsnake	*Lampropeltis zonata* Lockington ex Blainville
California shield-backed bug	*Vanduzeeina borealis* Van Duzee
Camas	*Camassia* spp. Lindl.
Canada lynx	*Lynx canadensis* Kerr
Cascade torrent salamander	*Rhyacotriton cascadae* Good and Wake
Cascades axetail slug	*Carinacauda stormi* Leonard, Chichester, Richart and Young
Cascades frog	*Rana cascadae* Slater

Table 6.1—Common and scientific names for plant, animal, and fungal species discussed in this chapter (continued)

Common name	Scientific name
Cassin’s finch	*Haemorhous cassinii* S.F. Baird
Cheatgrass	*Bromus tectorum L.*
Chestnut-backed chickadee	*Poecile rufescens* J.K. Townsend
Chipmunk	*Tamias* spp. Illiger
Chipping sparrow	*Spizella passerina* Bechstein
Clark’s grebe	*Aechmophorus clarkii* Lawrence
Clark’s nutcracker	*Nucifraga columbiana* A. Wilson
Clouded salamander	*Aneides ferreus* Cope
Columbia Gorge caddisfly	*Neothremma andersoni* Wiggins
Columbia Gorge oregonian	*Cryptomastix hendersoni* Pilsbry
Columbia pebblesnail	*Fluminicola columbiana* Hemphill
Columbia River tiger beetle	*Cicindela columbica* Hatch
Columbia sideband	*Monadenia fidelis* J.E. Gray
Columbian white-tailed deer	*Odocoileus virginianus leucurus* Douglas
Common loon	*Gavia immer* Brunnich
Cope’s giant salamander	*Dicamptodon copei* Nussbaum
Coyote	*Canis latrans* Say
Crater Lake tightcoil	*Pristiloma crateris* Pilsbry
Crowned tightcoil	*Pristiloma pilsbryi* Vanatta
Dalles hesperian	*Vespericola columbiana depressa* Pilsbry & Henderson
Dalles juga	*Juga hemphilli dallesensis* J. Henderson
Dalles sideband	*Monadenia fidelis minor* W.G. Binney
Deschutes mountainsnail	*Oreohelix variabilis* J. Henderson
Dog star skipper	*Polites sonora siris* W.H. Edwards
Douglas-fir	*Pseudotsuga menziesii* (Mirb.) Franco
Douglas’s squirrel	*Tamiasciurus douglasii* Bachman
Elk	*Cervus elaphus* L.
Ermine	*Mustela erminea* L.
Ferruginous hawk	*Buteo regalis* G.R. Gray
Flammulated owl	*Psiloscops flammeolus* Kaup
Foliaceous lace bug	*Derephysia foliacea* Fallén
Fringed myotis	*Myotis thysanodes* Miller
Golden hairstreak	*Habrodais grunus* Boisduval
Grand fir	*Abies grandis* (Douglas ex D. Don) Lindl.
Grasshopper sparrow	*Ammodramus savannarum* J.F. Gmelin
Gray wolf	*Canis lupus* L.
Gray blue butterfly	*Plebejus podarce* C. Felder and R. Felder
Gray-crowned rosy finch	*Leucosticte tephrocotis* Swainson
Gray flycatcher	*Empidonax wrightii* S.F. Baird
Great basin fritillary	*Speyeria egleis* Behr
Great gray owl	*Strix nebulosa* J.R. Forster
Greater sage-grouse	*Centrocercus urophasianus* Bonaparte
Green-tailed towhee	*Pipilo chlorurus* Audubon
Ground squirrel	*Spermophilus* spp. F. Cuvier
Harlequin duck	*Histrionicus histrionicus* L.
Horned grebe	*Podiceps auritus* L.
Horned lark	*Eremophila alpestris* L.
Huckleberry	*Vaccinium* spp. L.
Incense cedar	*Calocedrus decurrens* (Torr.) Florin
Jackson Lake springsnail	*Pyrgulopsis robusta* Walker
Johnson’s hairstreak	*Callophrys johnsoni* Skinner
Larch Mountain salamander	*Plethodon larselli* Burns
Least bittern	*Ixobrychus exilis* Gmelin
Lewis’ woodpecker	*Melanerpes lewis* G.R. Gray

Table 6.1—Common and scientific names for plant, animal, and fungal species discussed in this chapter (continued)

Common name	Scientific name
Limber pine	*Pinus flexilis* James
Lodgepole pine	*Pinus contorta* var. *murrayana* Douglas
Long-tailed weasel	*Mustela frenata* Lichtenstein
Long-toed salamanders	*Ambystoma macrodactylum* Baird
Malone jumping-slug	*Hemphillia malonei* Pilsbry
Mardon skipper	*Polites mardon* W.H. Edwards
Meadow voles	*Microtus* spp. Schrank
Merlin	*Falco columbarius* L.
Monarch butterfly	*Danaus plexippus* L.
Mountain bluebird	*Sialia currucoides* Bechstein
Mountain goat	*Oreamnos americanus* Blainville
Mountain hemlock	*Tsuga mertensiana* (Bong.) Carrière
Mountain lion	*Puma concolor* L.
Mountain quail	*Oreortyx pictus* Douglas
Nerite ramshorn	*Vorticifex neritoides*
Noble fir	*Abies procera* Rehder
Northern flying squirrel	*Glaucomys sabrinus* Shaw
Northern goshawk	*Accipiter gentilis* L.
Northern Pacific rattlesnake	*Crotalus oreganus oreganus* Holbrook
Northern raccoon	*Procyon lotor* L.
Northern spotted owl	*Strix occidentalis caurina* Merriam
Northern waterthrush	*Parkesia noveboracensis* J.F. Gmelin
Olive-sided flycatcher	*Contopus cooperi* Nuttall
Olympia pebblesnail	*Fluminicola virens* Lea
One-spot rhyacophilan caddisfly	*Rhyacophila unipunctata* Schmid
Orange-crowned warbler	*Oreothlypis celata* Say
Oregon megomphix	*Megomphix hemphilli* W.G. Binney
Oregon slender salamander	*Batrachoseps wrighti* Bishop
Oregon spotted frog	*Rana pretiosa* Baird and Girard
Oregon vesper sparrow	*Pooecetes gramineus affinis* G.S. Miller
Oregon white oak	*Quercus garryana* var. *garryana* Douglas ex Hook
Pacific chorus frog	*Pseudacris regilla* Baird and Girard
Pacific clubtail	*Gomphus kurilis* Hagen in Selys
Pacific fisher	*Pekania pennanti* Erxleben
Pacific giant salamander	*Dicamptodon tenebrosus* Baird and Girard
Pacific madrone	*Arbutus menziesii* Pursh
Pacific marten	*Martes caurina* Merriam
Pacific silver fir	*Abies amabilis* Douglas ex J. Forbes
Pacific-slope flycatcher	*Empidonax difficilis* S. F. Baird
Painted turtle	*Chrysemys picta* Schneider
Pallid bat	*Antrozous pallidus* LeConte
Pileated woodpecker	*Dryocopus pileatus* L.
Pine siskin	*Spinus pinus* A. Wilson
Pine grosbeak	*Pinicola enucleator* L.
Pocket gopher	*Thomomys* spp. Wied-Neuwied
Ponderosa pine	*Pinus ponderosa* C. Lawson
Pristine springsnail	*Pristinicola hemphilli* Pilsbry
Propertius duskywing	*Erynnis propertius* Scudder and Burgess
Puget oregonian	*Cryptomastix devia* Gould
Purple-lipped juga	*Juga hemphilli maupinensis* J. Henderson
Purple martin	*Progne subis* L.
Pygmy nuthatch	*Sitta pygmaea* Vigors
Pygmy rabbit	*Brachylagus idahoensis* Merriam
Quaking aspen	*Populus tremuloides* Michx.

Table 6.1—Common and scientific names for plant, animal, and fungal species discussed in this chapter (continued)

Common name	Scientific name
Reed canarygrass	*Phalaris arundinacea* L.
Red alder	*Alnus rubra* Bong.
Red crossbill	*Loxia curvirostra* L.
Red fox	*Vulpes vulpes* L.
Red tree vole	*Arborimus longicaudus* True
Rocky Mountain duskysnail	*Colligyrus greggi* Pilsbry
Sagebrush	*Artemisia* spp. L.
Sage thrasher	*Oreoscoptes montanus* J.K. Townsend
Salal	*Gaultheria shallon* Pursh
Scott's apatanian caddisfly	*Allomyia scotti* Wiggins
Shiny tightcoil	*Pristiloma wascoense* Hemphill
Shortface lanx	*Fisherola nuttalli* Haldeman
Sierra Nevada red fox	*Vulpes vulpes necator* Merriam
Slender-billed nuthatch	*Sitta carolinensis aculeata* Cassin
Snowshoe hare	*Lepus americanus* Erxleben
Sonora skipper	*Polites sonora* Scudder
Southern flying squirrel	*Glaucomys volans* L.
Streaked horned lark	*Eremophila alpestris strigata* Henshaw
Striped skunk	*Mephitis mephitis* Schreber
Striped whipsnake	*Coluber taeniatus* Hallowell
Subalpine fir	*Abies lasiocarpa* (Hook.) Nutt.
Sudden oak death	*Phytophthora ramorum* Werres et al.
Tombstone Prairie caddisfly	*Oligophlebodes mostbento* Schmid
Townsend's big-eared bat	*Corynorhinus townsendii* Cooper
Valley silverspot	*Speyeria zerene bremnerii* W.H. Edwards
Van Dyke's salamander	*Plethodon vandykei* Van Denburgh
Varied thrush	*Ixoreus naevius* Gmelin
Vaux's swift	*Chaetura vauxi* J.K. Townsend
Ventenata	*Ventenata dubia* (Leers) Coss.
Wahkeena Falls flightless stonefly	*Nanonemoura wahkeena*
Western bluebird	*Sialia mexicana* Swainson
Western bumblebee	*Bombus occidentalis* Greene
Western gray squirrel	*Sciurus griseus* Ord
Western hemlock	*Tsuga heterophylla* (Raf.) Sarg
Western juniper	*Juniperus occidentalis* Hook.
Western meadowlark	*Sturnella neglecta* Audubon
Western painted turtle	*Chrysemys picta bellii* Gray
Western pond turtle	*Actinemys marmorata* Baird and Girard
Western redcedar	*Thuja plicata* Donn ex D. Don
Western ridged mussel	*Gonidea angulata* Lea
Western spotted skunk	*Spilogale gracilis* Merriam
Western toad	*Anaxyrus boreas* Baird and Girard
Whitebark pine	*Pinus albicaulis* Engelm.
White-breasted nuthatch	*Sitta carolinensis* Latham
White-headed woodpecker	*Picoides albolarvatus* Cassin
White pine blister rust	*Cronartium ribicola* A. Dietr.
White salmon pocket gopher	*Thomomys talpoides limosus Merriam*
Wild turkey	*Meleagris gallopavo* L.
Williamson's sapsucker	*Sphyrapicus thyroideus* Cassin
Winged floater	*Anodonta nuttalliana* Lea
Wolverine	*Gulo gulo* L.
Yellow-billed cuckoo	*Coccyzus americanus* L.
Yellow-bellied marmot	*Marmota flaviventris* Audubon and Bachman
Yuma skipper	*Ochlodes yuma* W.H. Edwards

Climate Change Projections

The climate in the CMWAP assessment area is changing rapidly. Projections indicate that temperatures will be warmer, increasing by 4.6 °C by the end of the century (chapter 2). Growing-degree days may double by the end of the century, potentially increasing vegetation productivity (chapter 5). Projected annual precipitation trends are unclear, but increasing temperatures will lead to increasing drought stress, with a doubling of historical climatic water deficit by the end of the 21st century, particularly at elevations above 2100 m (chapter 2). In addition, more precipitation will fall as rain rather than snow at higher elevations, affecting vegetation, soil moisture, and streamflow (chapter 3), leading to a loss of habitat for montane species associated with spring snowpack. In addition, both vegetation and wildlife will be exposed to higher levels of climatic variability, including droughts, heat waves, and storms (Vázquez et al. 2017).

Climate change will affect wildfire, insects, and disease across the CMWAP assessment area. Hotter and drier conditions will likely increase fire frequency and extent (chapter 5). Trees stressed by increased growing-season drought are expected to be more vulnerable to insect outbreaks and some diseases, and temperature-limited pathogens may be able to move to higher elevations. However, pathogen dynamics will vary by region and host and pathogen species.

Characteristic Sensitive and Threatened and Endangered Species

Responses of individual species to climate change will depend on their life history characteristics and the ecosystems of which they are a part. Several species with reduced populations are of particular importance to resource managers because of regulations associated with management of their habitat, and these species may be further stressed by changing climatic conditions. These include species listed as threatened or endangered at the state or federal level, and Interagency Special Status/Sensitive Species Program (ISSSSP) species. When discussing each focal habitat, we provide a table of the ISSSSP species associated with that habitat, drawing from the 2015 ISSSSP species list for the U.S. Department of Agriculture, Forest Service, Pacific Northwest Region.

In the CMWAP assessment area, there are four federally listed species: northern spotted owl, yellow-billed cuckoo, Oregon spotted frog, and gray wolf (in the White River Wolf Activity Area on Mount Hood National Forest). The Pacific fisher is proposed to be listed, but it is unknown if it occurs in the assessment area. The streaked horned lark, which uses grassland habitats in the Willamette Valley, is listed as threatened but is not thought to be present in the assessment area; however, future climatic conditions may create suitable habitat at lower elevations. Mountain quail is a federal species of concern east of the Cascade Range. Wolverine, listed by Oregon as threatened, is not regularly present in the assessment area, but they may disperse through the region. The presence of Canada lynx (federally listed as threatened) in the assessment area is unclear, but there is potential for dispersing individuals to use the region (Ruediger et al. 2000).

Most top carnivores have been extirpated from most of the assessment area, including gray wolves, wolverines, and Pacific fishers. The trophic effects of these losses are uncertain for the assessment area, although they have been studied in other regions. Recolonizing gray wolves have recently established packs in the Mount Hood and Willamette National Forests and are likely to recolonize most of the Oregon Cascades (Larsen and Ripple 2006). Other mammalian carnivores found in the area include red fox, coyote, American marten, bobcat, black bear, mountain lion, northern raccoon, American mink, long-tailed weasel, ermine, and striped and western spotted skunks (Mcfadden-Hiller and Hiller 2015).

Oak Woodlands

Description

We consider oak woodlands, savannas, and prairies on both the east and west sides of the Cascade Range in this section. West-side oak woodlands and prairies are distributed in small, remnant patches throughout the Willamette Valley and bordering and extending into the CMWAP assessment area. Before Euro-American settlement, indigenous communities maintained oak woodlands by intentional burning (Walsh 2008). Following Euro-American settlement and fire suppression practices, many areas that were previously oak woodlands in the region have transitioned to coniferous forests, with younger Douglas-fir trees overtopping remnant oak trees (Vesely and Rosenberg 2010). Oregon white oak is the dominant tree species, with California black oak occurring to the south of the assessment area in Lane County (Hagar and Stern 2001).

East-side oak woodlands occur in the transition zone between conifer forest and shrub-steppe, in a narrow band of climatic and disturbance conditions that allow for dominance of Oregon white oaks. Ponderosa pine is a frequent associate of oaks on xeric sites on the east side. The east-side Oregon white oak restoration strategy emphasizes that the primary conservation goal for this vegetation type is the “restoration of healthy, reproducing oak trees, as well as ponderosa pine, native understory vegetation, and associated wildlife species” (Devine et al. 2013).

Habitat attributes—

West-side oak woodlands typically comprise mosaics of trees, grasses, and shrubs; the proximity of these resources to each other is important to many species (Hagar and Stern 2001, Vesely and Rosenberg 2010). Oak trees provide acorns and cavities for wildlife species (for a review, see McShea and Healy 2002). Oak woodlands were sustained by frequent fire-return intervals, which were largely lost with Euro-American settlement in the region; over 95 percent of native prairie and oak woodlands have been lost (Hamman et al. 2011). Local extirpations of Lewis's woodpecker from Willamette National Forest are likely due to the loss of oak woodland habitat (Hagar and Stern 2001).

East-side oak woodlands provide similar resources; acorns, leaves, and invertebrates are notable food resources, and structural resources include cavities, perches, and shade (Devine et al. 2013). Several wildlife species require both large oak and ponderosa pine trees in combination, including western gray squirrel, wild turkey, and Lewis's woodpecker. East-side oaks occur in oak-dominated woodland patches, in mixed stands with ponderosa pine, and as late-seral trees in denser, mixed-conifer stands.

Characteristic species—

Characteristic species in east-side oak woodlands include the white-headed woodpecker, Lewis's woodpecker, western gray squirrel, and ash-throated flycatcher. Historical and present-day wildlife species assemblages in Willamette Valley oak woodlands were reviewed by Vesely and Rosbenberg (2010), who estimated that 50 native mammals, 87 avian species, 13 amphibians, and more than 15 species of reptiles use the habitat for feeding and breeding. They highlight the northern Pacific rattlesnake, western pond turtle, western painted turtle, western gray squirrel, acorn woodpecker, streaked horned lark, white-breasted nuthatch, western bluebird, chipping sparrow, Oregon vesper sparrow, and western meadowlark. Wildlife-habitat associations in this vegetation type were reviewed by Altman et al. (2001).

Over a dozen butterfly species in the Willamette Valley are associated with oak woodlands and are considered at risk. Most are extirpated from the assessment area, but the Propertius duskywing and the Sonora skipper are still present (Schultz et al. 2011). A breeding population of monarch butterflies occurs on the Middle Fork Willamette River in Willamette National Forest.[2]

The historical ranges of the streaked horned lark (federally threatened) and Columbian white-tailed deer (federally endangered), both associated with oak woodlands, overlap the CMWAP assessment area, although neither are known to occur within it. Oak woodland-associated ISSSSP species include Lewis's woodpecker, grasshopper sparrow, merlin, American peregrine falcon, bald eagle, pallid bat, Townsend's big-eared bat, and fringed myotis (table 6.2). Breeding

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[2] Joseph Doerr. 2019. Personal communication. Wildlife biologist, Willamette National Forest, 3106 Pierce Parkway Suite D, Springfield, OR 97477.

populations of Lewis's woodpeckers are not presently found in Willamette National Forest, likely owing to loss of oak woodland habitat, but are found in east-side oak woodlands in Mount Hood National Forest. Oregon Conservation Strategy "strategy species" found in oak woodlands include Columbian white-tailed deer, chipping sparrow, white-breasted nuthatch, and Lewis's woodpecker.

Nonclimatic stressors—

Nonclimatic stressors in oak woodland ecosystems include lack of fire, increased density of conifers, land development, invasive species, and urban recreation (ODFW 2006). Less than 5 percent of original oak woodlands remain in the Willamette Valley, mostly on private lands (ODFW 2006, Vesely and Rosenberg 2010). Historical and ongoing land conversion to agricultural, residential, and other uses has led to the loss of much of this habitat type (Altman 2011). Euro-American settlement of the Willamette Valley ended indigenous burning practices that previously maintained oak woodland habitat. Historical and continued fire suppression has led to encroachment by conifers, increasing tree densities, loss of savanna-like structures in remaining oak forests, and fewer large-diameter oaks with lateral limb structure and cavities. These structural changes have increased risk to high-severity fire (Altman 2011). Oak woodlands also experience heavy recreational use.

Invasive species can have substantial impacts on wildlife habitat in oak woodlands. European invasive annual grasses have replaced native perennial grasses in many areas (Standiford and Purcell 2015), competing for soil moisture with oak seedlings. Overgrazing by cattle has directly and indirectly facilitated the spread of invasive annual grasses and the associated decline of native perennial grasses (Standiford and Purcell 2015). Cattle can also reduce oak regeneration by consuming young oak shoots.

Exposure

The effects of climate change on oak woodlands are uncertain, but paleoecological studies suggest that with warmer, drier conditions, oak woodlands are likely to expand upslope and in areas along the eastern margins of the Willamette Valley (chapter 5). Projected increases in fire frequency are likely to favor large, fire-resistant oaks, provided that large oak trees can survive initial fires in areas that have high fuel loads. In lower elevation areas along the western boundary of the assessment area, the MC2 vegetation model projected a transition from the current moist coniferous forest type to a warm mixed-forest type by mid-21st century (fig. 6.2), and a subtropical mixed-forest type by the end of the century (chapter 5). This simulated transition suggests that future conditions will be conducive to hardwoods, including oak, bigleaf maple, and Pacific madrone.

Table 6.2—Interagency Special Status/Sensitive Species Program species associated with oak woodland habitat

			Occurrence status[b c]			
Region	**Common name**	**Status[a]**	**CRG-WA**	**CRG-OR**	**MTH**	**WIL**
West-side oak woodlands	Acorn woodpecker	WA-SEN	D			
East- and west-side oak woodlands	California mountain kingsnake	WA-SEN	D			
East-side oak woodlands	Lewis's woodpecker	SEN	D	D	D	S
East side oak woodlands	Pallid bat	OR-SEN		D		S
West side oak woodlands	Slender-billed nuthatch	WA-STR	S			
West side oak woodlands	Valley silverspot	OR-STR/WA-SEN				S
East- and west-side oak woodlands	Western gray squirrel	WA-SEN	D			

[a] SEN = Sensitive in Oregon and Washington; OR-SEN = Sensitive in Oregon; OR-STR = Strategic in Oregon; WA-SEN = Sensitive in Washington; WA-STR= Strategic in Washington.

[b] CRG-WA = Columbia River Gorge National Scenic Area in Washington; CRG-OR = Columbia River Gorge National Scenic Area in Oregon; MTH = Mount Hood National Forest; WIL = Willamette National Forest.

[c] D = documented occurrence: a species located on land administered by the Forest Service based on historical or current known sites of a species reported by a credible source for which the Forest Service has knowledge of written, mapped, or specimen documentation of the occurrence; S = suspected occurrence: species is not documented on land administered by the Forest Service, but may occur on the unit because (1) the national forest is considered to be within the species' range, and (2) appropriate habitat is present, or (3) there is known occurrence of the species (historical or current) in the vicinity such that the species could occur on Forest Service land.

Sensitivity

The reduced extent and fragmented nature of oak woodlands increase their sensitivity and the sensitivity of the wildlife populations they support to climate change. Fragmented habitat patches make it more difficult for populations to disperse or recolonize locally extirpated habitats. Fragmentation and high levels of human activity also increase exposure to invasive species, whose spread will likely be facilitated by disturbances associated with climate change.

Fire exclusion has led to denser oak woodlands composed of smaller, less fire-resistant trees. These conditions, along with invasive annual grasses, may lead to stand-replacing fires. Should this occur, important habitat structures, such as large-diameter trees and snags that provide food resources and cavities, will be lost. Although Oregon white oak is not affected by sudden oak death, California black oaks near the southern portion of the assessment area may become more susceptible under increasingly warm, wet conditions (Václavík et al. 2010). Oak woodland habitats are attractive areas for real estate development, and increased development would likely increase fragmentation of landscapes through increased habitat conversion on private lands (ODFW 2006).

Adaptive Capacity

Oaks and prairie grasses are drought resistant, and oaks are fire resistant. These traits suggest that oaks will be relatively tolerant of increased drought and fire frequency with climate change. Increased fire frequency will help maintain woodland conditions characterized by mosaics of trees, shrubs, and grasses.

Adaptive capacity in areas where oaks have been lost, or in future suitable areas, is limited by the relatively long period required for oak woodlands to develop large, widely spaced trees intermixed with grasslands and shrubs. The topographic position of oak woodlands in the Willamette Valley and foothills provides this habitat type with significant potential to shift upslope as conditions become warmer and drier, but many decades will be needed for important habitat features to develop. Oaks depend on animal dispersal of acorns, so upslope range shifts depend on sufficient connectivity to allow dispersal of acorns and other plant seeds by animals (Nathan et al. 2008).

The Oregon Conservation Strategy recommends identifying areas upslope of the current range that may support habitats (ODFW 2006). Climate-smart strategies that have been recommended for Pacific Northwest prairies and can be applied to oak woodlands include (1) leveraging the wide geographic distribution of these habitat types, (2) maintaining heterogeneous habitats to sustain populations and functions of multiple animal species, and (3) establishing new oak woodlands on lands that become newly suitable with climate change (Bachelet et al. 2011).

Coniferous Forests

We consider two general coniferous forest types in this chapter (combined in moist mixed-conifer forests in fig. 6.1). In this section we address the western hemlock zone, which is dominated by Douglas-fir. This zone covers 35 percent of the CMWAP assessment area. In the next section, we address montane coniferous forests in the Pacific silver fir zone, which occur at higher elevations than the western hemlock zone and cover 37 percent of the assessment area. This vegetation zone is characterized by noble fir and Pacific silver fir.

Description

The western hemlock zone is dominated by Douglas-fir, with western hemlock increasing in abundance in later successional stages. Numerous other coniferous and hardwood tree species are also present, depending on local climates and successional stages. Western redcedar is prevalent at lower elevations on moist sites. Common hardwoods include bigleaf maple and red alder, and Oregon white oak and Pacific madrone may be present at lower elevations (Franklin and Dyrness 1988). Compared to other vegetation zones in the region, this habitat is relatively warm and wet in winter, and hot and dry in summer, with snow uncommon except at higher elevations.

The historical fire regime was characterized by moderate- or low-frequency, and mixed- or high-severity fire, depending on location (chapter 5). Because fire-return intervals are long, the effects of fire suppression in this habitat type are not as significant as in forests with more frequent fire regimes (Halofsky et al. 2018b, Spies et al. 2018b). However, fire suppression in these areas has reduced the early-seral habitat and vegetation diversity (Brown 1985, Spies et al. 2018a).

Habitat attributes—

Wildlife habitat resources in western Oregon coniferous forests have been reviewed in several studies (Brown 1985, Johnson and O'Neil 2001, Ruggiero et al. 1991, Spies et al. 2018b). These reviews highlight commonly used habitat components of these forests, including live and dead trees (particularly large trees) and down wood and a mixture of coniferous and deciduous trees. Shrubs and other understory vegetation provide cover as well as food, as do numerous species of fungi. Important abiotic features include springs and seeps, talus, cliffs, and caves.

The habitat resources provided by coniferous forests differ depending on developmental stage and landscape configuration. For example, old forests provide large trees, snags, understory vegetation, small clearings, and mid-story canopy layers, whereas young to mature forests provide closed-canopy conditions, open mid-story, deciduous understory, and forest floor complexity. Young forests provide deciduous canopies (Altman and Alexander 2012). In addition, many understory shrubs (e.g., salal, huckleberry) and trees provide fruit, nuts, and browse (Shaw et al. 2004). Early-seral forests, particularly those generated by mixed-severity fires, provide areas for foraging, including by species that rely on older forests for nesting habitat, such as northern spotted owls and great gray owls (Lee 2018, Siegel et al. 2019).

Characteristic species—

Characteristic species include the northern spotted owl, northern goshawk, northern flying squirrel, olive-sided flycatcher, red tree vole, terrestrial mollusks, and salamanders. Notable bird species associated with multilayered, late-successional forests include pileated woodpecker, brown creeper, Pacific-slope flycatcher, and varied thrush (Altman and Alexander 2012, Johnson and O'Neil 2001). Large carnivores include black bears and mountain lions, and gray wolves are actively recolonizing the region. Wolverines and Pacific fishers have been extirpated but may be present as dispersing individuals. Fisher reintroduction efforts to the south of the CMWAP assessment area may provide dispersing individuals in this area. Large ungulates include black-tailed deer and elk. Although it is likely that they were present in the assessment area historically, the endangered Columbian white-tailed deer are only found south of the assessment area.

Forest-associated bats rely heavily on large trees and snags for roosting sites; roosting structures are thought to be the primary factor limiting their distribution (Hayes 2003). Trees and snags used by bats for roosting provide important thermoregulatory structures, with some roosts providing warmth needed by pregnant females and others providing cool conditions that allow male bats to enter torpor to reduce thermoregulatory costs (Hayes 2003).

The western hemlock zone contains many terrestrial mollusk species, which comprise a significant proportion of the sensitive and strategic species found in the assessment area. Mollusks are notable for facilitating decomposition and nutrient cycling. Many are associated with older forests and depend on down wood and forest floor litter to provide cool, moist microclimates (Jordan and Black 2012), and they are considered sensitive because of their limited distributions.

Species listed under the U.S. Endangered Species Act (ESA) that are associated with coniferous forests include northern spotted owls and gray wolves. In addition, both Pacific fisher and Pacific marten have been petitioned for listing under the ESA (Linnell et al. 2018). ISSSSP species include two birds, four amphibians, and four mammals; 11 mollusks, and 10 other invertebrates are ISSSSP-listed and associated with coniferous forests in the assessment area (table 6.3).

Nonclimatic stressors—

Timber harvest in the western hemlock zone has resulted in loss of late-seral stands and an increase in amount of young forest (Spies et al. 2018a). Timber harvests configured in dispersed clearcut patches have increased forest edge and decreased interior habitat (Nonaka and Spies 2005). Clearcut stands were often replaced with Douglas-fir plantations characterized by uniform stand density, fewer snags, and fewer down wood structures (Spies et al. 2018a).

Roads present in this zone can degrade habitat, hinder dispersal, and alter landscape gene flow of many species. Loss and fragmentation of natural habitats because of logging and road building have resulted in both extinction and extinction risk for many mollusk species (Foltz Jordan and Hoffman Black 2012). Road culverts and sedimentation from timber harvest also negatively affect salamanders (Foster and Olson 2014).

Exposure

The western hemlock zone will get warmer, resulting in increased drought stress and a longer growing season. Exposure to change will vary by elevation and aspect. Lower elevations and south-facing slopes are likely to experience warmer temperatures and drought stress not currently typical for western hemlock forests in the assessment area.

Across much of the western portion of the assessment area, the MC2 model projected that conditions would remain conducive to the moist coniferous forest type in 2050 (figs. 6.2 and 6.3; chapter 5). However, by 2080, lower elevation areas will transition to warm, mixed-forest conditions, with small areas of subtropical,

Table 6.3—Interagency Special Status/Sensitive Species Program species associated with coniferous forest habitat

		Occurrence status[b c]			
Common name	**Status[a]**	**CRG-WA**	**CRG-OR**	**MTH**	**WIL**
Bald eagle	SEN	D	D	D	D
Black swift	OR-SEN		S		D
Blue-gray taildropper	WA-SEN	S			
Broadwhorl tightcoil	OR-STR/WA-SEN			S	D
Cascades axetail slug	OR-STR			D	D
Columbia Gorge caddisfly	OR-SEN		D		
Columbia sideband	OR-SEN		D	S	
Cope's giant salamander	OR-SEN		D	D	
Crater Lake tightcoil	OR-SEN			D	D
Crowned tightcoil	OR-SEN/WA-STR	S	S	S	
Dalles hesperian	STR	D		D	
Dalles sideband	SEN	S	S	D	
Fringed myotis	OR-SEN		D	D	D
Golden hairstreak	WA-SEN	S			
Great grey owl	WA-SEN				
Johnson's hairstreak	SEN	S	S	D	D
Larch Mountain salamander	SEN	D	D	D	
Malone jumping-slug	WA-SEN	D			
Oregon megomphix	WA-STR	S			
Oregon slender salamander	SEN			D	
Pacific fisher	STR	S	S		
Puget oregonian	SEN	S	D	D	
Purple martin	OR-SEN		D		S
Shiny tightcoil	SEN	S	S	D	
Slender-billed nuthatch	WA-STR	S			
Townsend's big-eared bat	SEN	D	D	D	D
Van Dyke's salamander	WA-SEN				
Wahkeena Falls flightless stonefly	OR-SEN		D		

[a] SEN = Sensitive in Oregon and Washington; OR-SEN = Sensitive in Oregon; OR-STR = Strategic in Oregon; WA-SEN = Sensitive in Washington; WA-STR= Strategic in Washington.

[b] CRG-WA = Columbia River Gorge National Scenic Area in Washington; CRG-OR = Columbia River Gorge National Scenic Area in Oregon; MTH = Mount Hood National Forest; WIL = Willamette National Forest.

[c] D = documented occurrence: a species located on land administered by the Forest Service based on historical or current known sites of a species reported by a credible source for which the Forest Service has knowledge of written, mapped, or specimen documentation of the occurrence; S = suspected occurrence: species is not documented on land administered by the Forest Service, but may occur on the unit because (1) the national forest is considered to be within the species' range, and (2) appropriate habitat is present, or (3) there is known occurrence of the species (historical or current) in the vicinity such that the species could occur on Forest Service land.

mixed-forest conditions. Lands to the west and lower in elevation than the assessment area will transition to warm, mixed-forest conditions by 2050, and to subtropical, mixed-forest conditions by 2080, likely affecting growing conditions on private timberlands adjacent to national forests.

Under most MC2 scenarios for 2080, coniferous forests will experience moderate declines but still comprise a significant portion of the assessment area. However, the lower elevation areas that are now in the western hemlock zone will transition to mixed-forest types (likely with an increased hardwood component), and the western hemlock zone may shift upward into areas historically in the Pacific silver fir zone.

The MC2 model projects long-term equilibrium conditions at coarse spatial scales, so although climatic conditions in some areas may transition to those presently found in warm mixed forest, these changes may take decades unless disturbance expedites species shifts. However, drought stress may already be affecting some forests. For example, dry conditions have contributed to mortality of late-seral western hemlock trees in the Wind River Experimental Forest, just north of the CMWAP assessment area (Bell et al. 2020).

Sensitivity

Local vegetation sensitivity is likely to differ by tree species composition and local biogeographic conditions. For example, western hemlock zone forests on the drier end of the spectrum (e.g., areas on the Willamette National Forest with ponderosa pine and incense cedar) may be resilient to drier conditions in the future. Lower elevation forests in the western hemlock zone may transition to mixed forests or possibly oak woodlands. These same lower elevation areas experience nonclimatic stresses because of their proximity to populated areas.

The future distribution and characteristics of western hemlock zone habitats will be shaped by the interplay and spatial dynamics of natural disturbances, management actions, and regeneration dynamics. Wildlife species traits likely to affect sensitivity include the following:

- **Dependence on slow-developing habitat features (e.g., late-seral associates)**—Areas with suitable habitat (large snags, coarse woody debris, large trees) may require decades or centuries to develop, limiting near-term availability for species dependent on these features. For example, species associated with scarce, fragmented early-seral and late-seral habitats may have more difficulty reaching habitat than species associated with young forests. Old-growth conditions develop after 200 to 250 years (Franklin et al. 2017), and although some locations may have “old forests” after 80 years, these stands do not have the structural habitat characteristics of old-growth forests.

- **Limited dispersal abilities**—Species with restricted dispersal distances or abilities will have reduced capacity to move to suitable areas. This will be particularly true for species whose dispersal behavior is constrained by diminished and fragmented habitat. For example, dispersal of red tree voles and northern flying squirrels is limited by fragmentation from timber harvests, which reduce landscape connectivity needed for population persistence, even without the added stress of climate change (Dunk and Hawley 2009, Trapp et al. 2019).
- **Mismatch between habitat features and thermal suitability**—In the future, abiotic and biotic features on which some species depend may no longer be present in areas that are climatically suitable. For example, many bat species rely on roosting snags for thermal refuge; warmer conditions could shift suitable air temperatures for bats out of areas with sufficient snags.

Of particular management concern is the potential for large fires in the western hemlock zone to reduce the extent of patches of late-seral forests, leading to a bottleneck of suitable habitat (McKenzie et al. 2004). However, wildfires in this zone, though typically high in severity, often include pockets of low- and moderate-intensity fire with live trees (Franklin et al. 2017). In addition, mixed-severity fire generates down and dead woody debris, supporting species associated with both low- and high-severity fire regimes. For example, northern flying squirrels and northern goshawks use the habitat heterogeneity and structures generated by mixed-severity fires (Lehmkuhl et al. 2006, Reynolds et al. 2008), although the development of sufficient cover for squirrels may require decades.

The sensitivity of the northern spotted owl to climate change is unclear relative to habitat loss and competition from barred owls. However, climate change could lead to additional stresses, synergistic with barred owl competition, that are detrimental to spotted owls (Dugger et al. 2015). Increased drought is likely to result in increased tree mortality (Choat et al. 2018, Lindenmayer and Laurance 2017, Reilly and Spies 2016). Tree mortality may increase the short-term availability of snags and logs, while reducing the long-term availability of large live trees that provide nesting platforms, canopy cover, and thermal refugia (van Mantgem et al. 2009).

Townsend’s big-eared bat, which is associated with coniferous forests as well as several other vegetation types, is an example of a species with a complex life history that makes it difficult to infer climate change effects. Breeding females depend on surface water, which may be reduced with warming temperatures and lower summer streamflows (chapter 3). Adults consume primarily moths, whose abundance and distribution may be affected by altered water availability, insect phenology, vegetation communities, and disturbance dynamics. Breeding and resting behaviors rely on roosts, the availability and suitability of which will be altered by fire and higher temperature (Gervais 2017).

Trophic or functional links between species potentially magnify sensitivity to climate change. Altered timing and amount of plant, fungus, or insect biomass could affect food resources for wildlife. The effects of reduced food availability in small mammals could extend to mesocarnivores that prey on them. In addition, seed dispersal by mammals may be affected by altered timing and amount of seed production. Changes in insect abundance and species composition will affect the mammals and birds that depend on them. Mollusks have limited dispersal abilities, and roads, logging, and other human activities may make it more difficult for them to move across the landscape in response to climate change (Foltz Jordan and Hoffman Black 2012, Foster and Olson 2014).

Adaptive Capacity

Spatial patterns of forest stand age and structure across landscapes will determine the amount and quality of available habitat for wildlife species and species ability to move in response to changing climatic conditions. The relatively wide range of elevation spanned by the western hemlock zone may buffer some species from the effects of climate change; many higher elevation forests in the western hemlock zone will likely remain suitable habitat. Species that currently occupy the lower elevation portions of the zone may shift their distributions upward as conditions warm. High topographic complexity will also provide climatic microrefugia.

The ability of individual species to cope with temperature and moisture changes and disperse to different locations will help determine how they are affected by changes in climate and vegetation, habitat structure, and food resources. Large mammals that migrate or seasonally shift home ranges (including portions of elk, deer, and bear populations in the assessment area) may be able to track shifting availability of forage and other resources. Species with broad thermal and moisture tolerances will fare better than those sensitive to desiccation or heat stress. If large live and dead tree structures are retained following disturbances, many species will be able to rely on them for nesting, resting, and climatic microrefugia (including moisture refugia for amphibians).

Existing reserve networks, if sufficiently connected, can facilitate adaptation. A simulation study of reserve networks that assessed the relative importance of late-successional reserves (intended to protect northern spotted owl habitat under the Northwest Forest Plan) and congressional reserves (wilderness areas, parks) in protecting 130 species found that, under climate change scenarios, the habitat value of Congressional reserves increased because of their high-elevation location (Carroll et al. 2010). The study found that, “the current reserve system will face challenges conserving its current suite of species under future climates. However, fixed reserve networks built with a consideration of climate change…may be relatively effective at maintaining species owing to inclusion of areas of climatic and topographic heterogeneity that allow even species with limited dispersal to colonize future habitat" (Carroll et al. 2018).

A study that modeled projected range shifts of amphibians in the CMWAP assessment area found that interdecadal variability in climate change can cause gaps in the routes available to species that require aquatic habitat. Traits (e.g., those associated with dispersal, demography, physiology, and behavior) that contribute to persistence through unfavorable conditions helped species shift their distributions (Early and Sax 2011). Notably, the Pacific giant salamander and the Larch Mountain salamander survived Pleistocene glaciation by establishing a refugium along the Columbia River Gorge (Steele and Storfer 2006), highlighting the potential for the gorge to provide refugia in a future climate.

The ISSSSP conservation assessment for Cope's giant salamander discusses climate change effects, highlighting the importance of reduced summer streamflow, higher water temperatures, and scouring from rain-on-snow events (Foster and Olson 2014). Range shift dynamics may also be shaped by interspecific competition. For example, a study in eastern North America documented how southern flying squirrels have expanded northward with warmer conditions, displacing northern flying squirrels (Wood et al. 2016). This study found that range shifts may be a largely stochastic process facilitated by the co-occurrence of multiple species- and site-specific factors.

Montane Coniferous Forests

Description

The Pacific silver fir zone is found primarily in middle elevations on the western slopes of the Cascades, above the western hemlock zone and below the mountain hemlock zone. A large proportion of precipitation falls as snow that accumulates into persistent winter snowpack. Dominant tree species include noble fir, with Pacific silver fir becoming dominant in mature and late-seral stands, but several other coniferous species are present. This zone has less of a hardwood component compared to the western hemlock and lower elevation zones. A diversity of *Vaccinium* species and other shrubs is found in the Pacific silver fir zone, providing important food resources. Mountain streams and riparian areas are important habitat features. This zone is characterized by low-frequency (500- to 800-year fire-return interval), high-severity fire; windstorms, insects, and fungi are also important disturbance agents (Chappell 2001). The plant associations of the Pacific silver fir zone and their timber production and wildlife values in the Mount Hood and Willamette National Forests are described in detail in Brockway et al. (1983).

Habitat attributes—

Key habitat features for older forests in this zone are closed, multilayer canopies with trees of a variety of ages (including big, old trees); snags and down logs; and multiscale spatial and structural heterogeneity. Large quantities of standing and down woody debris are often present; this habitat type has the highest snag density of any in the assessment area (Rose et al. 2001). Winter snowfall and persistent snowpack are a defining feature, and many animal species rely on subnivean habitats in this zone. Pacific silver fir stands provide hiding, cover, and thermal protection (Cope 1993a). Understory development takes longer than in lower elevation forests, and complex multilayered canopies require centuries to develop.

Old-growth stands of Pacific silver fir are important habitat for mountain goats and many bird species. Seeds are eaten by birds, rodents, and squirrels. Fungal fruiting bodies found in mature and old-growth forests in the Pacific silver fir zone supplement the diets of many forest animals and are a staple for several small mammals (North et al. 1997). Various species of berries of the genera *Vaccinium, Ribes, Symphoricarpos, Gaultheria, Mahonia,* and *Arctostaphylos* dominate or codominate the understory, providing important food resources (Chappell 2001). Early-seral habitats within the Pacific silver fir and mountain hemlock zones are an important source of forage for elk, especially with the decline in early-seral habitats in the western Cascades (Rowland et al. 2018).

Characteristic species—

Characteristic species found in this vegetation type include Clark’s nutcracker, Lewis’s woodpecker, white-headed woodpecker, Pacific marten, and Sierra Nevada red fox (table 6.4). However, the woodpeckers do not breed in Willamette National Forest (although Lewis’s woodpeckers are present in the Willamette Valley and on the eastern slopes of the Cascades). Other species associated with montane forests include chestnut-backed chickadee, northern goshawk, northern spotted owl, olive-sided flycatcher, band-tailed pigeon, black swift, pine siskin, Vaux’s swift, brown creeper, and clouded salamander. If Pacific fishers recolonize or are reintroduced to the assessment area, they would be found in this vegetation type in areas where they are not excluded by deep snows. They would be expected to move to higher elevation if snowpack decreases in the future (Aubry and Houston 1992).

Nonclimatic stressors—

Because noble fir, a dominant species in the Pacific silver fir zone, is a commercially valuable species (Cope 1993b), this vegetation zone has experienced high levels of timber harvest, leading to loss and fragmentation of old-forest habitats and to barriers from roads (Chappell 2001). Clearcutting and replanting in tree plantations (especially of noble fir) have resulted in less diverse tree canopies,

Table 6.4—Interagency Special Status/Sensitive Species Program species associated with montane coniferous forest vegetation

		Occurrence status[b] [c]			
Common name	**Status**[a]	**CRG-WA**	**CRG-OR**	**MTH**	**WIL**
Cascade torrent salamander	OR-SEN	D			
Cope's giant salamander	OR-SEN		D	D	
Crater Lake tightcoil	OR-SEN			D	D
Fringed myotis	OR-SEN		D	D	D
Larch Mountain salamander	SEN	D	D	D	
One-spot rhyacophilan caddisfly	OR-STR			D	D
Oregon slender salamander	SEN			D	
Pacific fisher	STR	S	S		
Sierra Nevada red fox	OR-SEN			D	D
Townsend's big-eared bat	SEN	D	D	D	D
Van Dyke's salamander	WA-SEN				
Western bumblebee	SEN			D	D
Wolverine	SEN	D	D	S	S

[a] SEN = Sensitive in Oregon and Washington; OR-SEN = Sensitive in Oregon; OR-STR = Strategic in Oregon; WA-SEN = Sensitive in Washington; WA-STR= Strategic in Washington.

[b] CRG-WA = Columbia River Gorge National Scenic Area in Washington; CRG-OR = Columbia River Gorge National Scenic Area in Oregon; MTH = Mount Hood National Forest; WIL = Willamette National Forest.

[c] D = documented occurrence: a species located on land administered by the Forest Service based on historical or current known sites of a species reported by a credible source for which the Forest Service has knowledge of written, mapped or specimen documentation of the occurrence; S = ssuspected occurrence: species is not documented on land administered by the Forest Service, but may occur on the unit because (1) the national forest is considered to be within the species' range, and (2) appropriate habitat is present, or (3) there is known occurrence of the species (historical or current) in the vicinity such that the species could occur on Forest Service land.

less coarse woody debris, and slow development of late-seral characteristics. These effects are intensified by relatively low productivity and slow successional processes compared to lower elevations. Insect and disease outbreaks are important disturbances in this system, generating food and habitat structures used by many wildlife species (Chappell 2001).

Exposure

MC2 projections suggest that the climatically suitable area for Pacific silver fir forests will not change much with warming (moist mixed-conifer forest in fig. 6.2a). However, with climate change, lower elevation portions of the Pacific silver fir zone will likely receive less snowfall, and lower elevation species from the western hemlock zone may become more abundant in these areas. Dominant tree species in the Pacific silver fir zone are relatively intolerant to drought and fire, and they may decrease in abundance on drier sites as a result of drought stress (chapter 5). Isolated patches of noble fir and Pacific silver fir that occur on the tops of ridges and peaks may become locally extirpated, particularly in the southern portion of the assessment area. As these habitats change, associated wildlife populations in isolated patches are likely to lose population connectivity and experience declines. Additional habitat elements that could be degraded or lost include snowpack and subnivean habitats, and depending on disturbance patterns, large trees.

Sensitivity

Although the area capable of supporting Pacific silver fir forests is projected to remain about the same, the future distribution and characteristics of forest wildlife habitats in this zone will be determined largely by large-scale disturbance processes, particularly fire. Increased summer drought is projected to amplify the risk of high-severity fire throughout western North America (Wehner et al. 2017). Recent (fall 2020) large-scale fires in the assessment area highlight the importance of these disturbances. High-severity fire can affect wildlife populations by reducing spatial and structural heterogeneity of forest habitats at large scales and may increase fragmentation and isolation of old-forest patches.

Although it is important to recognize that postfire landscapes have unique biodiversity values (see the discussion of early-seral habitats below), structurally diverse closed-canopy forest may become increasingly rare with more frequent and severe disturbance. Reduced availability of closed-canopy forest and associated large trees, snags, and logs that provide thermal microrefugia may increase vulnerability to thermal stress for many species, including small mammals and mesocarnivores. Specialized old-forest species, including northern spotted owls, will likely be particularly sensitive to loss of old-forest nesting structures and thermal refugia.

Ecological change in unburned forests may be relatively subtle owing to long tree lifespans, but there may be important impacts to wildlife habitat components even without large-scale tree mortality. Altered temperature and seasonal precipitation patterns could contribute to changes in timing and abundance of plant, fungus, and insect food availability. Reduced availability of plant and fungus food for small mammals can have cascading effects on mesocarnivore populations dependent on small mammals for prey. The combined effects of lengthened warm season and carbon dioxide fertilization on trees could alter insect population composition and abundance, with implications for their predators, including small mammals, birds, and bats. Drought-induced tree mortality may contribute to short-term increases in snag and log abundance but would eventually lead to a longer term decline in availability of such structures if the number of large live trees that serve as snag and log replacements is reduced (van Mantgem et al. 2009).

Few studies have assessed the sensitivity of specific wildlife species to climate change in the Pacific silver fir zone. Martens are an exception, and they are projected to experience direct and indirect stresses as a result of climate change. Fir forests are likely to shift upward in elevation, resulting in shifts in habitat, and increasing fire frequency and extent will affect habitat quality. In areas where fishers are successfully reintroduced, indirect stresses may arise from an upward expansion of fishers into areas occupied by martens (Lawler et al. 2012). Martens prefer mesic areas because their prey (red tree voles) is associated with fungus in those sites (Friggens et al. 2018).

Adaptive Capacity

Animals are likely to change seasonal movement and behavior patterns in response to extended growing seasons and warmer winters. Adaptive capacity of wildlife associated with Pacific silver fir habitats may be influenced by individual species ability to physiologically tolerate temperature and precipitation changes, behaviorally adapt to those changes, and move in response to changes in climate, forest structure, and food availability. In areas where the Pacific silver fir zone is adjacent to subalpine forests, some animal species may be able to shift upward in elevation to track suitable habitat, but such shifts may not be possible in the southern portion of the assessment area and along local peaks near the Cascade crest.

Fishers are thought to be limited by deep snow, and although the middle-elevation Pacific silver fir zone is suitable, fishers are limited by snow depth in the higher elevation mountain hemlock zone (Aubry and Houston 1992). Warming that reduces these snow levels would allow fishers, in areas where they still occur, to shift to higher elevations.

Subalpine Forests

Description

This section includes alpine meadows, subalpine parklands, and shrublands found above treeline, as well as closed forests, characterized by subalpine fir, lodgepole pine, and mountain hemlock, with Pacific silver fir also present at lower elevations (Franklin and Dyrness 1988) (fig. 6.1). Within the parklands, whitebark pine is a prominent species. Subalpine areas are diverse and heterogeneous, shaped by extremes of temperature, moisture, winds, growing season, snow dynamics, and solar radiation (Millar and Rundel 2016).

Habitat attributes—

Key habitat characteristics of the subalpine include:

- **Deep snow**—Deep, persistent snow provides habitat features used by numerous species adapted to subalpine conditions. Martens use areas with deep snow, unlike fishers, which are constrained to lower elevations (Aubry and Lewis 2003).

- **Meadows**—Meadows are generated by shallow water tables that exclude the recruitment of woody plants, and in supporting herbaceous plants, contribute to a large portion of plant, amphibian, and insect biodiversity in the subalpine zone (Millar and Rundel 2016). Meadows are classified as wet meadows, dry meadows, shrub meadows, and woodland meadows, with each supporting different species assemblages, soils, and hydrologic conditions (Millar and Rundel 2016).
- **Rock and talus**—Rock and talus features provide shelter from predation and the elements and are often associated with meadows and other areas that provide food resources. In addition, these areas have microclimates that may act as climatic refugia.
- **Food resources**—*Vaccinium*-dominated shrubby plant communities found in the subalpine zone provide berries and browse for birds, bears, ungulates, and others (Franklin and Dyrness 1988). In closed forests, fungal resources are important to rodents, which in turn support marten and avian predators. Grass, forbs, and browse found in and around meadows are important for ungulates and rodents.

Characteristic species—

American pika, Sierra Nevada red fox, Clark's nutcracker, and western bumblebee are the most emblematic and charismatic species of the subalpine zone (table 6.5). Martens have remained common in higher elevation subalpine forests in areas without extensive logging (Aubry and Lewis 2003). Similar to Clark's nutcrackers, Douglas's squirrel and chipmunk species act as seed predators and dispersers for subalpine conifers (Millar and Rundel 2016). Yellow-bellied marmots are also prominent subalpine species, requiring talus and vegetation for grazing nearby.

Subalpine-associated bird species cataloged in Millar and Rundel (2016) include mountain bluebird, red crossbill, pine grosbeak, Cassin's finch, Williamson's sapsucker, black-backed woodpecker, and Clark's nutcracker. Subalpine meadows contain a high diversity of pond-dwelling amphibian, including Cascades frog, Pacific chorus frog, western toad, and long-toed salamander (table 6.6). The status of western bumblebee (associated with high-elevation wetlands and meadows) and Sierra Nevada red fox (associated with subalpine grasslands and mountain hemlock forests) populations is unclear, but both species are rare and significant for the ecology of subalpine systems.

Table 6.5—Interagency Special Status/Sensitive Species Program species associated with subalpine vegetation

		Occurrence status[b c]			
Common name	**Status[a]**	**CRG-WA**	**CRG-OR**	**MTH**	**WIL**
Caddisfly species	STR			S	S
Sierra Nevada red fox	OR-SEN			D	D
Western bumblebee	SEN			D	D
Wolverine	SEN	D	D	S	S

[a] SEN = Sensitive in Oregon and Washington; OR-SEN = Sensitive in Oregon; OR-STR = Strategic in Oregon; WA-SEN = Sensitive in Washington; WA-STR= Strategic in Washington.

[b] CRG-WA = Columbia River Gorge National Scenic Area in Washington; CRG-OR = Columbia River Gorge National Scenic Area in Oregon; MTH = Mount Hood National Forest; WIL = Willamette National Forest.

[c] D = documented occurrence: a species located on land administered by the Forest Service based on historic or current known sites of a species reported by a credible source for which the Forest Service has knowledge of written, mapped or specimen documentation of the occurrence; S = suspected occurrence: species is not documented on land administered by the Forest Service, but may occur on the unit because (1) the national forest is considered to be within the species' range, and (2) appropriate habitat is present, or (3) there is known occurrence of the species (historical or current) in the vicinity such that the species could occur on Forest Service land.

Table 6.6—Interagency Special Status/Sensitive Species Program species associated with montane or forest meadows

			Occurrence status[b c]			
Meadow type	**Common name**	**Status[a]**	**CRG-WA**	**CRG-OR**	**MTH**	**WIL**
Montane meadows	California shield-backed bug	OR-STR			D	S
Forest meadows	Dog star skipper	STR	S	S	S	S
Montane meadows	Foliaceous lace bug	OR-STR				D
Montane meadows	Gray blue butterfly	OR-SEN				S
Montane meadows	Great basin fritillary	WA-SEN	S			
Forest meadows	Mardon skipper	SEN	S	S	S	S
Forest and montane meadows	Western bumblebee	SEN			D	D

[a] SEN = Sensitive in Oregon and Washington; OR-SEN = Sensitive in Oregon; OR-STR = Strategic in Oregon; WA-SEN = Sensitive in Washington; WA-STR= Strategic in Washington.

[b] CRG-WA = Columbia River Gorge National Scenic Area in Washington; CRG-OR = Columbia River Gorge National Scenic Area in Oregon; MTH = Mount Hood National Forest; WIL = Willamette National Forest.

[c] D = documented occurrence: a species located on land administered by the Forest Service based on historical or current known sites of a species reported by a credible source for which the Forest Service has knowledge of written, mapped, or specimen documentation of the occurrence; S = suspected occurrence: species is not documented on land administered by the Forest Service, but may occur on the unit because (1) the national forest is considered to be within the species' range, and (2) appropriate habitat is present, or (3) there is known occurrence of the species (historical or current) in the vicinity such that the species could occur on Forest Service land.

Nonclimatic stressors—

Recreation is a nonclimate stressor to wildlife in subalpine systems of the assessment area. High-elevation ecosystems are valued recreation areas with unique aesthetic characteristics. Hiking, climbing, mountain biking, and cross-country skiing are common activities in the assessment area, and there are several ski areas in the subalpine portions of the assessment area (chapter 7). Vegetation damage and soil compaction can be problems in areas with high levels of recreational use (Gaines et al. 2003). Motorized winter recreation may contribute to snow compaction and reduction of subnivian habitat values in heavily used areas (Singleton et al. 2021).

High-elevation habitats are also affected by tree diseases. Whitebark pine, an important food source for numerous species, is already under stress from white pine blister rust, and further loss of whitebark pine stands would reduce habitat for Clark's nutcrackers and other species dependent on seeds from cones (McKinney et al. 2009).

Exposure

High-elevation cold-habitat types and associated wildlife species will have a high degree of exposure to projected changes in climate. MC2 projections suggest significant loss of climatic conditions associated with subalpine forest by late in the 21st century (figs. 6.2 and 6.3). Higher temperatures will likely lengthen the growing season by reducing snow cover duration and warming soils. There may also be increased potential for large-scale, high-severity fire in high-elevation habitats with increased summer drought. The historical disturbance regime in high-elevation cold forests was characterized by very infrequent, large-scale, high-severity fire events. Late-seral tree species (e.g., subalpine fir) in this type are not resilient to fire. A particular risk to this type may be the potential for high-severity fire to spread into these stands from adjacent mid-elevation forest during extreme events. Increased summer temperatures and drought stress may result in direct tree mortality or increased vulnerability to insects and diseases. High-elevation meadows will likely experience increased summer temperatures and drought stress.

Sensitivity

Loss of winter snowpack will have important consequences for wildlife associated with subalpine habitats. Adaptations for cold, snowy environments may be disadvantageous in a warmer, snowless future (Singleton et al. 2022). Winter warming, with fewer very cold or even below-freezing days, may be particularly important, potentially producing changes in winter thermoregulatory behaviors. Loss of winter snowpack may particularly affect wildlife that use subnivian habitats or are sensitive to competition or predation from common mesocarnivores.

For instance, American martens use deep-snow areas where bobcats are unlikely to occur for wintertime movements and have been found to be absent from some areas that have recently had lower snowpack (Moriarty et al. 2015).

Subalpine vegetation will likely shift with warming and loss of snowpack in the future. Tree species from lower elevations will likely become more competitive in subalpine environments, and drought stress and fire may become more common (chapter 5). Landscape context will affect how climate change affects the growth of subalpine fir; its growth is generally limited by the short growing season found near treeline but is limited by summertime precipitation on drier and warmer sites (Peterson et al. 2002). More severe droughts may contribute to tree mortality (Clark et al. 2016a).

Milder winters, longer frost-free seasons, and summer drought stress may contribute to increased severity of forest insect and disease outbreaks (Weed et al. 2013). Whitebark pine will be vulnerable to white pine blister rust. The loss of food resources from whitebark pine stands is likely to be significant for dependent wildlife species, with cascading effects through subalpine ecosystems (Friggens et al. 2018).

Tree encroachment in subalpine meadows in the Cascade Range has been documented for decades (Franklin and Dyrness 1988) and may intensify with climate change because of longer growing seasons. Subalpine meadows in the Oregon Cascades have seen an increase in proportion occupied by trees from 8 to 35 percent between 1950 and 2007, but the drivers of meadow invasion are complex and depend on landscape context (Lubetkin et al. 2017, Zald et al. 2012). The future distribution of these habitat conditions will, to some extent, be determined by tree establishment and disturbance processes; high-elevation meadow communities may be maintained by drought or regular fire.

Emerging phenological mismatches between high-elevation vegetation and invertebrate pollinators may be a particular concern for high-elevation herbaceous communities. Recreation pressures on higher elevation areas could increase as people seek cooler settings for recreation throughout the year. Winter recreation pressures may become more concentrated as snowpack diminishes and snow-based recreational opportunities are reduced (chapter 7).

Although no studies have specifically assessed responses of subalpine mammals of the Cascade Range to observed or projected climate change, climate-driven declines in Sierra Nevada mammals have been documented (Moritz et al. 2008). In the CMWAP assessment area, subalpine habitats are already small and fragmented, supporting correspondingly small populations of associated species. Contraction and disappearance of patches of subalpine habitat will increase the fragmentation and isolation of these populations. However, environmental heterogeneity may provide adequate refugia for wildlife species to persist (Millar and Rundel 2016).

Adaptive Capacity

Animals, plants, and other organisms associated with high-elevation habitats will have limited opportunities for upward range shifts. Organisms associated with these habitats are generally better adapted to cold than warm extremes. Habitat structure changes may be determined to a large degree by disturbance processes. If increased fire frequency and severity offset tree growth and encroachment, these habitat characteristics may be sustained on the landscape. However, substantial changes in seasonal temperature and snowpack characteristics are unavoidable.

Availability of thermal microrefugia (e.g., burrows, cavities, large logs, or shading vegetation) may be particularly important for short-term species persistence. Fine-scale topography may provide refuge for subalpine species and habitats in some circumstances. For example, limber pine in the Great Basin is found in low-elevation ravines and riparian areas, which provide cooler and wetter conditions with lower solar radiation, enabling persistence in the region (Millar et al. 2018). In the Cascades, north-facing slopes and cold air pockets may provide subalpine species with refugia, and low-fertility soils, and disturbances from landslides may slow down invasion by lower elevation species.

East-Side Forests and Mixed Woodlands

Description

Vegetation on the eastern slopes of the Cascade Range is organized along bands of elevation, with dry woodlands, shrublands, and grasslands found at the lowest elevations (fig. 6.1). Ponderosa pine forests are the lowest elevation and driest forest type, and these dry forests transition to more mesic mixed-conifer forests, with Douglas-fir and grand fir. Broadleaf species, such as quaking aspen and Oregon white oak, also occur in drier forest types, and at lower elevations, open stands provide light for shrubs, such as big sagebrush. As precipitation increases with elevation, wet mixed-conifer forests emerge, with grand fir and noble fir. Subalpine forests (discussed above) are found at elevations above wet mixed-conifer forest.

East-side forests are characterized by short growing seasons and low summer moisture, with spatial heterogeneity created by deeper soils and north-facing slopes (Franklin and Dyrness 1988, Stine et al. 2014). Fire regimes differ by elevation, with low-severity, high-frequency fire typical at lower elevations, and high-severity, low-frequency fire at higher, wetter sites, with a mixed-severity and frequency regime in between (Stine et al. 2014). Local spatial heterogeneity in plant communities is high, with north-facing slopes often supporting more mesic plant communities than adjacent south-facing slopes, and both fire and logging causing a patchwork of different stand conditions and ages. Compared to the western slopes of the Cascades, productivity is low on the eastern slopes, and centuries are required for the development of old-growth characteristics in drier stands.

Habitat attributes—

Key habitat components differ based on elevation and vegetation type, but can be organized around the following elements:

- **Water or moisture resources**—Surface water and soil moisture are important habitat components for both vertebrates and invertebrates owing to the semiarid conditions found at lower elevations in the eastern Cascades. This is particularly true for amphibians and mollusks, which in addition to being associated with seeps, springs, and streams, rely on woody debris and litter for microclimates with sufficient moisture.
- **Food resources**—A shrub understory is common in many locations, providing berries for birds and mammals (Altman 2000). Shrubs are also important forage plants for ungulates, which rely heavily on shrubs for winter browse. Mollusks and insects are an important food source for birds and mammals (Duncan et al. 2014), with snags and dead woody debris providing important foraging habitat for numerous bird species (Altman 2000).
- **Shelter or nesting**—Large trees, snags, riparian vegetation, and woody debris all provide shelter and nesting habitat for a wide range of species (Altman 2000, Stine et al. 2014). In addition, talus slopes, cliffs, and other geophysical features are important, providing microclimates that support amphibians and mollusks.

Characteristic species—

Biodiversity of vertebrate species is high in east-side habitats (Singleton et al. 2019). Characteristic wildlife species associated with open large-tree ponderosa pine forest include white-headed woodpeckers, flammulated owls, and pygmy nuthatches (Sallabanks et al. 2001). Other characteristic species of dry east-side forests and woodlands include Lewis's woodpecker, northern goshawk, Dalles sideband, Oregon slender salamander, western gray squirrel (in areas intermixed with oak woodlands), and ash-throated flycatcher (table 6.7).

Nonclimatic stressors—

Timber harvest in the eastern Cascades has caused the loss of old forests, and habitats have been degraded and fragmented by roads, fire exclusion, overgrazing, nonnative vegetation, and human development (Altman 2000). These stresses have resulted in the local loss of some species, such as white-headed woodpecker and Lewis's woodpecker, in portions of the eastern Cascades. In one analysis for east-side forests, over 70 percent of 91 species of vertebrates were negatively affected directly or indirectly by road development (Wisdom et al. 2000). For example, Oregon slender salamanders are negatively affected by road construction and timber harvest that result in overstory and large-tree loss, desiccation, and disturbance of ground cover and woody debris that provide microclimates and microhabitat refugia (Clayton and Olson 2009). Mollusks, such as the Dalles sideband (a largely east-side species), are negatively affected by grazing (particularly around springs and riparian areas), wildfire, timber harvest, and prescribed fire, all of which can increase temperature or drying, decrease food resources, and decrease woody debris and litter used for shelter (Duncan et al. 2014).

Large ponderosa pine trees are generally resistant to fire under historical fire regimes. High fuel loads as a result of fire exclusion and encroachment by shade-tolerant trees have increased the risk of large-scale, high-intensity wildfire and pine mortality when fire does occur. Colonization by invasive herbaceous species, such as cheatgrass, reduces understory diversity and productivity and degrades habitat suitability for ground-nesting birds, small mammals, herbivores, and invertebrates. Livestock grazing can facilitate colonization by invasive species and alter low-intensity fire dynamics. Continued residential development on private lands could further reduce the extent of favorable habitat, increase fragmentation, and limit management options (e.g., prescribed fire in the wildland-urban interface).

Table 6.7—Interagency Special Status/Sensitive Species Program species associated with eastside mixed forests

		Occurrence status[b] [c]			
Common name	**Status[a]**	**CRG-WA**	**CRG-OR**	**MTH**	**WIL**
Ash-throated flycatcher	WA-SEN	D			
California mountain kingsnake	WA-SEN	D			
Cope’s giant salamander	OR-SEN		D	D	
Dalles hesperian	STR	D		D	
Fringed myotis	OR-SEN		D	D	D
Gray flycatcher	WA-SEN	S			
Lewis’s woodpecker	SEN	D	D	D	S
Mountain quail	WA-SEN	S			
Oregon slender salamander	SEN			D	
Pallid bat	OR-SEN		D		S
Shiny tightcoil	SEN	S	S	D	
Van Dyke’s salamander	WA-SEN				
Western gray squirrel	WA-SEN	D			
White-headed woodpecker	SEN	S	S	D	D

[a] SEN = Sensitive in Oregon and Washington; OR-SEN = Sensitive in Oregon; OR-STR = Strategic in Oregon; WA-SEN = Sensitive in Washington; WA-STR = Strategic in Washington.

[b] CRG-WA = Columbia River Gorge National Scenic Area in Washington; CRG-OR = Columbia River Gorge National Scenic Area in Oregon; MTH = Mount Hood National Forest; WIL = Willamette National Forest.

[c] D = documented occurrence: a species located on land administered by the Forest Service based on historical or current known sites of a species reported by a credible source for which the Forest Service has knowledge of written, mapped or specimen documentation of the occurrence; S = suspected occurrence: species is not documented on land administered by the Forest Service, but may occur on the unit because (1) the national forest is considered to be within the species’ range, and (2) appropriate habitat is present, or (3) there is known occurrence of the species (historical or current) in the vicinity such that the species could occur on Forest Service land.

Exposure

Vegetation models project that dry forest distributions will generally remain stable (figs. 6.2 through 6.3), but fire frequency, composition, and structure of these forests may be altered in the future (chapter 5). Ponderosa pine may shift to higher elevations, and drought-intolerant species, such as grand fir, may decrease in abundance at lower elevations. Reduced tree growth from climate change may slow the development of large-tree habitat structures.

Sensitivity

Big, early-seral trees (ponderosa pine and Douglas-fir) are relatively resilient to disturbance and seasonal drought stress. Smaller trees and high-density stands are less resilient. Large-tree open understory forests are likely to be more resilient to climate change stressors than are other forest conditions. Ponderosa pine is distributed across a wide elevation range. Lower elevations may experience increased summer heat and drought stress. Some areas currently with low-elevation forest cover may not have historically retained that cover and have it now owing primarily to fire exclusion.

Transitions in fire regimes associated with changing climatic conditions are expected to produce more frequent fires and more area burned, with some loss of forest structure and spatial heterogeneity (Barbero et al. 2014). Stand and landscape characteristics that are currently inconsistent with historical fire regimes are likely to become increasingly vulnerable with projected increases in fire frequency. MC2 projected a decrease of mean fire-return interval, and there may also be an increase in fire severity (chapter 5). High-severity fire under extreme fire weather conditions can result in widespread tree mortality, even in stands that would be fire resilient under normal conditions. This is particularly true for stands surrounded by high fuel loadings (Kane et al. 2015). However, the transition to more frequent fire could also serve to maintain lower fuel loads in open forest types as long as those forests are able to survive the initial fire events that remove fuels accumulated as a consequence of recent fire suppression and forest management practices. Repeated fire may also reduce the abundance of snags, logs, and tree clumps, as well as reduce understory shrub structure.

Spatial homogenization resulting from increased disturbance frequency and tree mortality can cause detrimental changes in the availability and configuration of important habitat features for white-headed woodpeckers and other species that require a mix of open- and closed-canopy conditions. Consequences of the loss of structural diversity for animals associated with this habitat type may include loss of nesting and resting structures and thermal refugia associated with closed-canopy patches, large logs, and snags, and altered food availability from loss of mast-producing shrubs. Changes in overstory canopy cover, understory plant species composition, and growing season are expected to alter forage quality and quantity and might produce an increase in herbaceous forage availability during spring and autumn.

Adaptive Capacity

Many animal species on the east side of the Cascades are adapted to drought and warm, dry conditions, especially those that use habitats at lower elevations or on south-facing aspects. These species have evolved with a frequent, low-severity or mixed-severity fire regime. Adaptations to these conditions may facilitate persistence under climate change.

Similarly, the ponderosa pine forest type is adapted to warmer conditions and summer drought. It has good capacity for upslope plant species movement if pine is retained in mixed-species stands, and the transition to open structure is facilitated by forest thinning or low- to moderate-intensity fire. Many associated animal species have opportunities for upward range shifts if this habitat structure is provided at higher elevations. However, development of large trees, snags, and logs may not keep pace with climate-induced shifts in areas capable of supporting these habitat conditions. Retention of these structures in areas where they currently exist may be important for providing transitional opportunities for wildlife. Forest restoration treatments that promote fire- and drought-resilient stand structures and landscape patterns are likely to become increasingly important.

Shrub, Grass, and Rock

Description

Numerous species either specialize in, or regularly rely on, shrub, grass, or rock habitats (table 6.8). These habitats are found across the assessment area. Shrub- and grass-dominated areas occur at lower elevations, particularly on the east side of the Cascade Range, in meadows in forested areas, in the subalpine zone, and along windswept balds and ridgetops, particularly above treeline. Rocky habitats include cliffs and escarpments used by swallows, swifts, and raptors for nesting, and talus fields. Of particular note are the talus fields found in and around the Columbia Gorge, which support five species of endemic mollusks and the endemic Larch Mountain salamander. In addition, these talus habitats support American pika populations, including a low-elevation pika population in the Columbia River Gorge noted for behavioral adaptations to low-elevation climatic conditions (Simpson 2009)[3] (table 6.9).

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[3] Simpson, M. [N.d.]. Unpublished data and map of vegetation series and subseries across the Pacific Northwest. On file with: U.S. Department of Agriculture, Forest Service, Central Oregon Area Ecology and Forest Health Protection Service Centers, 63095 Deschutes Market Road, Bend, OR 97701.

Table 6.8—Interagency Special Status/Sensitive Species Program species associated with shrub, grass, or rock habitat

		Occurrence status[b c]			
Common name	**Status[a]**	**CRG-WA**	**CRG-OR**	**MTH**	**WIL**
Ash-throated flycatcher	WA-SEN	D			
California mountain kingsnake	WA-SEN	D			
Ferruginous hawk	WA-SEN	S			
Gray flycatcher	WA-SEN	S			
Great grey owl	WA-SEN				
Green-tailed towhee	WA-SEN	S			
Larch Mountain salamander	SEN	D	D	D	
Mountain quail	WA-SEN	S			
Pallid bat	OR-SEN		D		S
Striped whipsnake	WA-SEN	S			
Valley silverspot	OR-STR/ WA-SEN				S
White salmon pocket gopher	WA-STR	S			

[a] SEN = Sensitive in Oregon and Washington; OR-SEN = Sensitive in Oregon; OR-STR = Strategic in Oregon; WA-SEN = Sensitive in Washington; WA-STR= Strategic in Washington.

[b] CRG-WA = Columbia River Gorge National Scenic Area in Washington; CRG-OR = Columbia River Gorge National Scenic Area in Oregon; MTH = Mount Hood National Forest; WIL = Willamette National Forest.

[c] D = documented occurrence: a species located on land administered by the Forest Service based on historical or current known sites of a species reported by a credible source for which the Forest Service has knowledge of written, mapped or specimen documentation of the occurrence; S = suspected occurrence: species is not documented on land administered by the Forest Service, but may occur on the unit because (1) the national forest is considered to be within the species' range, and (2) appropriate habitat is present, or (3) there is known occurrence of the species (historical or current) in the vicinity such that the species could occur on Forest Service land.

Table 6.9— Interagency Special Status/Sensitive Species Program species associated with talus

		Occurrence status[b c]			
Common name	**Status[a]**	**CRG-WA**	**CRG-OR**	**MTH**	**WIL**
Columbia Gorge oregonian	SEN	D	S		
Dalles hesperian	STR	D		D	
Dalles sideband	SEN	S	S	D	
Deschutes mountainsnail	OR-SEN		S		
Juga spp.	STR	D	D	D	
Larch Mountain salamander	SEN	D	D	D	

[a] SEN = Sensitive in Oregon and Washington; OR-SEN = Sensitive in Oregon; OR-STR = Strategic in Oregon; WA-SEN = Sensitive in Washington; WA-STR = Strategic in Washington.

[b] CRG-WA = Columbia River Gorge National Scenic Area in Washington; CRG-OR = Columbia River Gorge National Scenic Area in Oregon; MTH = Mount Hood National Forest; WIL = Willamette National Forest.

[c] D = documented occurrence: a species located on land administered by the Forest Service based on historical or current known sites of a species reported by a credible source for which the Forest Service has knowledge of written, mapped or specimen documentation of the occurrence; S = suspected occurrence: species is not documented on land administered by the Forest Service, but may occur on the unit because (1) the national forest is considered to be within the species' range, and (2) appropriate habitat is present, or (3) there is known occurrence of the species (historical or current) in the vicinity such that the species could occur on Forest Service land.

Low-elevation grasslands and shrublands on the east side of the Cascades occupy a range of conditions characterized by a mix of grass and herbaceous ground cover, several species of sagebrush, other shrubs, and western juniper woodlands. Specific structural characteristics of these habitats are determined by local growing conditions and disturbance history. Grass and herb vegetation may be characteristic of early-seral conditions in some areas, and juniper woodlands may be characteristic of late-seral conditions (Vander Haegen et al. 2001). These habitats are defined by their relative aridity and exposure to environmental extremes. They occupy the lowest elevation and warmest climatic setting in the assessment area but can also occur at higher elevations depending on local disturbance history and site productivity characteristics.

Key ecological features of grasslands and shrublands include native bunchgrasses, shrubs, woodland tree structures, water sources, deep soils, rocky features (cliffs, talus), and ungulate forage (Altman and Holmes 2000, Vander Haegen et al. 2001, Wisdom et al. 2000). Woodland tree, shrub, and herbaceous vegetation structures provide shading, nest sites, and security cover for a variety of species. Different shrub species and growth forms provide different habitat structures (reviewed by Altman and Holmes [2000] and Vander Haegen et al. [2001]).

High-elevation meadows and grasslands are characterized by a mix of herb, shrub, and nonvegetated conditions at and above treeline at the highest elevations in the CMWAP assessment area. Meadow patches can also be maintained at lower elevation by cold-air drainage patterns or local soil and site moisture conditions (too wet or too dry) that create inhospitable local environments for tree growth. Open conditions on ridgetops and upper slopes may be maintained by occasional lightning-caused fires. Avalanches can also maintain open or shrub communities at upper to middle elevations in these cold, heavy-snow landscapes. Because of the association of subalpine meadows with the highest topographic mountaintop settings, habitat has patchy, isolated landscape patterns. Animal and habitat characteristics associated with this type were described by Martin (2001). Characteristic species include American pikas, yellow-bellied marmots, American pipits, and gray-crowned rosy finches. Seasonally abundant flowering plants support a variety of pollinating species, including western bumblebees. Many species that use alpine habitats are seasonal migrants (e.g., gray-crowned rosy finch, elk).

Rocky features can provide unique security and thermal values. Cliffs provide nesting and roosting sites for birds and mammals. Talus provides thermal microrefugia and security cover for mammals and reptiles.

Nonclimatic stressors—

Important nonclimate stressors affecting low-elevation shrubland and grassland habitats on the east side include disruption of historical disturbance regimes, expansion of juniper woodlands, establishment of nonnative annual grasses, and human development (Altman and Holmes 2000, Davies et al. 2011). In many areas, suppression of periodic fire has resulted in encroachment of conifers (particularly juniper) into areas that historically supported more open conditions. Juniper encroachment can have negative effects on habitat values for several species, including Brewer's sparrows, sage thrashers, green-tailed towhees, and greater sage-grouse (Baruch-Mordo et al. 2013, Noson et al. 2006). In contrast, substantial invasive grass colonization in some areas, particularly by cheatgrass or ventenata in warmer and drier settings, has contributed to more frequent and higher intensity fire, resulting in loss of bunchgrass and shrub habitat structures. Butterfly species, such as the valley silverspot, are closely linked to plants that provide food for larval and adult stages, which may be threatened by invasive grasses and shrubs (Hietala-Henschell et al. 2020).

Nonclimate stressors in high-elevation meadows and grasslands include invasive species, fire exclusion, herbivory, and recreation (USDA FS 2011). Invasive plants can substantially change meadow community composition and ecological values. Montane meadows can provide forage for migratory ungulates but may be affected by high levels of herbivory. These areas have high scenic value. Vegetation damage and soil compaction can be problems where motorized winter recreation contributes to snow compaction and degraded subnivean habitat (Gaines et al. 2003).

Stressors in rocky habitats include changes to surrounding habitats as well as threats to rock structures themselves. The ISSSSP assessment for the Larch Mountain salamander lists logging activity on areas adjacent to talus habitats as a potential threat (Crisafulli et al. 2008). Threats to rock features include talus removal for road, railway, and other forms of construction. Where talus fields or other rock features are associated with seeps or springs, changes in groundwater levels alter the microclimates these environments provide.

Exposure

Because shrub, grass, and rock habitats are found across the assessment area and across a broad range of elevations, the degree of exposure to climate change will differ. MC2 vegetation modeling does not generally capture potential changes in these fine-scale habitats. Where grass communities are maintained (e.g., in forest or alpine meadows) by specific soil-hydrology characteristics, increased evapotranspiration and drying may lead to changes in species composition (e.g., increased tree recruitment in areas that were previously too wet).

Although many east-side grassland and shrubland plants and animals are adapted to drought, warmer spring temperatures could lead to earlier winter snowmelt and increased evapotranspiration, contributing to earlier and more severe seasonal drought (Schlaepfer et al. 2012). Water sources in lower elevation, hotter settings may be more sensitive to changes in water availability because of higher temperatures, accelerated drying, and competition with human water uses.

Animals associated with high-elevation meadows and grasslands are projected to have a high degree of exposure to climate change. MC2 projections indicate that the subalpine vegetation type will transition to moist coniferous forest because of increased temperatures and longer growing seasons. However, the advance of treeline must include the successful establishment of tree seedlings within and above the current treeline, a process dependent on multiple factors (Holtmeier and Broll 2012, Macias-Fauria and Johnson 2013, Smith et al. 2003). This habitat will experience increased summer temperatures and drought stress as well as reduced winter snowpack depth and duration.

Sensitivity

Altered disturbance regimes will largely determine habitat structure and distribution in low-elevation shrubland and grassland habitats. Overall, MC2 projects more frequent fires in the assessment area. Elevated carbon dioxide concentrations have also been shown to increase biomass production of cheatgrass and other annual grasses, which could affect shrubland composition and disturbance regimes (Lucash et al. 2005). However, wildfires are generally limited in shrublands by a lack of ignition sources, particularly during the fire season.

Altered fire frequency may have two countervailing influences on the distribution of shrubland and grassland habitat characteristics. Increasing fire frequency will likely reduce structural diversity associated with shrubs and trees, contributing to a decline in habitat suitability for many species. However, increased fire frequency in low-elevation forest, as projected by MC2, may facilitate some expansion of shrubland and grassland habitat. The spatial and structural simplification caused by increased fire frequency is likely to provide habitat conditions favored by species like horned larks, while reducing the extent of spatially and structurally diverse shrub habitat favored by species like sage-grouse and pygmy rabbit.

Projected increases in mean annual temperatures, coupled with increased variability of summer maximum temperatures, may exceed thermal tolerances for some animals. Species that are best adapted to hot and dry conditions may be preadapted to increasingly arid and hot conditions. Small-bodied animals that can exploit fine-scale thermal refugia (e.g., rock crevices or burrows) may be less sensitive to extreme temperatures than large-bodied animals that have more limited physiological capacity for heat dissipation and fewer opportunities to escape the heat (Speakman and Krol 2010). Variability of summer maximum temperatures will be particularly important if water availability becomes more limiting for some species. For example, species that depend on open water sources (e.g., amphibians, large mammals) are likely to be at risk if those water sources dry up. Seasonal food availability (grass and herbaceous forage, fruit from mast-producing plants) may be reduced if the frequency and magnitude of drought increase.

The future distribution of high-elevation meadows and grasslands will be determined by tree establishment and disturbance processes. High-elevation meadow communities can be maintained by fire, particularly when encroaching trees are not fire resilient. Warmer winter temperatures and reduced depth and duration of snowpack can potentially affect resident mammal communities. Loss of subnivean habitats may reduce protection from predation and increase winter thermal stress for species like meadow voles. Changes in snowpack depth may increase access for bobcats and coyotes.

Longer summers may contribute to changes in migration timing and duration of residence for elevational migrants. Abundance and timing of food availability may be particularly important drivers of altered migratory behavior. Deer and elk populations may change the timing of migration or stop migration when forage is abundant, which may contribute to increased herbivory in high-elevation meadows. Higher summer maximum temperatures and potential for summer drought may increase vulnerability of summer residents to thermal stress and altered food availability. Emerging phenological mismatches between high-elevation vegetation and invertebrate pollinators may be a particular concern in herbaceous communities. Recreation pressures could increase as winter recreation opportunities become more limited and recreationists seek cooler settings in summer.

Riparian-associated snails that rely on talus will be sensitive to hydrologic change owing to climate change. Increased severity of droughts and floods, reduced summer streamflow, and increased air and water temperatures will likely negatively affect these species (Applegarth et al. 2015).

Adaptive Capacity

Adaptive capacity of wildlife associated with low-elevation shrublands and grasslands on the east side is expected to be strongly influenced by tolerance to extreme temperatures, behavioral adaptation to those temperatures, and mobility in response to changes in habitat structure and food availability. Availability of fine-scale thermal microrefugia (e.g., burrows, talus slopes, shading vegetation, and topography) is likely to become more important as animals attempt to behaviorally adapt to warmer temperatures. Topographic features like canyons and north-exposure slopes that provide cooler environments compared to the surrounding landscape may become increasingly important thermal refugia.

Species that can alter their behavior and habitat selection patterns to minimize heat stress may be most likely to persist. Because shrublands and grasslands are present at the lowest elevations on the east side of the CMWAP assessment area, there are ample opportunities for these habitat conditions and associated species to shift to higher elevations. Opportunities for seasonal movements and range shifts will be particularly important for wildlife responding to hotter and drier seasonal conditions. Human-created barriers (e.g., urban development, major highways) can negatively affect opportunities for these movements.

Species associated with high-elevation meadows and grasslands have limited opportunities for upward range shifts. There is some overlap in wildlife species composition between high- and low-elevation grassland communities (e.g., vesper sparrows, horned larks). Some of these species have genetically unique alpine subpopulations (e.g., horned larks), but at the species level, they may have the phenotypic plasticity to adapt to warmer, low-snow conditions. Resident nonmigratory species reliant on long-season, deep snow conditions for denning (e.g., yellow-bellied marmot, American pika) or predator avoidance (e.g., snowshoe hare, meadow vole) may be quite sensitive. Habitat structure changes may be determined to a large degree by disturbance processes. If increased fire frequency offsets tree growth and encroachment, current habitat characteristics may be sustained. However, substantial changes in seasonal temperature and snowpack characteristics are unavoidable.

Microclimates provided by talus and other rock features are likely to be an important component of the adaptive responses of associated species, particularly when situated on north-facing aspects, which are cooler and retain more snow and moisture than on other aspects. As more climate-sensitive components of their habitat requirements (e.g., hydrology or vegetation) are affected by climate change, the refugia offered by talus and other rock features may become more important.

Early-Seral Forests and Brushfields

Description

Early-seral forests are the vegetation assemblages following a disturbance (fire, insect outbreaks, disease, logging). This type can be found in relatively large patches after large, high-intensity fires, and in smaller patches with more spatial and structural heterogeneity after mixed-severity fires (Hessburg et al. 2016). A key component of early-seral habitat is the presence of large-diameter snags, logs, and other biological legacies from the predisturbance forest. Purple martins, great gray owls, and many other species rely on snags and remaining large-diameter trees for nesting and early-seral or other open habitats for foraging (table 6.10). The spatial arrangement of early-seral patches in proximity to nesting resources is critical to species that rely on these habitats.

Table 6.10— Interagency Special Status/Sensitive Species Program species associated with early-seral habitats

		Occurrence status[b] [c]			
Common name	**Status**[a]	**CRG-WA**	**CRG-OR**	**MTH**	**WIL**
Great grey owl	WA-SEN				
Mountain quail	WA-SEN	S			
Purple martin	OR-SEN		D		S

[a] SEN = Sensitive in Oregon and Washington; OR-SEN = Sensitive in Oregon; OR-STR = Strategic in Oregon; WA-SEN = Sensitive in Washington; WA-STR= Strategic in Washington.

[b] CRG-WA = Columbia River Gorge National Scenic Area in Washington; CRG-OR = Columbia River Gorge National Scenic Area in Oregon; MTH = Mount Hood National Forest; WIL = Willamette National Forest.

[c] D = documented occurrence: a species located on land administered by the Forest Service based on historical or current known sites of a species reported by a credible source for which the Forest Service has knowledge of written, mapped or specimen documentation of the occurrence; S = suspected occurrence: species is not documented on land administered by the Forest Service, but may occur on the unit because: (1) the national forest is considered to be within the species' range, and (2) appropriate habitat is present, or (3) there is known occurrence of the species (historical or current) in the vicinity such that the species could occur on Forest Service land.

Habitat attributes and characteristic species—

Key ecological features of middle-elevation, early-seral habitats include woody structures, specific plant species, and spatial patterns (e.g., large open areas). Biological legacies from previous forest stands, including snags, logs, and surviving large trees, provide resting structures for woodpeckers and other species (Swanson et al. 2011). Early-seral forests are often dominated by grass and shrub vegetation, and early-seral vegetation is often highly productive, providing forage, berry, and nectar resources that support a variety of species. Compared to the often inaccessible or older foliage found in coniferous forests, the young, largely deciduous vegetation found in early-seral areas is highly palatable to ungulates; deer and elk browse on this vegetation and benefit from it nutritionally (Rowland et al. 2018). Snags in early-seral habitat support several species of woodpeckers, whose excavations provide cavities used by other cavity-nesting birds and mammals. Shrubs provide nesting and security cover and support diverse migratory bird communities. Small mammals, including both fossorial mammals such as pocket gophers, as well as chipmunks and ground squirrels, use early-seral habitats. Ungulate and small mammal populations in turn support mesopredator and large carnivore communities.

Nonclimatic stressors—

Nonclimatic stressors for early-seral habitat include timber and wood harvest, wildfire, roads, invasive species, grazing, and recreation (Stine et al. 2014, USDA FS 2011). Loss of large snags, logs, and remnant trees following fire or harvest can have negative effects on wildlife habitat in early-seral landscapes. Road access into recently disturbed areas may contribute to loss of dead wood from firewood collection and facilitate invasive species colonization. Invasive species can reduce understory diversity and productivity, thereby reducing forage quality and cover required by ground-nesting birds. Recreation activities can contribute to site degradation and reduce animal access to resources. Lack of hiding cover and long visual distances can contribute to negative effects of human disturbance in early-seral habitats.

Exposure

Increasing area burned with climate change will likely increase the amount of early-seral forest across the CMWAP assessment area. However, the exposed physical characteristics of early-seral forests, with few standing structures to provide shade, moisture, and shelter, will cause fauna to be more exposed to the direct changes of temperature and moisture associated with climate change. Growth responses to warming may result in changes to forest structure, with a potential increase in density of young cohorts in forests that are not limited by growing-season water availability. Although species composition may not change, an increase in stand density would shade out understory species that contribute to habitat and forage for animals, such as elk and deer.

Sensitivity

Lower elevations are likely to experience increased heat and summer drought stress. Some areas may transition to grasslands or shrublands (Clark et al. 2016a). These transitions may be associated with high-intensity disturbance because fire kills trees and eliminates seed sources as climatic conditions become less suitable for tree regeneration. Such transitions could favor grassland species, including horned lark. Deciduous shrub productivity may increase with projected increases in productivity, favoring foliage-gleaning birds, like orange-crowned warblers. However, seasonal availability of fruit foods (i.e., berries and nuts) and herbaceous forage could change with extended summer drought. Such changes could affect frugivores (e.g., black bear) and herbivores (e.g., deer, elk). If disturbances become larger and more frequent, spatial configuration of early-seral habitats could become more homogeneous, with larger patch sizes and fewer biological legacies.

Adaptive Capacity

Species associated with early-seral forests tend to have traits that may increase their adaptive capacity, including good dispersal abilities and high reproductive rates (important for tracking patchy and transient postdisturbance conditions) (Singleton et al. 2022). These traits should help populations of these species shift spatially or otherwise adapt to new climatic conditions in situ. In addition, as climate change increases the frequency and intensity of disturbances, the amount of habitat available for these species may increase. However, if fire severity increases or reburns of early-seral forests occur frequently, then the availability of biological legacies (snags, logs) may be reduced.

Riparian, Wetlands, and Water

The effects of climate change on fish are addressed in chapter 4. Here, we address other wildlife species associated with riparian habitats. Chapters 3 and 4 include more detailed discussions of the observed trends, mechanisms, and consequences of climate change on aquatic systems, providing an important context for this section.

Description

This habitat captures a variety of wetland, riparian, and open-water conditions found near streams, springs, and lakes, and in areas with abundant ground water. The CMWAP assessment area is rich in riparian habitats, which occur along water bodies ranging in size from the Columbia River to small alpine streams and springs. In addition, the area contains numerous groundwater-dependent ecosystems (springs, wetlands, rivers, lakes), particularly along the Cascade crest (Brown et al. 2011). Complex and diverse, these habitats are the interface between aquatic and terrestrial systems (Gregory et al. 1991, Penaluna et al. 2017). The distribution of this focal habitat is primarily determined by precipitation, evaporation, and hydrology, particularly surface and groundwater flow patterns. These habitats comprise a relatively small portion of the landscape but contribute biodiversity values disproportionate to their size (Penaluna et al. 2017).

Habitat attributes—

Key ecological features and habitat components of riparian, wetland, and open-water habitats include moving and still water, seasonal flow or wetness (ephemeral or perennial waters), riparian vegetation, woody debris including snags and logs, diverse and abundant invertebrate and plant food items, linear and connected spatial patterns (habitat connectivity), substantial topographic shading, and a cool, moist microclimate (Kauffman et al. 2001, Penaluna et al. 2017, USDA FS 2011). Riparian systems occupy the lowest topographic positions relative to surrounding areas, so they have substantial nutrient and energy inputs because organic matter simply flows into these systems (Gregory et al. 1991). Logs that fall into streams can create diverse systems of pools, providing habitat for aquatic vertebrate and invertebrate communities. Emergent adults of aquatic insects are prey for a variety of insectivorous wildlife, including birds, bats, reptiles, and amphibians (Baxter et al. 2005).

The linear, connected pattern of riparian systems can provide opportunities for animal movement through productive and secure settings. For example, headwater streams provide connectivity between and across watersheds for riparian-associated species (Olson and Burnett 2009), including connectedness across different elevations. Shade from streamside vegetation, as well as evaporative cooling from open water and cold air drainage, contribute to cool microhabitats.

Characteristic species—

Riparian forest ecosystems are hotspots of arthropod, mollusk, reptile, and amphibian diversity (Chan et al. 2004, Olson et al. 2014, Pollock et al. 2012) (table 6.11). All forest-associated amphibians in this system have either obligative or facultative associations with riparian habitats (Olson and Burnett 2009). A wide variety of birds, mammals, and reptiles also use resources associated with wetland and riparian habitats, even if they are not primarily associated with these conditions (Kauffman et al. 2001). American beavers are a keystone species for this habitat because of their influence on streamflow and groundwater recharge patterns. Wildlife communities associated with riparian habitats were described by Kauffman et al. (2001).

Table 6.11—Interagency Special Status/Sensitive Species Program species associated with riparian or water habitats

		Occurrence status[b c]			
Common name	**Status**[a]	**CRG-WA**	**CRG-OR**	**MTH**	**WIL**
Bald eagle	SEN	D	D	D	D
Barren juga	STR	S	S	S	
Basalt juga	STR	D	D	D	
Beller’s ground beetle	OR-SEN/WA-STR			D	
Black swift	OR-SEN		S		D
Broadwhorl tightcoil	OR-STR/WA-SEN			S	D
Bufflehead	OR-SEN		D	D	D
California floater	OR-SEN/WA-STR	S	D		S
Cascade torrent salamander	WA-SEN	D			
Clark’s grebe	WA-SEN	D			
Common loon	WA-SEN	D			
Cope’s giant salamander	OR-SEN		D	D	
Columbia duskysnail	STR	D	D	D	
Columbia Gorge caddisfly	OR-SEN		D		
Columbia Gorge oregonian	SEN	D	S		
Columbia pebblesnail	OR-SEN/WA-STR	S	S		
Columbia River tiger beetle	STR	S	S		
Columbia sideband	OR-SEN		D	S	

Table 6.11—Interagency Special Status/Sensitive Species Program species associated with riparian or water habitats (continued)

		Occurrence status[b] [c]			
Common name	**Status**[a]	**CRG-WA**	**CRG-OR**	**MTH**	**WIL**
Crater Lake tightcoil	OR-SEN			D	D
Crowned tightcoil	OR-SEN/WA-STR	S	S	S	
Dalles hesperian	STR	D		D	
Dalles juga	OR-STR		S	S	
Deschutes mountainsnail	OR-SEN		S		
Gray-blue butterfly	OR-SEN				S
Harlequin duck	SEN	D	D	D	D
Horned grebe	OR-SEN		D		
Jackson Lake springsnail	OR-SEN		S		
Juga spp.	STR	D	D	S	
Least bittern	OR-STR				S
Nerite ramshorn	STR	S	S		
Northern waterthrush	OR-SEN				D
Olympia pebblesnail	OR-SEN/WA-STR	S			D
One-spot rhyacophilan caddisfly	OR-STR			D	D
Oregon megomphix	WA-STR	S			
Oregon spotted frog	SEN	D	D	D	D
Pacific clubtail	WA-STR	S			
Painted turtle	OR-SEN		D		
Pristine springsnail	OR-STR/WA-SEN	D	D	D	
Purple-lipped juga	OR-STR		S	S	
Purple martin	OR-SEN		D		S
Scott’s apatanian caddisfly	OR-SEN			D	
Shortface lanx	OR-SEN/WA-STR	S	S		
Tombstone Prairie caddisfly	OR-STR				D
Van Dyke’s salamander	WA-SEN				
Wahkeena Falls flightless stonefly	OR-SEN		D		
Western pond turtle	SEN	D	D	D	D
Western ridged mussel	SEN	S	S		
Winged floater	STR	S	S		
Yuma skipper	OR-SEN/WA-STR	S	S		

[a] SEN = Sensitive in Oregon and Washington; OR-SEN = Sensitive in Oregon; OR-STR = Strategic in Oregon; WA-SEN = Sensitive in Washington; WA-STR = Strategic in Washington.

[b] CRG-WA = Columbia River Gorge National Scenic Area in Washington; CRG-OR = Columbia River Gorge National Scenic Area in Oregon; MTH = Mount Hood National Forest; WIL = Willamette National Forest.

[c] D = Documented occurrence: a species located on land administered by the Forest Service based on historical or current known sites of a species reported by a credible source for which the Forest Service has knowledge of written, mapped or specimen documentation of the occurrence; S = suspected occurrence: species is not documented on land administered by the Forest Service, but may occur on the unit because (1) the national forest is considered to be within the species’ range, and (2) appropriate habitat is present, or (3) there is known occurrence of the species (historical or current) in the vicinity such that the species could occur on Forest Service land.

Nonclimatic stressors—

Nonclimatic stressors for wildlife include fire, diseases, invasive species, land use change, grazing, timber harvest, roads, recreation, and human water use (Olson and Agee 2005, Penaluna et al. 2017, Van Rooij et al. 2015, USDA FS 2011). Invasive species in riparian areas can alter community interactions, reduce food availability, and change habitat structure. For example, breeding habitat for Oregon spotted frogs is degraded by invasive reed canarygrass (Kapust et al. 2012).

Historical clearcut harvesting and replanting have altered riparian forest structure and composition, reducing availability of large dead wood (Ruzicka et al. 2014). In headwater streams, forest thinning without stream buffers negatively affects resident amphibian communities (Olson et al. 2014), although this effect may be ameliorated by varying thinning density and including buffers of varying widths. Roads can alter flooding, sedimentation, and debris flow patterns in riparian systems (Jones et al. 2000).

Concentrated grazing by wild and domestic ungulates can contribute to loss of woody vegetation, streambed downcutting, compromised hydrologic function, and reduced aquatic insect diversity (Brookshire et al. 2002, Sakai et al. 2012). Riparian and open-water settings attract recreational and residential development, contributing to the loss of riparian vegetation, soil compaction, loss of dead wood habitat structures, and high levels of human disturbance (Gaines et al. 2003).

The historical role of fire in riparian areas is complex (Olson and Agee 2005). Relatively cool, moist riparian areas are less likely to burn than adjacent upland areaas. However, when fuels are dry, high-intensity fire can burn through riparian areas, with high fuel loads and the linear contour of riparian areas facilitating rapid fire spread across the landscape (Pettit and Naiman 2007).

Groundwater-dependent ecosystems in the CWMAP assessment area are threatened by increased groundwater extraction, pesticides and other toxic substances, and anthropogenic nutrient loading; these threats are highest in the northern portion of the assessment area (Brown et al. 2011). Declines in groundwater levels have been documented for hydrologic units in Mount Hood National Forest upstream of Hood River, Oregon (Brown et al. 2011).

Exposure

The degree of exposure to climate change effects in riparian areas and wetlands will largely be determined by changes in hydrology. Projections suggest that lower elevations of the assessment area may see minimal and local changes in hydrology, consisting primarily of higher rainfall intensity during winter months and less precipitation during summer (chapters 2 and 3). The higher elevation portions of the assessment area along the Cascade crest are expected to experience a shift from winter snow to winter rain-dominated systems, with increased peak flows during winter and decreased low flows during summer (chapter 3). Increased variability and potential for extreme precipitation events will contribute to the risk of damaging floods.

Cold, moving-water habitat conditions are expected to be highly exposed to climate change impacts because of their association with snowmelt-dominated hydrologic systems. Lower summer flows and reduced high-elevation snowpack (coldwater supply) are expected to contribute to increased summer stream temperatures and diminished cold, moving-water habitat characteristics in historically snow-dominated subwatersheds (chapter 3). Increased fire frequency and severity also have the potential to affect riparian areas, particularly if high-severity fire spreads into these areas from adjacent portions of the landscape.

Sensitivity

The sensitivity of riparian systems will differ by their hydrologic characteristics and landscape context. East-side riparian systems, which are situated in a semiarid landscape and are characterized by lower flow levels than hydrologic systems west of the Cascade crest, are a scarcer and more fragmented habitat, and declining summer streamflows will have a greater effect on fauna. Altered riparian vegetation, which is much more spatially constrained on the east side, could lead to higher stream temperatures and loss of habitat structures (nesting, resting, and foraging) provided by shrubs, snags, and logs. Changes in seasonal water availability and water temperature may affect aquatic insect populations that provide prey for insectivorous wildlife. Riparian areas west of the Cascade crest support rich amphibian and mollusk diversity, and altered flows as well as habitat loss from scouring events will negatively affect this faunal assemblage.

Distribution of cold, moving-water streams is likely to decrease as water temperatures increase and summer flows decrease. By increasing stream temperatures and reducing water storage, climate change will fragment coldwater areas, reducing genetic and population connectivity for species associated with cold water (Lawrence et al. 2014). Groundwater-fed stream systems that currently support these conditions may be less sensitive to climate change impacts than snowmelt-fed systems.

Loss of riparian vegetation resulting from increased frequency and severity of fire or winter flooding could also contribute to increased stream temperatures and loss of nesting and resting structures for wildlife (e.g., shrubs, snags, logs). More frequent and intense winter flood events can bury or scour riparian vegetation and damage or remove large tree and large wood habitat components. In drier areas, warmer temperature and drier soil may lead to more drought-tolerant conifers replacing riparian hardwoods (Dwire et al. 2018).

Adaptive Capacity

The adaptive capacity of wetland, riparian, and open-water areas and associated wildlife is limited by the hydrologic and topographic context in which they exist. Because the effects of climate change are likely to differ spatially (driven by hydrology, aspect, slope, microclimates, etc.), refugia are likely to persist for some species (Dwire et al. 2018). The linear, attitudinally connected pattern of riparian habitats may provide for upward range shifts for associated species to track cooler climatic conditions. If forest cover is undisturbed, connectivity along stream networks and across ridgelines between headwater streams is high (Olson and Burton 2019). Thus, riparian corridors may provide species with the ability to move across climatic gradients (Krosby et al. 2014).

Strategies to maintain instream flow, groundwater recharge, and riparian vegetation can be developed based on the unique landscape and hydrology characteristics of the areas under consideration. Reeves et al. (2016) reviewed actions that increase resilience of riparian reserves in a changing climate and suggested that riparian areas of sufficient size and tree densities can offset the potential local effects of climate change on water temperatures. Management strategies to retain or restore keystone species that contribute to hydrologic and nutrient cycling functions (e.g., American beaver) may become increasingly important. However, because beavers can have far-reaching effects on habitat, including flooding of streamside wetlands and removal of large live trees, careful consideration does need to be given to selection of appropriate areas for beaver reintroduction.

Managing Wildlife Habitat in the Face of Uncertainty

The effects of climate change on wildlife habitats, distributions, and abundances are uncertain, and it is challenging to project how, when, and where wildlife species will shift their distribution or experience changes in population dynamics. However, insights from biogeography, landscape ecology, and conservation biology can guide management of wildlife and wildlife habitats in a changing climate. These insights include:

- Species distributions are often shaped by climatic gradients and are likely to follow those gradients as they shift with climate change, often upward in elevation or poleward in latitude (Parmesan and Yohe 2003). However, there are important nuances. For example, species may shift downslope following shifting moisture availability rather than responding to temperature (Corlett and Westcott 2013).
- Many animal species are closely associated with specific vegetation types, seral stages, or configurations, and can be expected to track climate-driven

shifts in vegetation in addition to, or instead of, changing climatic patterns.

- Many species require specific structures (e.g., big trees or snags, closed canopies, cavities, talus slopes) and other resources (e.g., acorns, prey species, mineral licks, snow), or have obligate dependencies on other species in the community (e.g., mutualisms). These relationships may constrain their ability to track suitable climate conditions.
- Changes in vegetation may lag changes in climate and occur in a sporadic fashion, mediated by disturbance processes (insects, pathogens, fire) and cycles of climatic variability and extremes (e.g., droughts, wind and ice storms, extreme precipitation events). These lags may lead to spatial gaps in suitability along the routes species must follow to shift their distributions to future suitable space (Early and Sax 2011).
- Species can track shifting habitats only as their dispersal abilities, biotic interactions, and landscape permeability allow. These characteristics and relationships are typically complex and lack supporting data (Urban et al. 2013). The most frequently cited strategy to facilitate species movements in a changing climate is to maintain habitat connectivity, with attention to the potential effects of climate change (Littlefield et al. 2019).
- Increasing the ability of populations to persist through climatically stressful periods increases their ability to colonize newly available habitats during more favorable conditions by increasing the number of populations able to generate dispersing individuals.

See chapter 9 for further discussion of climate change adaptation options related to wildlife and wildlife habitat.

Literature Cited

Aikens, C.M.; Connolly, T.J.; Jenkins, D. 2011. Oregon archaeology. Corvallis, OR: Oregon State University Press. 148 p.

Altman, B. 2000. Conservation strategy for landbirds of the east-slope of the Cascade Mountains in Oregon and Washington. Version 2.0. Corvallis, OR: Oregon-Washington Partners in Flight and American Bird Conservancy and Klamath Bird Observatory. 88 p. https://avianknowledgenorthwest.net/resources/conservation-plans/or-wa-pif-plans. (7 December 2020).

Altman, B. 2011. Historical and current distribution and populations of bird species in prairie-oak habitats in the Pacific Northwest. Northwest Science. 85: 194–222.

Altman, B.; Alexander, J. 2012. Habitat conservation for landbirds in the coniferous forests of western Oregon and Washington. Ashland, OR: Oregon-Washington Partners in Flight, American Bird Conservancy and Klamath Bird Observatory. 88 p. https://avianknowledgenorthwest.net/resources/conservation-plans/or-wa-pif-plans/or-wa-pif-western-coniferous-forests. (12 December 2020).

Altman, B.; Hayes, M.; Janes, S.; Forbes, R. 2001. Wildlife of westside grasslands and chaparral habitats. In: Johnson, D.; O'Neil, T.A., eds. Wildlife-habitat relationships in Oregon and Washington. Corvallis, OR: Oregon State University Press: 261–291.

Altman, B.; Holmes, A. 2000. Conservation strategy for landbirds in the Columbia Plateau of eastern Oregon and Washington. Version 1.0. Corvallis, OR: Oregon-Washington Partners in Flight and American Bird Conservancy and Klamath Bird Observatory. 131 p.

Applegarth, J.S.; Duncan, N.; Foltz Jordan, S.; Hoffman Black, S. 2015. Conservation assessment for *Cryptomastix hendersoni*, Columbia Oregonian. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Region and U.S. Department of the Interior, Bureau of Land Management, Oregon and Washington Interagency Special Status and Sensitive Species Program. https://www.fs.fed.us/r6/sfpnw/issssp/documents3/ca-ig-cryptomastix-hendersoni-201504-508.pdf. (23 December 2020).

Aubry, K.B.; Houston, D.B. 1992. Distribution and status of the fisher (*Martes pennanti*) in Washington. Northwestern Naturalist. 73: 69–79.

Aubry, K.B.; Lewis, J.C. 2003. Extirpation and reintroduction of fishers (*Martes pennanti*) in Oregon: implications for their conservation in the Pacific states. Biological Conservation. 114: 79–90.

Bachelet, D.; Johnson, B.R.; Bridgham, S.D. [et al.]. 2011. Climate change impacts on western Pacific Northwest prairies and savannas. Northwest Science. 85: 411–429.

Barbero, R.; Abatzoglou, J.T.; Steel, E.A.; Larkin, N.K. 2014. Modeling very large-fire occurrences over the continental United States from weather and climate forcing. Environmental Research Letters. 9: 124009.

Baruch-Mordo, S.; Evans, J.S.; Severson, J.P. [et al.]. 2013. Saving sage-grouse from the trees: a proactive solution to reducing a key threat to a candidate species. Biological Conservation. 167: 233–241.

Baxter, C.V.; Fausch, K.D.; Saunders, W.C. 2005. Tangled webs: reciprocal flows of invertebrate prey link streams and riparian zones. Freshwater Biology. 50: 201–220.

Bell, D.M.; Pabst, R.J.; Shaw, D.C. 2020. Tree growth declines and mortality were associated with a parasitic plant during warm and dry climatic conditions in a temperate coniferous forest ecosystem. Global Change Biology. 26: 1714–1724.

Brockway, D.G.; Topik, C.; Hemstrom, M.A.; Emmington, W.H. 1983. Plant association and management guide for the Pacific silver fir zone: Gifford Pinchot National Forest. Misc. Publ. R6-Ecol-130A-1983. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Region. 122 p.

Brookshire, E.N.J.; Kauffman, J.B.; Lytjen, D.; Otting, N. 2002. Cumulative effects of wild ungulate and livestock herbivory on riparian willows. Oecologia. 132: 559–566.

Brown, E.R. 1985. Management of wildlife and fish habitats in forests of western Oregon and Washington. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Region. 332 p.

Brown, J.; Bach, L.; Aldous, A. [et al.]. 2011. Groundwater-dependent ecosystems in Oregon: an assessment of their distribution and associated threats. Frontiers in Ecology and the Environment. 9: 97–102.

Carroll, C.; Dunk, J.R.; Moilanen, A. 2010. Optimizing resiliency of reserve networks to climate change: multispecies conservation planning in the Pacific Northwest, USA. Global Change Biology. 16: 891–904.

Carroll, C.; Parks, S.A.; Dobrowski, S.Z.; Roberts, D.R. 2018. Climatic, topographic, and anthropogenic factors determine connectivity between current and future climate analogs in North America. Global Change Biology. 24: 5318–5331.

Case, M.J.; Lawler, J.J.; Tomasevic, J.A. 2015. Relative sensitivity to climate change of species in northwestern North America. Biological Conservation. 187: 127–133.

Chan, S.; Anderson, P.; Cissel, J. [et al.]. 2004. Variable density management in riparian reserves: lessons learned from an operational study in managed forests of western Oregon, USA. Forest Snow and Landscape Research. 78: 151–172.

Chapman, S.; Mustin, K.; Renwick, A.R. [et al.]. 2014. Publishing trends on climate change vulnerability in the conservation literature reveal a predominant focus on direct impacts and long time-scales. Diversity and Distributions. 20: 1221–1228.

Chappell, C.B.; Crawford, R.C.; Barrett, C. 2001. Montane mixed conifer forest. In: Johnson, D.; O'Neil, T.A., eds. Wildlife-habitat relationships in Oregon and Washington. Corvallis, OR: Oregon State University Press: 22–114.

Choat, B.; Brodribb, T.; Brodersen, C. [et al.]. 2018. Triggers of tree mortality under drought and forest mortality. Nature. 558: 531–539.

Clark, J.S.; Iverson, L.; Woodall, C.W. 2016a. Impacts of increasing drought on forest dynamics, structure, diversity, and management. In: Vose, J.M.; Clark, J.S.; Luce, C.H.; Patel-Weynard, T., eds. Effects of drought on forests and rangelands in the United States: a comprehensive science synthesis. Gen. Tech. Rep. WO-93b. Washington, DC: U.S. Department of Agriculture, Forest Service: 59–96.

Clark, P.U.; Shakun, J.D.; Marcott, S.A. [et al.]. 2016b. Consequences of twenty-first-century policy for multi-millennial climate and sea-level change. Nature Climate Change. 6: 360–369.

Clayton, D.R.; Olson, D.H. 2009. Conservation assessment for the Oregon slender salamander (*Batrachoseps wrighti*). Version 2.0. Publ. 4518. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Region, and U.S. Department of the Interior, Bureau of Land Management, Oregon and Washington Interagency Special Status and Sensitive Species Program. 76 p. https://andrewsforest.oregonstate.edu/publications/4518. (12 July 2021).

Cope, A.B. 1993a. *Abies amabilis*. In: Fire Effects Information System. Missoula, MT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory. https://www.fs.fed.us/database/feis/plants/tree/abiama/all.html. (23 December 2020).

Cope, A.B. 1993b. *Abies procera*. In: Fire Effects Information System. Missoula, MT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory. https://www.fs.fed.us/database/feis/plants/tree/abipro/all.html. (23 December 2020).

Corlett, R.T.; Westcott, D.A. 2013. Will plant movements keep up with climate change? Trends in Ecology and Evolution. 28: 482–488.

Crisafulli, C.M.; Clayton, D.R.; Olson, D.H. 2008. Conservation assessment for the Larch Mountain salamander (*Plethodon larselli*). Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Region, and U.S. Department of the Interior, Bureau of Land Management, Oregon and Washington Interagency Special Status and Sensitive Species Program. https://www.fs.fed.us/r6/sfpnw/issssp/documents/planning-docs/ca-ha-plethodon-larselli-2008-10-28.doc. (23 December 2020).

Davies, K.W.; Boyd, C.S.; Beck, J.L. [et al.]. 2011. Saving the sagebrush sea: an ecosystem conservation plan for big sagebrush plant communities. Biological Conservation. 144: 2573–2584.

Devine, W.; Bower, A.; Miller, J.; Aubry, C. 2013. Oregon white oak restoration strategy for National Forest System lands east of the Cascade Range. Olympia, WA: U.S. Department of Agriculture, Forest Service, Pacific Northwest Region. 98 p.

Dugger, K.M.; Gremel, S.A.; Forsman, E.D. [et al.]. 2015. The effects of habitat, climate, and barred owls on long-term demography of northern spotted owls. The Condor. 118: 57–116.

Duncan, N.; Foltz Jordan, S.; Hoffman Black, S. 2014. Conservation assessment for *Monadenia fidelis minor* (Dalles sideband). Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Region, and U.S. Department of the Interior, Bureau of Land Management, Oregon and Washington Interagency Special Status and Sensitive Species Program.

Dunk, J.R.; Hawley, J.J. 2009. Red-tree vole habitat suitability modeling: implications for conservation and management. Forest Ecology and Management. 258: 626–634.

Dwire, K.A.; Mellmann-Brown, S.; Gurrieri, J.T. 2018. Potential effects of climate change on riparian areas, wetlands, and groundwater-dependent ecosystems in the Blue Mountains, Oregon, USA. Climate Services. 10: 44–52.

Early, R.; Sax, D.F. 2011. Analysis of climate paths reveals potential limitations on species range shifts. Ecology Letters. 14: 1125–1133.

Foltz Jordan, S.; Hoffman Black, S. 2012. Effects of forest land management on terrestrial mollusks: a literature review. The Xerces Society for Invertebrate Conservation. https://xerces.org/sites/default/files/publications/12-054.pdf. (23 December 2020).

Foster, A.D.; Olson, D.H. 2014. Conservation assessment for the Cope's giant salamander (*Dicamptodon copei*). Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Region, and U.S. Department of the Interior, Bureau of Land Management Oregon and Washington, Interagency Special Status and Sensitive Species Program. 57 p. https://www.fs.fed.us/r6/sfpnw/issssp/species-index/fauna-amphibians.shtml. (23 December 2020).

Franklin, J.; Dyrness, C.T. 1988. Natural vegetation of Oregon and Washington. 2nd ed. Corvallis, OR: Oregon State University Press. 452 p.

Franklin, J.F.; Spies, T.A.; Swanson, F.J. 2017. Setting the stage: vegetation ecology and dynamics. In: Olson, D.H.; Van Horne, B., eds. People, forests, and change: lessons from the Pacific Northwest. Washington, DC: Island Press: 16–32.

Friggens, M.M.; Williams, M.I.; Bagne, K.E. [et al.]. 2018. Effects of climate change on terrestrial animals. In: Halofsky, J.E.; Peterson, D.L.; Ho, J.J. [et al.], eds. Climate change vulnerability and adaptation in the Intermountain Region [Part 2]. Gen. Tech. Rep. RMRS-GTR-375. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 264–315.

Gaines, W.L.; Singleton, P.H.; Ross, R.C. 2003. Assessing the cumulative effects of linear recreation routes on wildlife habitats on the Okanogan and Wenatchee National Forests. Gen. Tech. Rep. PNW-GTR-586. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 79 p.

Gervais, J. 2017. Conservation assessment for the Townsend's big-eared bat (*Corynorhinus townsendii*) in Oregon and Washington. Portland, OR; U.S. Department of Agriculture, Forest Service, Pacific Northwest Region, and U.S. Department of the Interior, Bureau of Land Management Oregon and Washington, Interagency Special Status and Sensitive Species Program. http://www.oregonwildlife.org/publication/download/conservation-assessment-for-the-townsends-big-eared-bat-corynorhinus-townsendii-in-oregon-and-washington. (23 December 2020).

Gregory, S.V.; Swanson, F.V.; McKee, W.A.; Cummins, K.W. 1991. An ecosystem perspective of riparian zones. BioScience. 41: 510–551.

Hagar, J.C.; Stern, M.A. 2001. Avifauna in oak woodlands of the Willamette Valley, Oregon. Northwestern Naturalist. 82: 12–25.

Halofsky, J.E.; Peterson, D.L.; Ho, J.J. [et al.], eds. 2018a. Climate change vulnerability and adaptation in the Intermountain Region. Gen. Tech. Rep. RMRS-GTR-375. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. Parts I and II.

Halofsky, J.E.; Peterson, D.L.; O'Halloran, K.A.; Hawkins Hoffman, C. 2012. Adapting to climate change at Olympic National Forest and Olympic National Park. Gen. Tech. Rep. PNW-GTR-844. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 130 p.

Halofsky, J.S.; Conklin, D.R.; Donato, D.C. [et al.]. 2018b. Climate change, wildfire, and vegetation shifts in a high-inertia forest landscape, Western Washington, U.S.A. PLoS ONE. 13: 1–23.

Hamman, S.T.; Dunwiddie, P.W.; Nuckols, J.L.; McKinley, M. 2011. Fire as a restoration tool in Pacific Northwest prairies and oak woodlands: challenges, successes, and future directions. Northwest Science. 85: 317–328.

Hayes, J.P. 2003. Habitat ecology and conservation of bats in western coniferous forests. In Zabel, C.J.; Anthony, R.G., eds. Mammal community dynamics: management and conservation in the coniferous forests of western North America. Cambridge, United Kingdom: Cambridge University Press: 81–119.

Hessburg, P.F.; Spies, T.A.; Perry, D.A. [et al.]. 2016. Tamm review: management of mixed-severity fire regime forests in Oregon, Washington, and northern California. Forest Ecology and Management. 366: 221–250.

Hietala-Henschell, K.; Foltz Jordan, S.; Jepsen, S.; Scheuering, E. 2020. Interagency Special Status/Sensitive Species Program species fact sheet: *Speyeria zerene bremnerii*. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Region, and U.S. Department of the Interior, Bureau of Land Management, Oregon and Washington Interagency Special Status and Sensitive Species Program. https://www.fs.fed.us/r6/sfpnw/issssp/species-index/fauna-invertebrates.shtml. (23 December 2020).

Holtmeier, F.K.; Broll, G. 2012. Landform influences on treeline patchiness and dynamics in a changing climate. Physical Geography. 33: 403–437.

Inkley, D.B.; Anderson, M.G.; Blaustein, A.R. [et al.]. 2004. Global climate change and wildlife in North America. Tech. Rev. 04-2. Bethesda, MD: The Wildlife Society. 26 p.

Johnson, D.; O'Neil, T.A., eds. 2001. Wildlife-habitat relationships in Oregon and Washington. Corvallis, OR: Oregon State University Press. 736 p.

Jones, J.A.; Swanson, F.J.; Wemple, B.C.; Snyder, K.U. 2000. Effects of roads on hydrology, geomorphology, and disturbance patches in stream networks. Conservation Biology. 14: 76–85.

Kane, V.R.; Cansler, C.A.; Povak, N.A. [et al.]. 2015. Mixed severity fire effects within the Rim Fire: relative importance of local climate, fire weather, topography, and forest structure. Forest Ecology and Management. 358: 62–79.

Kapust, H.Q.W.; McAllister, K.R.; Hayes, M.P. 2012. Oregon spotted frog (*Rana pretiosa*) response to enhancement of oviposition habitat degraded by invasive reed canary grass (*Phalaris arundinacea*). Herpetological Conservation and Biology. 7: 358–366.

Kauffman, J.B.; Mahrt, M.; Mahrt, L.; Edge, W.D. 2001. Wildlife of riparian habitats. In: Johnson, D.H.; O'Neil, T.A., eds. Wildlife-habitat relationships in Oregon and Washington. Corvallis, OR: Oregon State University Press: 361–388.

Krosby, M.; Norheim, R.; Theobald, D.M.; McRae, B.H. 2014. Riparian climate-corridors: identifying priority areas for conservation in a changing climate. Seattle, WA: Climate Impacts Group, University of Washington. 21 p.

Larsen, T.; Ripple, W.J. 2006. Modeling gray wolf (*Canis lupus*) habitat in the Pacific Northwest, U.S.A. Journal of Conservation Planning. 2: 17–33.

Lawler, J.J.; Girvetz, E.; Safford, H. 2012. Martens and fishers in a changing climate: a new synthesis. In: Aubry, K.B.; Zielinski, W.J.; Raphael, M. [et al.], eds. Biology and conservation of martens, sables, and fishers. Ithaca, NY: Cornell University Press. 580 p.

Lawler, J.; Shafer, S.; White, D.; Kareiva, P. 2009. Projected climate-induced faunal change in the Western Hemisphere. Ecology. 90: 588–597.

Lawrence, D.; Stewart-Koster, B.; Olden, J.D. [et al.]. 2014. The interactive effects of climate change, riparian management, and a nonnative predator on stream-rearing salmon. Ecological Applications. 24: 895–912.

Lee, D. 2018. Spotted owls and forest fire: a systematic review and meta-analysis of the evidence. Ecosphere. 9: e02354.

Lehmkuhl, J.F.; Kistler, K.D.; Begley, J.S.; Boulanger, J. 2006. Demography of northern flying squirrels informs ecosystem management of western interior forests. Ecological Applications. 16: 584–600.

Lindenmayer, D.B.; Laurance, W.F. 2017. The ecology, distribution, conservation and management of large old trees. Biological Reviews. 92: 1434–1458.

Linnell, M.A.; Moriarty, K.; Green, D.S.; Levi, T. 2018. Density and population viability of coastal marten: a rare and geographically isolated small carnivore. PeerJ. 6: e4530.

Littlefield, C.E.; Krosby, M.; Michalak, J.L.; Lawler, J.J. 2019. Connectivity for species on the move: supporting climate-driven range shifts. Frontiers in Ecology and the Environment. 17: 270–278.

Lubetkin, K.C.; Westerling, A.L.; Kueppers, L.M. 2017. Climate and landscape drive the pace and pattern of conifer encroachment into subalpine meadows. Ecological Applications. 27: 1876–1887.

Lucash, M.S.; Farnsworth, B.; Winner, W.E. 2005. Response of sagebrush steppe spedies to elevated CO_2 and soil temperature. Western North American Naturalist. 65: 80–86.

Macias-Fauria, M.; Johnson, E.A. 2013. Warming-induced upslope advance of subalpine forest is severely limited by geomorphic processes. Proceedings of the National Academy of Sciences, USA. 110: 8117–8122.

Martin, K.M. 2001. Wildlife of alpine and subalpine habitats. In: Johnson, D.H.; O'Neil, T.A., eds. Wildlife-habitat relationships in Oregon and Washington. Corvallis, OR: Oregon State University Press: 285–310.

Mcfadden-Hiller, J.E.; Hiller, T.L. 2015. Non-invasive survey of forest carnivores in the Northern Cascades of Oregon, USA. Northwestern Naturalist. 96: 107–117.

McKenzie, D.; Gedalof, Z.; Peterson, D.L.; Mote, P. 2004. Climatic change, wildfire, and conservation. Conservation Biology. 18: 890–902.

McKinney, S.T.; Fiedler, C.E.; Tomback, D.F. 2009. Invasive pathogen threatens bird-pine mutualism: implications for sustaining a high-elevation ecosystem. Ecological Applications. 19: 597–607.

McShea, W.J.; Healy, W.M. 2002. Oak forest ecosystems: ecology and management for wildlife. Baltimore, MD: Johns Hopkins University Press. 432 p.

Millar, C.I.; Charlet, D.A.; Westfall, R.D. [et al.]. 2018. Do low-elevation ravines provide climate refugia for subalpine limber pine (*Pinus flexilis*) in the Great Basin, USA? Canadian Journal of Forest Research. 48: 663–671.

Millar, C.I.; Rundel, P.W. 2016. Subalpine forests. In: Mooney, H.; Zavaleta, E., eds. Ecosystems of California. Oakland, CA: University of California Press: 579–611.

Moriarty, K.M.; Epps, C.W.; Betts, M.G. [et al.]. 2015. Experimental evidence that simplified forest structure interacts with snow cover to influence functional connectivity for Pacific martens. Landscape Ecology. 30: 1865–1877.

Moritz, C.; Patton, J.L.; Conroy, C.J. [et al.]. 2008. Impact of a century of climate change on small-mammal communities in Yosemite. Science. 322: 261–264.

Morrison, M.L.; Marcot, B.G.; Mannan, R.W. 2006. Wildlife-habitat relationships: concepts and applications. 3rd ed. Washington, DC: Island Press. 493 p.

Nathan, R.; Schurr, F.M.; Spiegel, O. [et al.]. 2008. Mechanisms of long-distance seed dispersal. Trends in Ecology and Evolution. 23: 638–647.

Nonaka, E.; Spies, T.A. 2005. Historical range of variability in landscape structure: a simulation study in Oregon, USA. Ecological Applications. 15: 1727–1746.

North, M.; Trappe, J.; Franklin, J. 1997. Standing crop and animal consumption of fungal sporocarps in Pacific Northwest forests. Ecology. 78: 1543–1554.

Noson, A.C.; Schmitz, R.A.; Miller, R.F. 2006. Influence of fire and juniper encroachment on birds in high-elevation sagebrush steppe. Western North American Naturalist. 66: 343–353.

Olson, D.H.; Burnett, K.M. 2009. Design and management of linkage areas across headwater drainages to conserve biodiversity in forest ecosystems. Forest Ecology and Management. 258: 117–126.

Olson, D.H.; Burton, J.I. 2019. Climate associations with headwater streamflow in managed forests over 16 years and projections of future dry headwater stream channels. Forests. 10: 968.

Olson, D.H.; Leirness, J.B.; Cunningham, P.G.; Steel, E.A. 2014. Riparian buffers and forest thinning: effects on headwater vertebrates 10 years after thinning. Forest Ecology and Management. 321: 81–93.

Olson, D.L.; Agee, J.K. 2005. Historical fires in Douglas-fir dominated riparian forests of the southern Cascades, Oregon. Fire Ecology. 1: 50–74.

Oregon Department of Fish and Wildlife [ODFW]. 2006. The Oregon conservation strategy. Salem, OR. https://www.dfw.state.or.us/conservationstrategy/read_the_strategy.asp. (3 December 2021)

Pacifici, M.; Foden, W.B.; Visconti, P. [et al.]. 2015. Assessing species vulnerability to climate change. Nature Climate Change. 5: 215–225.

Parks, S.A.; Dobrowski, S.Z.; Shaw, J.D.; Miller, C. 2019. Living on the edge: trailing edge forests at risk of fire-facilitated conversion to non-forest. Ecosphere. 10: e02651.

Parmesan, C.; Yohe, G. 2003. A globally coherent fingerprint of climate change impacts across natural systems. Nature. 421: 37–42.

Penaluna, B.E.; Olson, D.H.; Flitcroft, R.L. [et al.]. 2017. Aquatic biodiversity in forests: a weak link in ecosystem services resilience. Biodiversity Conservation. 26: 3125–3155.

Peterson, D.W.; Peterson, D.L.; Ettl, G.J. 2002. Growth responses of subalpine fir to climatic variability in the Pacific Northwest. Canadian Journal of Forest Research. 32: 1503–1517.

Pettit, N.E.; Naiman, R.J. 2007. Fire in the riparian zone: characteristics and ecological consequences. Ecosystems. 10: 673–687.

Pollock, M.M.; Beechie, T.J.; Imaki, H. 2012. Using reference conditions in ecosystem restoration: an example for riparian conifer forests in the Pacific Northwest. Ecosphere. 3: 98.

Reeves, G.H.; Pickard, B.R.; Johnson, K.N. 2016. An initial evaluation of potential options for managing riparian reserves of the Aquatic Conservation Strategy of the Northwest Forest Plan. Gen. Tech. Rep. PNW-GTR-937. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 97 p.

Reilly, M.J.; Spies, T.A. 2016. Disturbance, tree mortality, and implications for contemporary regional forest change in the Pacific Northwest. Forest Ecology and Management. 374: 102–110.

Reynolds, R.T.; Graham, R.T.; Boyce Jr, D.A. 2008. Northern goshawk habitat: an intersection of science, management, and conservation. The Journal of Wildlife Management. 72: 1047–1055.

Rose, C.L.; Marcot, B.G.; Mellen, T.K. [et al.]. 2001. Decaying wood in Pacific Northwest forests: concepts and tools for habitat management. In: Johnson, D.; O’Neil, T.A., eds. 2001. Wildlife-habitat relationships in Oregon and Washington. Corvallis, OR: Oregon State University Press: 580–623.

Rowland, M.M.; Wisdom, M.J.; Nielson, R.M. [et al.]. 2018. Modeling elk nutrition and habitat use in western Oregon and Washington. Wildlife Monographs. 199: 1–69.

Ruediger, B.; Claar, J.; Mighton, S. [et al.]. 2000. Canada lynx conservation assessment and strategy. R1-00-53. Missoula, MT: U.S. Department of Agriculture, Forest Service, Northern Region; U.S. Department of the Interior, Fish and Wildlife Service, Bureau of Land Management, and National Park Service. 142 p.

Ruggiero, L.F.; Aubry, K.B.; Carey, A.B.; Huff, M.H., tech. eds. 1991. Wildlife and vegetation of unmanaged Douglas-fir forests. Gen. Tech. Rep. PNW-GTR-285. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 533 p.

Ruzicka, K.J.; Puettmann, K.J.; Olson, D.H. 2014. Management of riparian buffers: upslope thinning with downslope impacts. Forest Science. 60: 881–892.

Sakai, M.; Natuhara, Y.; Imanishi, A. [et al.]. 2012. Indirect effects of excessive deer browsing through understory vegetation on stream insect assemblages. Population Ecology. 54: 65–74.

Sallabanks, R.; Marcot, B.G.; Riggs, R.A. [et al.]. 2001. Wildlife of eastside (interior) forests and woodlands. In: Johnson, D.H.; O'Neil, T.A., eds. Wildlife-habitat relationships in Oregon and Washington. Corvallis, OR: Oregon State University Press: 213–238.

Schlaepfer, D.R.; Lauenroth, W.K.; Bradford, J.B. 2012. Effects of ecohydrological variables on current and future ranges, local suitability patterns, and model accuracy in big sagebrush. Ecography. 35: 374–384.

Schloss, C.A.; Nuñez, T.A.; Lawler, J.J. 2012. Dispersal will limit ability of mammals to track climate change in the Western Hemisphere. Proceedings of the National Academy of Sciences, USA. 109: 8606–8611.

Schultz, C.B.; Hamman, S.; Carleton, A. [et al.]. 2011. Conservation of prairie-oak butterflies in Oregon, Washington, and British Columbia. Northwest Science. 85: 361–388.

Shaw, D.C.; Franklin, J.F.; Bible, K. [et al.]. 2004. Ecological setting of the Wind River old-growth forest. Ecosystems. 7: 427–439.

Siegel, R.B.; Eyes, S.A.; Tingley, M.W. [et al.]. 2019. Short-term resilience of great gray owls to a megafire in California, USA. The Condor. 121: 19.

Simpson, W.G. 2009. American pikas inhabit low-elevation sites outside the species' previously described bioclimatic envelope. Western North American Naturalist. 69: 243–250.

Singleton, P.H.; Case, M.J.; Keown, K. [et al.]. 2019. Climate change, wildlife, and wildlife habitats in south-central Oregon. In: Halofsky, J.E.; Peterson, D.L.; Ho, J.J., eds. Climate change vulnerability and adaptation in south-central Oregon. Gen. Tech. Rep. PNW-GTR-974. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 297–345.

Singleton, P.H.; Vaughn, R.M.; Clayton, D.; Garcia, B.A. 2021. Climate change effects on wildlife in southwest Oregon. In: Halofsky, J.E.; Peterson, D.L.; Gravenmier, R.A., eds. Climate change vulnerability and adaptation in southwest Oregon. Gen. Tech. Rep. PNW-GTR-995. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 293–359.

Smith, W.K.; Germino, M.J.; Hancock, T.E.; Johnson, D.M. 2003. Another perspective on altitudinal limits of alpine timberlines. Tree Physiology. 23: 1101–1112.

Speakman, J.R.; Krol, E. 2010. Maximal heat dissipation capacity and hyperthermia risk: neglected key factors in the ecology of endotherms. Journal of Animal Ecology. 79: 726–746.

Spies, T.A.; Hessburg, P.F.; Skinner, C.N. [et al.]. 2018a. Old growth, disturbance, forest succession, and management in the area of the Northwest Forest Plan. In: Spies, T.; Stein, P.; Gravenmier, R.; Long, J. [et al.], eds. Synthesis of science to inform land management within the Northwest Forest Plan area. Gen. Tech. Rep. PNW-GTR-966. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 95–243. Vol. 1.

Spies, T.A.; Stine, P.A.; Gravenmier, R.; J.W. Long, J.W. [et al.] 2018b. Synthesis of science to inform land management within the Northwest Forest Plan area. Gen. Tech. Rep. PNW-GTR-966. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 1020 p. 3 vol.

Standiford, R.B.; Purcell, K.L., tech. coords. 2015. Proceedings of the seventh California oak symposium: managing oak woodlands in a dynamic world. Gen. Tech. Rep. PSW-GTR-251. Berkeley, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. 579 p.

Steele, C.A.; Storfer, A. 2006. Coalescent-based hypothesis testing supports multiple Pleistocene refugia in the Pacific Northwest for the Pacific giant salamander (*Dicamptodon tenebrosus*). Molecular Ecology. 15: 2477–2487.

Stine, P.; Hessburg, P.; Spies, T. [et al.]. 2014. The ecology and management of moist mixed-conifer forests in eastern Oregon and Washington: a synthesis of the relevant biophysical science and implications for future land management. Gen. Tech. Rep. PNW-GTR-897. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 254 p.

Swanson, M.E.; Franklin, J.F.; Beschta, R.L. [et al.]. 2011. The forgotten stage of forest succession: early-successional ecosystems on forest sites. Frontiers in Ecology and Environment. 9: 117–125.

Trapp, S.E.; Day, C.C.; Flaherty, E.A. [et al.]. 2019. Modeling impacts of landscape connectivity on dispersal movements of northern flying squirrels (*Glaucomys sabrinus griseifrons*). Ecological Modelling. 394: 44–52.

Turner, B.L.; Kasperson, R.E.; Matsone, P.A. [et al.]. 2003. A framework for vulnerability analysis in sustainability science. Proceedings of the National Academy of Sciences, USA. 100: 8074–8079.

Urban, M.C.; Zarnetske, P.L.; Skelly, D.K. 2013. Moving forward: dispersal and species interactions determine biotic responses to climate change. Annals of the New York Academy of Sciences. 1297: 44–60.

U.S. Department of Agriculture, Forest Service [USDA FS]. 2011. Region 6 terrestrial restoration and conservation strategy. Portland, OR: Pacific Northwest Region. http://www.fs.usda.gov/detail/r6/plants-animals/wildlife/?cid=stelprdb5440388. (2 February 2021).

Václavík, T.; Kanaskie, A.; Hansen, E.M. [et al.]. 2010. Predicting potential and actual distribution of sudden oak death in Oregon: prioritizing landscape contexts for early detection and eradication of disease outbreaks. Forest Ecology and Management. 260: 1026–1035.

Vander Haegen, W.M.; McCorquodale, S.M.; Peterson, C.R. [et al.]. 2001. Wildlife of eastside shrubland and grassland habitats. In: Johnson, D.H.; O'Neil, T.A., managing directors. Wildlife-habitat relationships in Oregon and Washington. Corvallis, OR: Oregon State University Press: 292–316.

van Mantgem, P.J.; Stephenson, N.L.; Byrne, J.C. [et al.]. 2009. Widespread increase of tree mortality rates in the Western United States. Science. 323: 521–524.

Van Rooij, P.; Martel, A.; Haesebrouck, F.; Pasmans, F. 2015. Amphibian chytridiomycosis: a review with focus on fungus-host interactions. Veterinary Research. 46: 137.

Vázquez, D.P.; Gianoli, E.; Morris, W.F.; Bozinovic, F. 2017. Ecological and evolutionary impacts of changing climatic variability. Biological Reviews. 92: 22–42.

Vesely, D.G.; Rosenberg, D.K. 2010. Wildlife conservation in the Willamette Valley's remnant prairies and oak habitats: a research synthesis. http://w.oregonwildlife.org/documents/Wildlife Synthesis Vers 1_1_final.pdf. (22 January 2021).

Walsh, M.K. 2008. Natural and anthropogenic influences on the Holocene fire and vegetation history of the Willamette Valley, northwest Oregon and southwest Washington. Eugene, OR: University of Oregon. 382 p. Ph.D. dissertation.

Weed, A.S.; Ayres, M.P.; Hicke, J.A. 2013. Consequences of climate change for biotic disturbances in North American forests. Ecological Monographs. 83: 441–470.

Wehner, M.F.; Arnold, J.R.; Knutson, T. [et al.]. 2017. Droughts, floods, and wildfires. In: Wuebbles, D.J.; Fahey, D.W.; Hibbard, K.A. [et al.], eds. Climate science special report: fourth national climate assessment. Volume I. Washington, DC: U.S. Global Change Research Program: 231–256.

Williams, S.E.; Shoo, L.P.; Isaac, J.L. [et al.]. 2008. Toward an integrated framework for assessing the vulnerability of species to climate change. PLoS Biology. 6: e325.

Wisdom, M.J.; Holthausen, R.S.; Wales, B.C. [et al.]. 2000. Source habitats for terrestrial vertebrates of focus in the interior Columbia basin: broadscale trends and management implications. Gen. Tech. Rep. PNW-GTR-485. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 3 vol.

Wood, C.M.; Witham, J.W.; Hunter, M.L. 2016. Climate-driven range shifts are stochastic processes at a local level: two flying squirrel species in Maine. Ecosphere 7: 1–9.

Zald, H.S.J.; Spies, T.A.; Huso, M.; Gatziolis, D. 2012. Climatic, landform, microtopographic, and overstory canopy controls of tree invasion in a subalpine meadow landscape, Oregon Cascades, USA. Landscape Ecology. 27: 1197–1212.

Chapter 7: Effects of Climate Change on Outdoor Recreation

Anna B. Miller, David L. Peterson, Lorelei Haukness, and Matthew Peterson[1]

Introduction

Public lands provide opportunities for people to participate in outdoor recreation and connect with nature. Outdoor recreation provides numerous physiological, psychological, social, and cultural benefits to public land visitors (Bowler et al. 2010, Thompson Coon et al. 2011) as well as economic benefits to local communities (White et al. 2016). Access to recreation opportunities is a key consideration that shapes where people live, work, and travel. Collectively, 4.1 million people live within a 160-km drive of the Columbia River Gorge National Scenic Area (CRGNSA), Mount Hood National Forest (NF), and Willamette NF. Oregon had the ninth-fastest growing population of all U.S. states in 2017, with inmigration accounting for four out of five new Oregonians and natural growth accounting for just one of five new Oregonians (Njus, n.d.). Outdoor recreation opportunities and environmental quality are important draws attracting new residents to the Western United States (Hamilton et al. 2016, Rudzitis 1999). The increasing population and specific interest in outdoor recreation opportunities, coupled with a nationwide increase in outdoor recreation participation (Cordell 2012), emphasizes the importance of understanding the vulnerability of outdoor recreation to climate change, which will in turn help land managers develop adaptation options.

Spanning Oregon and a small portion of southern Washington, the CRGNSA, Mount Hood NF, and Willamette NF provide and manage for numerous outdoor recreation opportunities. These three units, collectively referred to as the CMW Adaptation Partnership (CMWAP) assessment area, host an estimated 6.2 million visits per year (data from the U.S. Department of Agriculture [USDA]), Forest Service National Visitor Use Monitoring program; https://www.fs.usda.gov/about-agency/nvum). Outdoor recreation in this area provides benefits to individuals and communities throughout the region. Publicly managed outdoor recreation opportunities contribute substantially to the economic well-being of communities throughout the CMWAP assessment area, where $199 million is spent annually

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[1] **Anna B. Miller** is an assistant professor, Utah State University, 5215 Old Main Hill, Logan, UT 84322; **David L. Peterson** is a research biological scientist (emeritus), U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, 400 N 34th Street, Suite 201, Seattle, WA 98103; **Lorelei Haukness** is the recreation program manager, U.S. Department of Agriculture, Forest Service, Columbia River Gorge National Scenic Area, 902 Wasco Avenue, Suite 200, Hood River, OR 97031; **Matthew Peterson** is the assistant recreation staff officer, U.S. Department of Agriculture, Forest Service, Willamette National Forest, 3106 Pierce Parkway Suite D, Springfield, OR 97477.

on visits to recreation destinations managed by the Forest Service (USDA FS 2012a, 2016). The wide-ranging economic benefits provided by publicly managed outdoor recreation opportunities can be attributed to the many activities available throughout the year (table 7.1).

Recreation opportunities offered on public lands throughout the assessment area are as diverse as the ecosystems upon which they depend, spanning elevations from sea level at the Columbia River to 3426 m at the summit of Mount Hood, and containing distinctive landscape features that attract recreationists. As climate change alters the conditions of these ecological systems, it also directly affects the ability of public land management agencies to consistently provide high-quality outdoor recreation opportunities to the public (Loomis and Richardson 2006, O'Toole et al. 2019, Richardson and Loomis 2004).

Recreationists often value specific places in particular ways. Although preferences for certain landscapes may be somewhat innate, individual experiences and sociocultural components play important roles in a sense of place for recreationists (Farnum et al. 2005). For the individual, repeated experiences can strengthen attachments or emotional ties to a place (Stedman 2003). Social

Table 7.1—Categories of recreation activities by primary season

Recreation activity[a]	Winter	Spring	Summer	Autumn
Boating		✓	✓	✓
Camping, picnicking		✓	✓	✓
Cycling (mountain biking, road biking)		✓	✓	✓
Fishing		✓	✓	✓
Hiking, backpacking (including long-distance hiking)		✓	✓	✓
Horseback riding		✓	✓	✓
Motorized recreation (snowmobiles)	✓			
Motorized recreation (off-road vehicles)		✓	✓	✓
Nonmotorized winter recreation (downhill skiing, cross-country skiing, fat-tire bikes, dog sledding, sledding/tubing, general slow play, mountaineering)	✓			
Recreation residences	✓	✓	✓	✓
River rafting			✓	
Scenic driving (nature viewing)	✓	✓	✓	✓
Special forest products (e.g., mushrooms, cones)		✓	✓	✓
Swimming			✓	
Other forest uses (Christmas tree harvest, firewood cutting)	✓	✓	✓	✓
Wildlife-related activities	✓	✓	✓	✓

[a] Note that these may differ somewhat from the official categories in the National Visitor Use Monitoring data (table 7.3).

relationships can also play a role in the meanings that individuals ascribe to a place (Smith et al. 2011). In addition, different communities value areas that are closer to their home for different reasons, such as enabling time spent with family and friends or economic benefits (Eisenhauer et al. 2000). Examples of highly valued places in the CMWAP assessment area and some of their unique values are summarized in table 7.2.

Table 7.2—Highly valued places in the Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest Adaptation Partnership assessment area

Unit	Location	Examples of distinctive values
Columbia River Gorge National Scenic Area	Historic Columbia River Highway	A registered National Historic Landmark, this corridor has scenic, cultural, and recreational significance. Points of interest include Vista House,[a] which provides sweeping views of the Gorge; Multnomah Falls, the most-visited recreation site in the Pacific Northwest; and Eagle Creek Recreation Area, hosting the oldest developed Forest Service campground.
	Historic Columbia River Highway State Trail[b]	On this trail, people enjoy hiking along the cliffs of the Columbia River Gorge, and viewing spectacular geologic formations and scenery.
	Beacon Rock State Park[c]	This park provides opportunities for year-round camping, hiking, equestrian activities, mountain biking, access to the Columbia River for fishing and boating, and some of the best "traditional climbing" in the Northwest. The core of an ancient volcano, Beacon Rock overlooks a section of the Columbia River Gorge. with walls of columnar basalt and mountains rising on both sides.
Willamette National Forest	Central Cascade Mountains	These mountains provide a range of outdoor recreation opportunities including hiking, backpacking, skiing, scenery, and wilderness experience.
	McKenzie River	The upper portion of this river is popular for fishing, rafting, drift boating, scenery, hiking, and biking. Biking is popular along the 42-km McKenzie River Trail, which passes waterfalls, lava fields, and old-growth forest.
	Waldo Lake	The second deepest lake in Oregon, and with pristine water quality, Waldo Lake provides opportunities for camping, hiking, biking, and wilderness experience.
	Oakridge area	This area is popular for mountain biking, hiking, and camping, and has spectacular mountain scenery.
Mount Hood National Forest	Mount Hood	Glaciers, lakes, waterfalls, and alpine meadows attract visitors to Mount Hood year round. This area hosts hiking, mountaineering, mountain biking, opportunities to view scenery, and year-round snow-based recreation, and has two historic lodges. Timberline Trail circles the mountain and overlaps with the Pacific Crest National Scenic Trail.
	Mount Hood and West Cascades Scenic Byways	Scenic highways have historical and cultural significance and scenic views, and connect local communities. On the Mount Hood Scenic Byway, visitors can learn about Oregon's cultural history. The West Cascades Scenic Byway follows the Clackamas River to near its headwaters on Mount Jefferson.
	Clackamas River	The Clackamas River features developed recreation access points and year-round whitewater boating.

Note: Unless otherwise noted, sites are managed by the U.S. National Forest System.

[a] Managed by Oregon State Parks.

[b] Managed by Oregon Parks and Recreation Department.

[c] Managed by Washington State Parks.

Changing climatic conditions may alter the supply of and demand for outdoor recreation opportunities, affecting recreation visitation and attainment of benefits directly or indirectly (Bark et al. 2010, Matzarakis and de Freitas 2001, Morris and Walls 2009). Historical data from the National Park Service suggest that visitation levels will increase as temperatures increase, although visitation decreases when temperatures are very high (Fisichelli et al. 2015). Increased annual visitation is largely attributed to the fact that most parks see their highest visitation levels in summer, as is the case for CRGNSA and Willamette NF.

In addition to occurring in summer, warm-weather recreation occurs in the "shoulder" seasons, which generally start in late spring and end in early fall, or when trails and other infrastructure are clear of snow and ice. As the shoulder seasons become more comfortable for recreation, the length of time amenable to warm weather recreation will expand, and aggregate visitation levels will increase. Lengthened shoulder seasons have been found in other regions as well, such as Alaska (Albano et al. 2013) and the Southeastern United States (Bowker et al. 2013). Visitors can also spread spatially within public lands, such as moving to higher elevations (Hand and Lawson 2018) or concentrating around water bodies (Loomis and Crespi 2004, Mendelsohn and Markowski 2004).

Just as with visitation levels, the aggregate benefits provided by outdoor recreation opportunities are expected to increase as the climate warms, because increases in warm-weather activities will outweigh decreases in winter activities (Hand and Lawson 2018, Hand et al. 2018, Loomis and Crespi 2004, Mendelsohn and Markowski 2004). However, as the availability of different types of recreation changes, some recreationists are likely to be displaced from their preferred recreation area and will need to choose alternative recreational activities or choose a different location for their preferred recreation activity. There is also potential for the density of recreationists to increase within diminishing areas such as those with decreased snowpack. However, knowledge is sparse regarding the effects of climate-related tradeoffs on the benefits that recreationists receive.

Broad trends in recreation participation under climate change are becoming better understood at the regional and subregional scales, including in the Pacific Northwest (Hand et al. 2019). This chapter describes five broad categories of outdoor recreation activities (warm-weather activities, snow-based activities, wildlife-related activities, water-based activities, and gathering forest products) believed to be sensitive to climate change and assesses the likely effects of projected climate change on visitor-use patterns and the ability of outdoor recreationists to obtain desired experiences and benefits.

Relationships Between Climate Change and Recreation Participation

Participation in outdoor recreation is affected by the supply of and demand for outdoor recreation opportunities. These opportunities are sensitive to climate through (1) a direct effect of changes in temperature and precipitation affecting recreationists' decisions to visit or not visit a site, and (2) an indirect effect of climate on the characteristics and ecological conditions of recreation settings (Loomis and Crespi 2004, Mendelsohn and Markowski 2004, Shaw and Loomis 2008) (fig. 7.1).

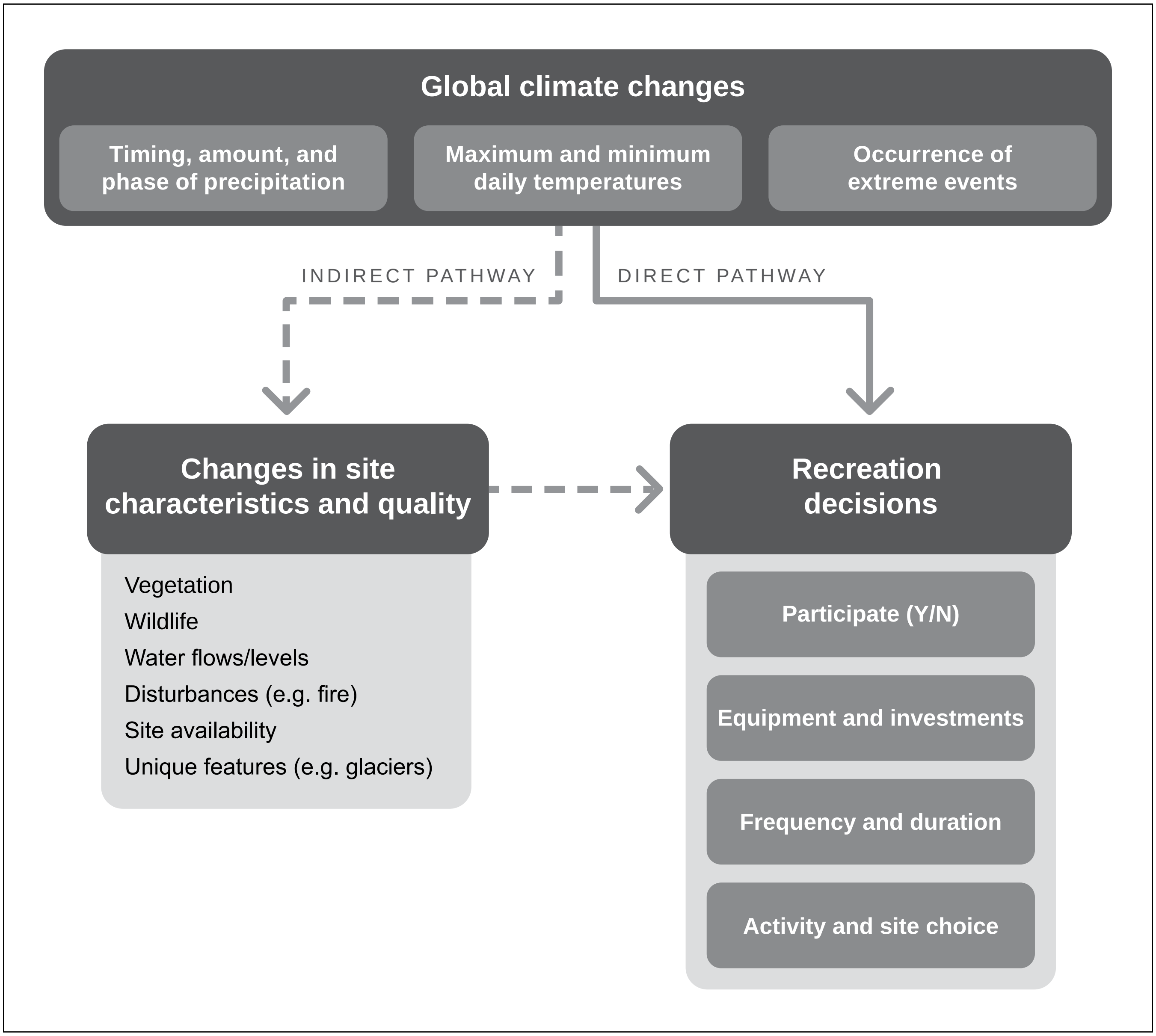

Figure 7.1—Direct and indirect effects of climate on recreation decisions (from Hand and Lawson 2018).

The direct effects of altered temperature and precipitation patterns are likely to affect most outdoor recreation activities in some way. Direct effects are important for skiing and other snow-based activities that depend on seasonal temperatures and the amount, timing, and phase of precipitation (Englin and Moeltner 2004, Irland et al. 2001, Klos et al. 2014, Smith et al. 2016, Stratus Consulting 2009, Wobus et al. 2017). Warm-weather activities are also sensitive to direct effects of climate change. Higher minimum temperatures have been associated with increased visitation to protected areas, particularly during nonpeak shoulder seasons (Scott et al. 2007). The number of projected warm-weather days is positively associated with expected public land visitation (Albano et al. 2013, Fisichelli et al. 2015). Overall visitation is expected to be lower during heat waves (Richardson and Loomis 2004), although water-based recreation may increase. Temperature and precipitation directly affect the comfort and enjoyment that participants derive from engaging in an activity on a given day (Mendelsohn and Markowski 2004). As increased temperatures contribute to increased frequency and extent of wildfire, access to and interest in recreation may be directly affected by related area closures, fire restrictions, and the presence of smoke.

Indirect effects are important for recreation activities and opportunities that depend on ecosystem inputs, such as wildlife, vegetation, and surface water. For example, coldwater fishing is expected to decline in the future because of climate effects on temperature and streamflow that threaten fish habitat (Jones et al. 2013, Lamborn and Smith 2019) (chapters 3 and 4). Surface-water area and streamflows are also important for water-based activities (e.g., whitewater rafting and boating). Recreation visits to sites with highly valued natural characteristics, such as subalpine areas and popular wildlife species for hunting, fishing, and viewing (chapters 5 and 6), may be reduced under some future climate scenarios if the quality of those characteristics is threatened (Scott et al. 2007). The indirect effects of climate on disturbances, and wildfire in particular, may also play a role in recreation behavior, although the effects may be diverse and variable over time (Englin et al. 2001, Loomis and Crespi 2004, Sánchez et al. 2016).

Skiing provides an important example of the direct and indirect effects of climate change on outdoor recreation. Warming winter temperatures have a direct effect on individual decisions to visit or not visit a site which results in the indirect effect of a decrease in the supply of skiing opportunities (Wobus et al. 2017). This indirect pathway connects climatic conditions to the provision of recreation opportunities through climate-related effects on the outdoor recreation setting conditions. Although the indirect effect in this example is negative, the direction of effects will depend on a variety of factors specific to individual recreationists.

Recreation Participation and Management

Recreation is an important component of public land management in the CMWAP assessment area. Sustainable recreation serves as a guiding principle in the planning and management of Forest Service lands (USDA FS 2010, 2012b). Sustainable recreation seeks to "sustain and expand benefits to America that quality recreation opportunities provide" (USDA FS 2010). Recreation managers aim to provide diverse recreation opportunities that span the Recreation Opportunity Spectrum, from modern and developed to primitive and undeveloped (Clark and Stankey 1979) (box 7.1).

Box 7.1

The Recreation Opportunity Spectrum

The Recreation Opportunity Spectrum (ROS) is a classification tool used by federal resource managers since the 1970s to provide visitors with varying challenges and outdoor experiences (Clark and Stankey 1979, USDA FS 1990). The ROS classifies lands into six management class categories defined by setting and the probable recreation experiences and activities it affords: modern developed, rural, roaded natural, semiprimitive motorized, semiprimitive nonmotorized, and primitive. Setting characteristics that define ROS include the following:

- Physical: type of access, remoteness, size of the area
- Social: number of people encountered
- Managerial: visitor management, level of development, naturalness (evidence of visitor impacts or management activities)

The ROS is helpful for determining the types of recreational opportunities that can be provided. After a decision has been made about the opportunity desirable in an area, the ROS provides guidance about appropriate planning approaches and standards by which each factor should be managed. Decisionmaking criteria include (1) relative availability of different opportunities, (2) their reproducibility, and (3) their spatial distribution. The ROS Primer and Field Guide (USDA FS 1990) specifically addresses access, remoteness, naturalness, facilities and site management, social encounters, and visitor impacts. The ROS can be used for the following:

- Inventory existing opportunities
- Analyze the effects of other resource activities
- Estimate the consequences of management decisions on planned opportunities
- Link user desires with recreation opportunities
- Identify complementary roles of all recreation suppliers
- Develop standards and guidelines for planned settings and monitoring activities
- Help design integrated project scenarios for implementing resource management plans

In summary, the ROS approach provides a framework that allows federal land managers to classify recreational sites and opportunities and to allocate improvements and maintenance within the broader task of sustainable management of large landscapes.

People participate in a wide variety of outdoor recreation activities in the CMWAP assessment area. The national visitor use monitoring (NVUM) survey, conducted by the Forest Service to monitor recreation visitation and activity on national forests, identifies 27 recreation activities in which visitors participate. Current recreation visitation activities and expenditures illustrate the importance and diversity of recreation in the assessment area.

The CRGNSA, Mount Hood NF, and Willamette NF together host 7.8 million annual visits[2] (table 7.3). These three areas are characterized by somewhat different recreational profiles, because of the distinctive landscape features present in each area. For example, recreation is dominated by warm-weather activities in CRGNSA, snow-based winter activities are the most popular activity in Mount Hood NF, and most wildlife-dependent activities (especially terrestrial) occur in Willamette NF. However, it is important to note that the visitation data presented in this report come entirely from the NVUM survey, which accounts only for recreation taking place on lands managed by the National Forest System. Because CRGNSA is managed through a partnership of federal, state, local, and tribal governments, NVUM data do not accurately represent visitation within CRGNSA (box 7.2).

Additional detail characterizing recreation participation across the CMWAP assessment area is provided in table 7.3 and described below. A map of developed recreation sites and trails is shown in figure 7.2. The activities listed in table 7.1 account for the primary recreation activities by visitors to national forests that are most likely affected by climate change. These activities fall under one of the following broad categories:

- **Warm-weather activities** are the most popular type of recreation in the assessment area, accounting for over 64 percent of primary recreation objectives. This category includes hiking and walking, viewing natural features, developed and primitive camping, bicycling, backpacking, horseback riding, picnicking, and driving for pleasure. By unit, warm-weather activities accounted for 90.1 percent of primary outdoor recreation in CRGNSA, 63.1 percent in Willamette NF, and 35.3 percent in Mount Hood NF. "Hiking and walking" was the most popular warm-weather activity in all units.
- **Snow-based activities** are also a popular type of recreation, including downhill skiing, snowmobiling, and cross-country skiing. In 2016–2017, these were primary activities for 52.4 percent of visitors in Mount Hood NF and 8.9 percent in Willamette NF. Downhill skiing was the most popular snow-based activity in both national forests. Although CRGNSA does have snow-based recreation, it is not captured in the NVUM survey.

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[2] Data for CRGNSA and Mount Hood NF are from 2016; data for Willamette NF are from 2017.

- **Wildlife-dependent activities** include hunting, fishing, and viewing wildlife. Wildlife activities accounted for 11.8 percent of visits in Willamette NF, 1.7 percent of visits in Mount Hood NF, and 1.5 percent of visitors in CRGNSA. Of these activities, fishing was most popular in Willamette and Mount Hood NFs, whereas viewing wildlife was the most popular wildlife activity in the CRGNSA. However, because most water-access areas in CRGNSA are managed by agencies other than the Forest Service, participation in water-based wildlife-related activities, such as fishing, are likely to be much higher than the estimate above.
- **Water-based activities** such as boating and swimming comprised a relatively small amount of recreation—5.1 percent of visits to Willamette NF and less than one percent to each Mount Hood NF and CRGNSA. In CRGNSA, 0.7 percent of visitors to lands managed by the Forest Service report water-based activities as their primary reason to visit. However, the level of water-based recreation in CRGNSA is estimated to be much higher than this figure suggests, because most water-access areas are managed by other agencies and are not represented in this number.
- **Forest products gathering** such as berries and mushrooms comprised the smallest category of recreation in the assessment area. This was the primary activity for 0.1 percent of visitors to CRGNSA, 0.8 percent of visitors to Mount Hood NF, and 1.5 percent of visitors to Willamette NF. However, this activity is more often considered secondary by visitors and is an important cultural activity for many participants. Gathering forest products is not always defined as recreation, so this number likely does not capture the full extent of participation in this activity.

In 2008, nonlocal visitors spent $27 million while visiting CRGNSA, $84 million while visiting Mount Hood NF, and $21 million while visiting Willamette NF. Nonlocal visitors spent a total of more than $133 million to visiting land managed by the National Forest System in the assessment area (table 7.4) in 2008. We focus on spending by nonlocal visitors because the economic benefits realized from these visits would not have occurred in local communities otherwise. “Gas and oil” was the highest spending category overall, at 21 percent ($5.7 million) in CRGNSA, 17.5 percent ($14.7 million) in Mount Hood NF, and 25 percent ($5.5 million) in Willamette NF. Lodging, restaurants, and groceries were the second highest spending categories. The remaining expenditure categories of other transportation, entry fees, recreation and entertainment, sporting goods, and souvenirs comprise 15.5 percent of all spending for CRGNSA, 33.8 percent for Mount Hood NF, and 24.4 percent for Willamette NF. Local spending for visits to National Forest System lands in the CMWAP assessment area was over $65 million, about half of expenditures resulting from nonlocal visits to the assessment area.

Table 7.3—Participation in different recreational activities in Columbia River Gorge National Scenic Area, Mount Hood National Forest in 2016, and Willamette National Forest in 2017

Activity	Visitors for whom this was their primary activity						Relationship to climate and environmental conditions
	Columbia River Gorge National Scenic Area		Mount Hood National Forest		Willamette National Forest		
	Percent	*Number*	*Percent*	*Number*	*Percent*	*Number*	
Warm-weather activities:	91	2,946,580	35.3	1,039,585	63.1	1,002,659	Participation typically occurs during warm weather; dependent on the availability of snow- and ice-free sites, dry weather with moderate daytime temperatures, and the availability of sites where air quality is not impaired by smoke from wildfires.
Hiking/walking	65.1	2,107,938	16.4	482,980	25.1	398,839	
Viewing natural features	20.7	670,266	7.2	212,040	14.6	231,994	
Developed camping	0.5	16,190	3.4	100,130	6.7	106,463	
Bicycling	2	64,760	0.8	23,560	2.8	44,492	
Other nonmotorized	0.4	12,952	3.2	94,240	4.8	76,272	
Picnicking	0.9	29,142	1.3	38,285	1	15,890	
Primitive camping	0	—	0.7	20,615	1.3	20,657	
Backpacking	0.4	12,952	1.1	32,395	1.8	28,602	
Driving for pleasure	0.9	29,142	1.2	35,340	5	79,450	
Horseback riding	0.1	3,238	0	—	0	—	
Snow-based activities:[a]	0	—	52.4	1,543,180	8.9	141,421	Participation depends on the timing and amount of precipitation as snow and cold temperatures to support consistent snow coverage. Inherently sensitive to climate variability and inter-annual weather patterns.
Downhill skiing	0	—	46.5	1,369,425	6.8	108,052	
Snowmobiling	0	—	1.1	32,395	0.2	3,178	
Cross-country skiing	0	—	4.8	141,360	1.9	30,191	
Wildlife activities:	1.5	48,570	1.7	50,065	11.8	187,502	Temperature and precipitation are related to habitat suitability through effects on vegetation, productivity of food sources, species interactions, and water quantity and temperature (for aquatic species). Disturbances (wildfire, invasive species, insect outbreaks) may affect amount, distribution, and spatial heterogeneity of suitable habitat.
Hunting	0	—	0.4	11,780	4.5	71,505	
Fishing	0.2	6,476	1	29,450	5.7	90,573	
Viewing wildlife	1.3	42,094	0.3	8,835	1.6	25,424	

Activity	**Visitors for whom this was their primary activity**						**Relationship to climate and environmental conditions**
	Columbia River Gorge National Scenic Area		**Mount Hood National Forest**		**Willamette National Forest**		
	Percent	*Number*	*Percent*	*Number*	*Percent*	*Number*	
Gathering forest products	0.1	3,238	0.8	23,560	1.5	23,835	Depends on availability and abundance of target species (e.g., berries, mushrooms), which are related to patterns of temperature, precipitation, and snowpack. Disturbances may alter availability and productivity of target species in current locations and affect opportunities for species dispersal.
Water-based activities:[a]	0.7	22,666	0.9	26,505	5.1	81,039	
Nonmotorized activities	0.7	22,666	0.9	26,505	2.7	42,903	
Motorized activities	0	—	0	—	2.4	38,136	
Other:	5.5	178,090	9	265,050	11.0	174,790	
Relaxing	3.7	119,806	4.3	126,635	7	111,230	
Nature center activities	0.2	6,476	0	—	0.2	3,178	
Visiting historic sites	0.1	3,238	0.1	2,945	0	—	
Nature study	0.2	6,476	0.1	2,945	0.4	6,356	
Resort use	0	—	0.5	14,725	0.5	7,945	
Some other activity	1.3	42,094	4	117,800	2.9	46,081	
Motorized recreation:	0.1	3,238	0.4	11,780	0.1	1,589	
Off-highway vehicle use	0	—	0.1	2,945	0.1	1,589	
Motorized trail activity	0	—	0.2	5,890	0	—	
Other motorized	0.1	3,238	0.1	2,945	0	—	
No activity reported	1.2	38,856	0.3	8,835	0.4	6,356	
Total (estimate)		3,238,000		2,945,000		1,589,000	

Source: USDA FS (n.d.). Includes data from Columbia River Gorge National Scenic Area (NSA), Mount Hood NF and Willamette NF, National Visitor Use Monitoring. The survey was administered in Willamette National Forest in 2017, and in Mount Hood National Forest and Columbia River Gorge National Scenic Area in 2016.

[a] In Columbia River Gorge NSA, snow-based activities and water-based activities are not accurately quantified by the NVUM survey, which collects data only on national forest lands. Most snow-based recreation areas and water access areas in Columbia River Gorge NSA are managed by other agencies.

Box 7.2

Columbia River Gorge National Scenic Area: management and visitation

The Columbia River Gorge is a spectacular 130-km river canyon where the Columbia River carves the only near-sea level route through the Cascade Range. One of the longest inhabited places of North America, the gorge has long been a source of abundant food and sites for human communities, as well as an important trade and transportation corridor. Decades of interest in protecting natural resources while maintaining a working landscape led to the Columbia River Gorge being designated as a national scenic area by Congress in 1986.

The Columbia River Gorge National Scenic Area (hereafter CRGNSA) was established to protect and provide for the enhancement of the scenic, cultural, recreational, and natural resources of the Columbia River Gorge and support the economy of the Columbia Gorge area in a manner consistent with protecting those resources. The CRGNSA Management Plan created a partnership of federal, state, local, and tribal governments working together to protect resources on public and private lands. Although the U.S. Forest Service manages some of the most popular recreation sites within the gorge (e.g., Multnomah Falls, Eagle Creek Trail, and Dog Mountain), many other federal, state, and local partners play important roles in providing recreation access and opportunities.

As a result, the National Visitor Use Monitoring data presented in this report reflects only use occurring on National Forest System lands and does not include water-based activities (e.g., whitewater rafting, kiteboarding, windsurfing) and wildlife-dependent activities (e.g., freshwater fishing) occurring on the Columbia River. The town of Hood River and surrounding areas within CRGNSA are often referred to as the windsurfing and kiteboarding capital of the world. Oregon State Parks, Washington State Parks, the U.S. Army Corps of Engineers, the Port of Hood River, and private landowners provide access to the Columbia River for water-based and wildlife-dependent recreational activities.

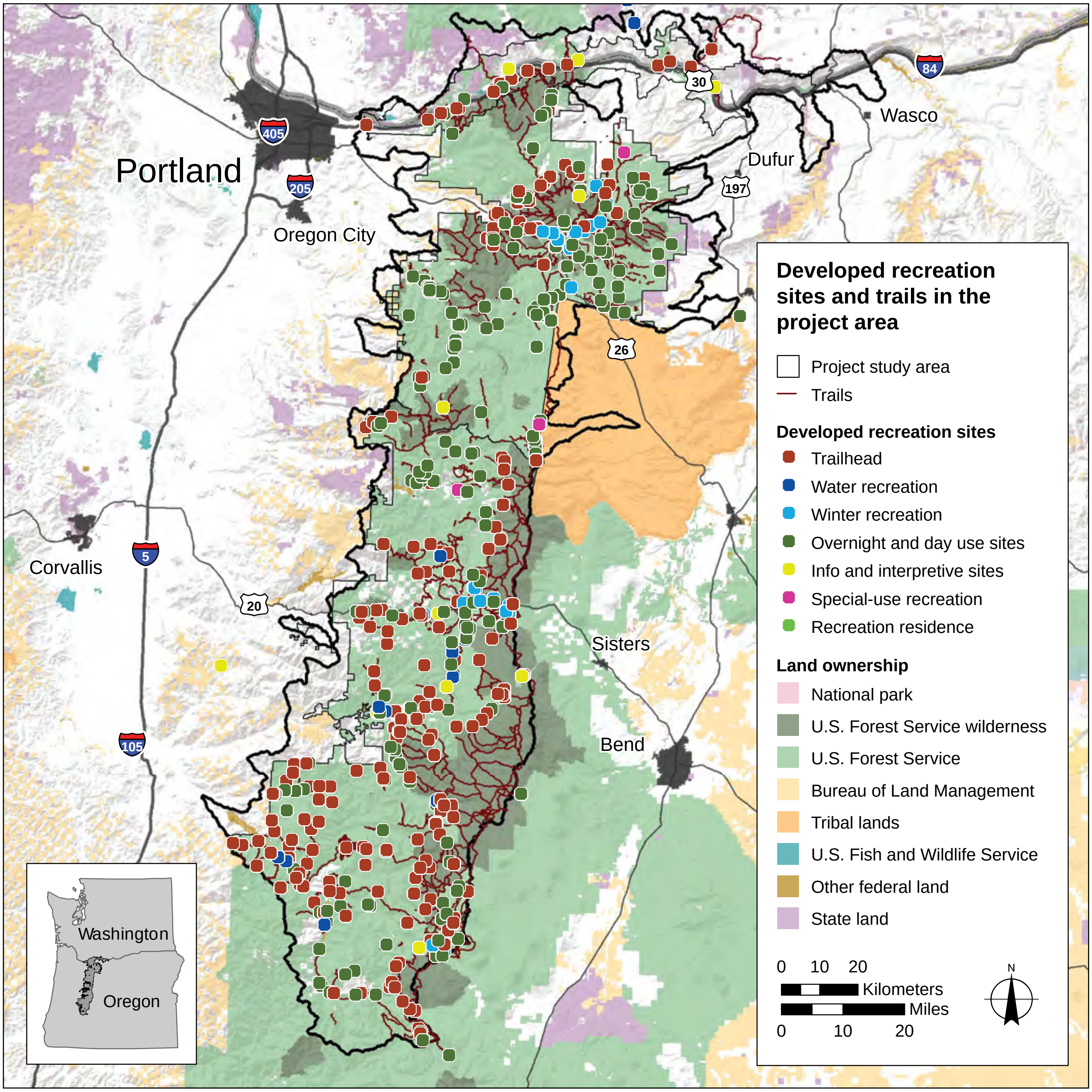


Figure 7.2—Developed recreation sites and trails in the Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest Adaptation Partnership assessment area.

Table 7.4—Estimated total annual expenditures by visitors to national forests in the Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest assessment area

	Nonlocal spending[a]		Local spending	
Spending category	**Total annual expenditures**	**Spending by category**	**Total annual expenditures**	**Spending by category**
	Dollars	*Percent*	*Dollars*	*Percent*
Motel	26,863,447	20.2	3,321,601	5.1
Camping	4,945,672	3.7	2,439,291	3.7
Restaurant	24,726,999	18.6	9,526,279	14.5
Groceries	17,723,011	13.3	13,432,907	20.5
Gas and oil	25,881,640	19.4	20,120,802	30.7
Other transportation	604,082	0.5	162,803	0.2
Entry fees	13,136,976	9.9	7,109,636	10.9
Recreation and entertainment	11,047,866	8.3	3,863,301	5.9
Sporting goods	4,458,681	3.3	4,467,550	6.8
Souvenirs and other expenses	3,765,159	2.8	1,050,877	1.6
Total	133,153,533	100.0	65,495,047	100.0

[a] Nonlocal refers to trips that required traveling more than 80 km.

Source: Includes data from National Visitor Use Monitoring, based on surveys in 2012 and 2016.

Climate Change Vulnerability Assessment

Environmental conditions determined by the climate have both direct and indirect effects on outdoor recreation participation. For example, skiing opportunities depend on the availability of areas with snow-covered terrain, which is determined by patterns of temperature and snowfall. As climate change affects seasonal trends in temperature and precipitation, the availability of some sites for snow-based recreation may change. Likewise, wildlife-related activities, such as fishing, depend on the availability of desirable fish species, whose distribution can be affected by changes in water temperatures, streamflow, and timing of snowmelt (Lamborn and Smith 2019).

To assess how recreation patterns may change in the CMWAP assessment area, we identified five categories of outdoor recreation activities that may be sensitive to climate change in similar ways (described above and quantified in fig. 7.3). For the purposes of this assessment, an outdoor recreation activity is sensitive to climate change if changes in environmental conditions that depend on climate would result in a substantial change in the demand for or supply of that outdoor recreation activity. Following the example of snow-based recreation, skiing would be considered sensitive to climate change if temperatures are expected to increase enough to cause precipitation to fall in the form of rain instead of snow, if snowfall is substantially reduced, or if the first substantial snowfall is delayed, shortening the ski season (box 7.3).

The expected sensitivities of these five categories of outdoor recreation to climate change in the assessment area are summarized in box 7.3. Other types of recreation that occur in the assessment area are not expected to be highly sensitive to climate change; these activities include relaxing, visiting a nature center, and visiting historical sites. These activities are not in this vulnerability assessment but do contribute to total annual visitation in the area.

The overall effect of climate change on recreation activity is likely to differ between warm-weather activities (overall increase in participation) and snow-based activities (short-term increase in concentration in fewer sites and shorter seasons, followed by a long-term decrease in participation). In general, warmer temperatures and increased season length appropriate for warm-weather activities will increase the duration and quality of weather for activities like hiking, camping, and mountain biking. However, reduced snowpack will decrease the duration and quality of conditions for downhill skiing, cross-country skiing, and snowmobiling.

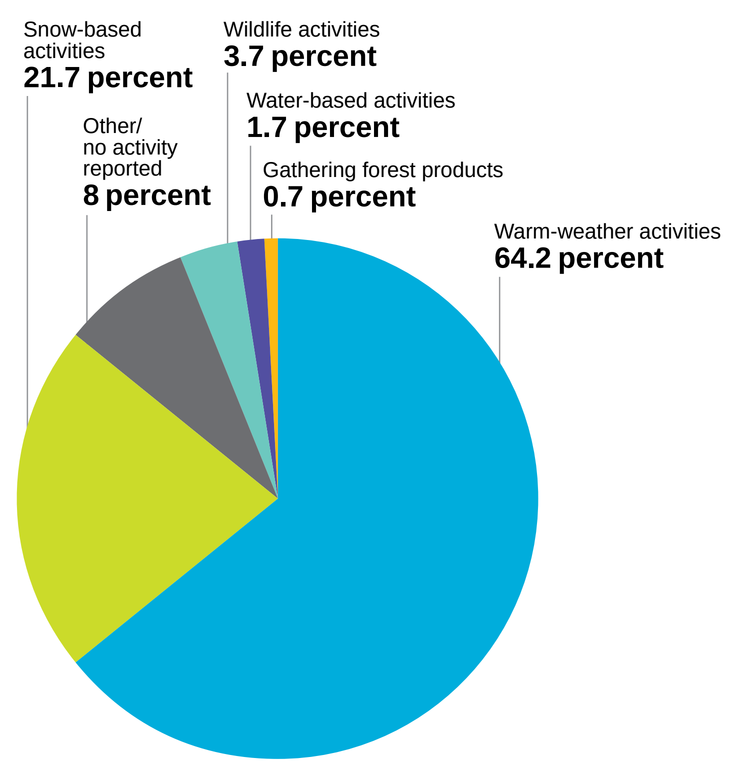


Figure 7.3—Percentage of total visits to the three areas managed by the U.S. Forest Service in the Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest Adaptation Partnership assessment area, by climate-sensitive primary activity. Data are from the National Visitor Use Monitoring survey, which was administered in Willamette National Forest in 2017, and in Mount Hood National Forest and Columbia River Gorge National Scenic Area in 2016.

Box 7.3

Summary of climate change effects on recreation

All categories of recreation considered to be potentially sensitive to the effects of climate change in the Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest Adaptation Partnership assessment area were aggregated into five activity categories. Positive (+) and negative (–) signs indicate expected direction of effect on overall benefits derived from recreation activity; (+/–) indicates that both positive and negative effects may occur. These effects are what we expect to see by the end of the 21st century, based on 2080 projections. In situations where short-term effects are not linear with long-term effects (e.g., snow-based activities), short-term effects based on 2040 projections are provided as well.

Activity category	Likelihood of climate effect	Magnitude of climate effect	Direct effects	Indirect effects
Warm-weather activities	High	Moderate (+/–)	Warmer temperature (+) Higher likelihood of extreme hot temperatures (–)	Increased incidence, area, and severity of wildfire (–) Increased smoke from wildfire (–)
Snow-based activities	High	High (–)	Warmer temperature (–) Reduced precipitation as snow (–) Later snowfall (–) Short term: increased crowding on fewer sites during a shorter snow season (–)	Increased incidence, area, and severity of wildfire (–)
Wildlife activities	Moderate	Terrestrial wildlife: low (+) Fishing: moderate (–)	Warmer temperature (+) Reduced snowpack (hunting –) Higher incidence of low streamflow (fishing –)	Increased smoke from wildfire (–) Increased incidence, area, and severity of wildfire (terrestrial wildlife +/–) Reduced coldwater habitat, incursion of warm-water tolerant species (fishing –)
Gathering forest products	Moderate	Low (+/–)	Warmer temperature (+) Longer growing season (+) Increased drought stress (–)	More frequent wildfires (+/–) Higher severity wildfires (–)
Water-based activities	Moderate	Moderate (+/–)	Warmer temperature (+) Higher likelihood of extreme hot temperatures (+)	Lower streamflows and reservoir levels (–) Increase in harmful algal blooms (–)

When changing weather patterns make a type of recreation unavailable in a certain location or during a certain time of year, recreationists can choose to adapt by changing the activity in which they participate, the location where they recreate, or the timing of their recreation; an example of these substitution processes is provided in box 7.4. The substitutability of recreational activities, locations, and timing is not well understood, although some research has been done in this area (e.g., Bristow and Jenkins 2018, Lamborn and Smith 2019, Orr and Schneider 2018). Considering only the **annual** visitation in a broad area, which has both warm-weather and snow-based recreation, can mask variation in the effects of climate on recreation among types of activities and geographic locations.

This section provides an assessment of the likely effects of climate on major climate-sensitive recreation activities in the region. The assessment is informed by studies investigating how outdoor recreation participation is influenced by climate-sensitive ecological parameters and by projections of ecological changes specific to the CMWAP assessment area, as described in other chapters in this volume.

Box 7.4

Low snowpack in the 2014–2015 ski season: a look into the future

The winter season of 2014–2015 had substantially later snowfall than usual. During this year, visitation to most ski resorts was much lower than in years with more typical amounts of snow (see fig. 7.8, p. 349). In Mount Hood National Forest (NF), Mount Hood Skibowl (elevation 1100 to 1550 m), and Mount Hood Meadows (elevation 1380 to 2750 m) experienced large declines in visitation in the 2014–2015 ski season, whereas the decline in visitation at Timberline ski area (also Mount Hood NF, elevation 1480–2600 m) was somewhat smaller.

Data collected at Timberline Lodge (Timberline Lodge 2019) indicates that snowpack reached 130 cm by January 1, 2015, and hovered just below that level until a spike in mid-March. The resort stayed open during this time, but the dip in attendance corresponds with a lack of fresh snow between early January and mid-March. Visits to Mount Bachelor ski area, outside of the CMWAP assessment area, also had a small decline during this low-snow year, but to a lesser degree than other sites (see fig. 7.9, p. 350). This suggests that snow-based recreationists might choose to change locations in order to participate in winter sports.

Three relatively low-elevation ski areas in the CMWAP assessment area also felt the effects of snowfall occurring later in the season. Willamette Pass (elevation 1560 to 2040 m), Hoodoo Ski Resort (elevation 1420 to 1740 m), and Cooper Spur (elevation 1200 to 1330 m) experienced decreased visitation during 2014–2015. Two of these ski areas have closed entirely during other years when local snowpack was relatively late or low: Cooper Spur (2009–2010) and Willamette Pass (2017–2018). When the first substantial snowfall occurs later in the season, low-elevation ski resorts may find that seasonal staff are no longer available by the time the resort would be able to operate and must determine whether opening is profitable.

Current Conditions and Existing Stressors

Managing recreation on public lands is a complex enterprise that varies seasonally and annually and is highly dependent on weather conditions. Recreation management includes (1) maintaining access to recreation areas via infrastructure and facilities (e.g., roads, hiking trails, campgrounds, boat ramps, parking areas), (2) regulating access for harvesting animals and plants (e.g., specifying hunting seasons and zones, operating permitting systems), (3) regulating access for motorized vehicle use (e.g., off-highway vehicles, snowmobiles), and (4) coordinating with private guides, outfitters, and concessionaires who operate ski resorts and other facilities (Cole et al. 1987, Seekamp et al. 2011).

Although demand for and supply of outdoor recreation opportunities fluctuate with weather conditions, other factors also affect demand and supply. Changing demographics, emerging recreational activities, and trends in recreation technology and social media contribute to a dynamic demand for outdoor recreation opportunities (Blahna et al. 2020; Sachdeva 2020). Meanwhile, land management agencies such as the Forest Service, as well as private guides, outfitters, and concessionaires, have different levels of flexibility to adapt to variation in weather patterns in addition to changing demand. The three major concerns relevant to the the CMWAP assessment area are:

- Low and/or late snowfall in winter, preventing ski areas from opening in a profitable way (see box 7.4).
- Expanding shoulder seasons, bringing recreationists into areas before seasonal staff can clear trails and prepare staff campgrounds and visitor centers in spring, and after campgrounds and visitor centers are closed in fall (box 7.5).
- Increasing incidence of intense fires, impairing access to outdoor recreation sites, and associated smoke affecting decisions to participate in outdoor recreation activities (boxes 7.6 and 7.7, fig. 7.4).

Current climatic and environmental conditions in the assessment area are characterized by high variability within and between years. These variable conditions include temperature, precipitation, water flows and levels, wildlife distributions, vegetative conditions, and wildfire activity. Recreationists often make decisions with a degree of uncertainty about conditions at the time of participation.

Recreation in the assessment area is affected by several challenges and stressors aside from changing climate patterns. High populations, particularly in proximity to public lands, can strain visitor services and facilities because of increased use. Projected population increases may exacerbate these effects. Outdoor recreation has become an important factor in attracting population growth in this area (Hamilton et al. 2016, Rudzitis 1999). Adequate preparedness is important in reducing risk

Box 7.5

Extended shoulder season in the CMWAP assessment area

Increasing temperatures are widely expected to result in extended recreational shoulder seasons, with snow melting earlier in spring and falling later in autumn. Recreation managers in the CMWAP assessment area are already noticing these extended shoulder seasons, especially in low- and mid-elevation areas. One assistant recreation staff officer at Willamette NF stated that recreational visits to waterfalls and hiking are expanding later into autumn than previously. A natural resource specialist at the Columbia River Gorge National Scenic Area noted similar patterns, with more recreation occurring later in the year owing to extended periods of heat.

A natural resource specialist at Mount Hood NF agreed that people are both recreating and living in the forest earlier in the year than they had previously (for a discussion of the social impacts of homelessness in national forests, see Baur and Cerveny [2019]). The resource specialist added that the extended shoulder seasons do not align well with the timing of seasonal employees. Although privately operated guides, outfitters, and resorts have more flexibility in hiring employees, even these entities can be affected by altered weather regimes, as in the case of extremely late snowfall postponing the opening of ski resorts until seasonal workers have found work elsewhere. Effects of an extended shoulder season have been felt by recreation managers on public lands in other parts of the United States as well (e.g., Hand et al. 2018). However, recreation managers in the CMWAP assessment area who were involved in this project are generally less concerned about adapting to extended shoulder seasons than adapting to other effects of climate change, such as intensified fire and smoke seasons, associated hazard tree removal, and altered snow seasons.

in outdoor recreation activities, and people who are not well-informed about the recreation areas they visit, perhaps because they are new to the area, may be unprepared for harsh environmental conditions (Brandenburg and Davis 2016, Procter et al. 2018).

Increased numbers of people participating in outdoor recreation can also contribute toward degradation of natural areas, and lead to crowded trails and campgrounds, compounding climate change effects. Increased use can create lasting impacts to natural resources, especially when support for maintenance infrastructure such as trails and campgrounds is sparse (Manning 2010). Both recreational activity and environmental conditions contribute to the constantly changing physical condition of recreation sites and natural resources. Recreation sites and physical infrastructure need maintenance, and deferred maintenance may increase congestion at other sites that are less affected or increase hazards for visitors who continue to use degraded sites.

Box 7.6

Connectivity of the Pacific Crest Trail with increasing incidence of high-intensity wildfires

The Cascade Range is one of the three major Western mountain ranges most at risk of increasing wildfire activity owing to climate change (Gergel et al. 2017). Following severe fires, falling rocks and trees pose hazards to the public, sometimes causing areas to remain closed long after a fire is suppressed. Trail crews work to remove hazardous obstacles, rebuild burned bridges, and rebuild trails, making these areas safe for recreationists before the areas can be reopened to the public, a process that can take months or years. In the meantime, managers and hikers of long-distance trails, such as the Pacific Crest Trail (PCT), face issues of connectivity when trail sections are closed.

In the Columbia River Gorge, the Eagle Creek Fire (2017) had an enormous impact on recreation, with some trails remaining closed more than 3 years after the fire started. This human-caused fire started on September 2, 2017, and spread to 19 400 ha before it was contained on November 30. Within this area, 55 percent of the land was either unburned or burned at a low intensity, 30 percent burned at moderate intensity, and 15 percent burned at high intensity. The cost of fire suppression was $22 million (USDA FS, n.d.).

The PCT, extending 4265 km between the U.S. borders with Mexico and Canada, runs through the area affected by the Eagle Creek Fire in the Columbia River Gorge National Scenic Area. The Pacific Crest Trail Association (PCTA) worked together with the U.S. Forest Service to place detours around closed portions of the trail. Reroute information was posted on the PCTA website, and signs were posted at closed trailheads. Some hikers used shuttles to get around closed trails and to reach public transportation hubs. Within the Columbia River Gorge National Scenic Area, the PCT reopened to the public on June 14, 2018, with the help of volunteers who collectively donated 5,000 hours toward rebuilding the trail. The Eagle Creek Trail, a preferred alternate route to the official PCT, reopened in 2021.

With approximately 160 km of the PCT closed starting in August, 2017, the Eagle Creek Fire is just one example of an area that affected the continuity of the PCT in Oregon in 2017. During a year with many PCT trail sections closed owing to fire, including in Mount Hood and Willamette NFs, some hikers reportedly switched to the Oregon Coast Trail (D. Hendricks, personal communication, Columbia Cascades regional representative, Pacific Crest Trail Association, 1331 Garden Highway, Sacramento, CA 95833; July 2018). The number of self-reported through-hikes (hiking a long end-to-end trail with continuous footsteps and completing it within one calendar year) declined in 2017, followed by a spike in 2018, suggesting that 2017 hikers returned to complete skipped sections of the trail in 2018 in order to call themselves through-hikers (PCTA 2019).

The Eagle Creek Fire may alter recreation levels for years to come. Research suggests that large, high-intensity burns correspond to a decline in recreation, an effect which decreases with time (Starbuck et al. 2006). However, moderate- and low-intensity prescribed burns that thin the forest while leaving larger trees intact can result in small increases in recreation visits (Bawa 2017, Sanchez et al. 2016, Starbuck et al. 2006). In the Mount Jefferson Wilderness (Willamette NF), recreational visits declined slightly after fires, although these fluctuations were less than those following unpopular regulation changes (Brown et al. 2008).

Understanding visitor perceptions of and responses to management decisions is critical for gaining support of management practices that affect recreation. In the Mount Jefferson Wilderness Area, onsite surveys suggested that following a fire, visitors would be most supportive of management policies focused on information, education, and ecological protection, whereas area closures and use limits would receive strong opposition (Brown et al. 2008). Although closures are necessary in some situations, the survey suggests that providing visitors with accessible information about the reasons for closures (e.g., safety and ecological protection) might improve public support of management decisions associated with wildfires.

Box 7.7

Wildfire and air quality in the wildland-urban interface

Located on the Pacific coast where westerly winds coming off the ocean generally have low pollution, Oregon experiences some of the best air quality in North America, providing both clean air for breathing and clear visual aesthetics across expansive landscapes. These conditions are no longer taken for granted in Oregon and other locations in the Pacific Northwest.

Wildfires during the past decade have created significant smoke impacts, affecting large numbers of people in northern and central Oregon. Poor air quality has been especially prominent in drier locations of central and eastern Oregon where most wildfires occur. However, in the past few years, wildfires closer to the wildland-urban interface on the west side of the Cascades have brought smoke into both rural communities and large municipalities. In addition, unusual meteorological conditions have carried wildfire smoke from the east and north to the west side, affecting hundreds of thousands of people.

Hazardous air quality with high concentrations of particulate matter less than 2.5 microns in size (PM 2.5) is particularly dangerous for sensitive people—generally those with preexisting respiratory conditions, older people, and children. During periods of hazardous air conditions, medical facilities are inundated with patients, and sensitive people are advised to stay indoors and avoid physical activity. Smoke also degrades recreational experiences, and some recreation areas may be closed during fire outbreaks. This is a major reduction in quality of life, with significant financial impacts, especially for the local recreation economy.

The Eagle Creek Fire (2017), as described in box 7.6, provided an excellent example of the effects of wildfire in the wildland-urban interface (fig. 7.4). This fire disrupted life for residents and travelers for nearly 2 months, closing much of the state’s most popular recreation corridor. On the 10-km stretch of the Historic Columbia River Highway between Bridal Veil and Ainsworth State Park, about 9,000 trees in danger of falling on the road were cut, and 1000 m of fencing were installed before the road was deemed safe for public travel. Many trails heavily damaged by the fire remained closed for 2 or more years (i.e., Wahclella Falls and Eagle Creek trails), while others will remain closed for the foreseeable future (i.e., Horsetail Falls and Oneonta Gorge trails), and some areas may stay closed for years.

The Eagle Creek Fire and other wildfires and smoke intrusions affecting large populations on the west side of the Cascades have provided a wakeup call for communities that have not typically experienced the adverse affects of wildfire. These conditions may be relatively uncommon in the short term, but a warmer climate will almost certainly increase their frequency in coming decades. Preparing for a future with more fire and smoke will increase the resilience of communities, thus protecting human health and local economies.

As expanding shoulder seasons make popular warm-weather activities available before seasonal staff are hired, the risks associated with unmanaged recreation, including hazards to recreationists and natural resource degradation (USDA FS 2010), will be increasingly prevalent (box 7.5). Natural hazards and disturbances may create further challenges for the provision of recreation opportunities. For example, wildfire affects recreation demand (as a function of site quality and characteristics) but may also damage physical assets or exacerbate other natural resource impacts such as erosion (chapter 3). Working with local partners can alleviate management issues, as in the case of search and rescue and postfire cleanup efforts (box 7.6).

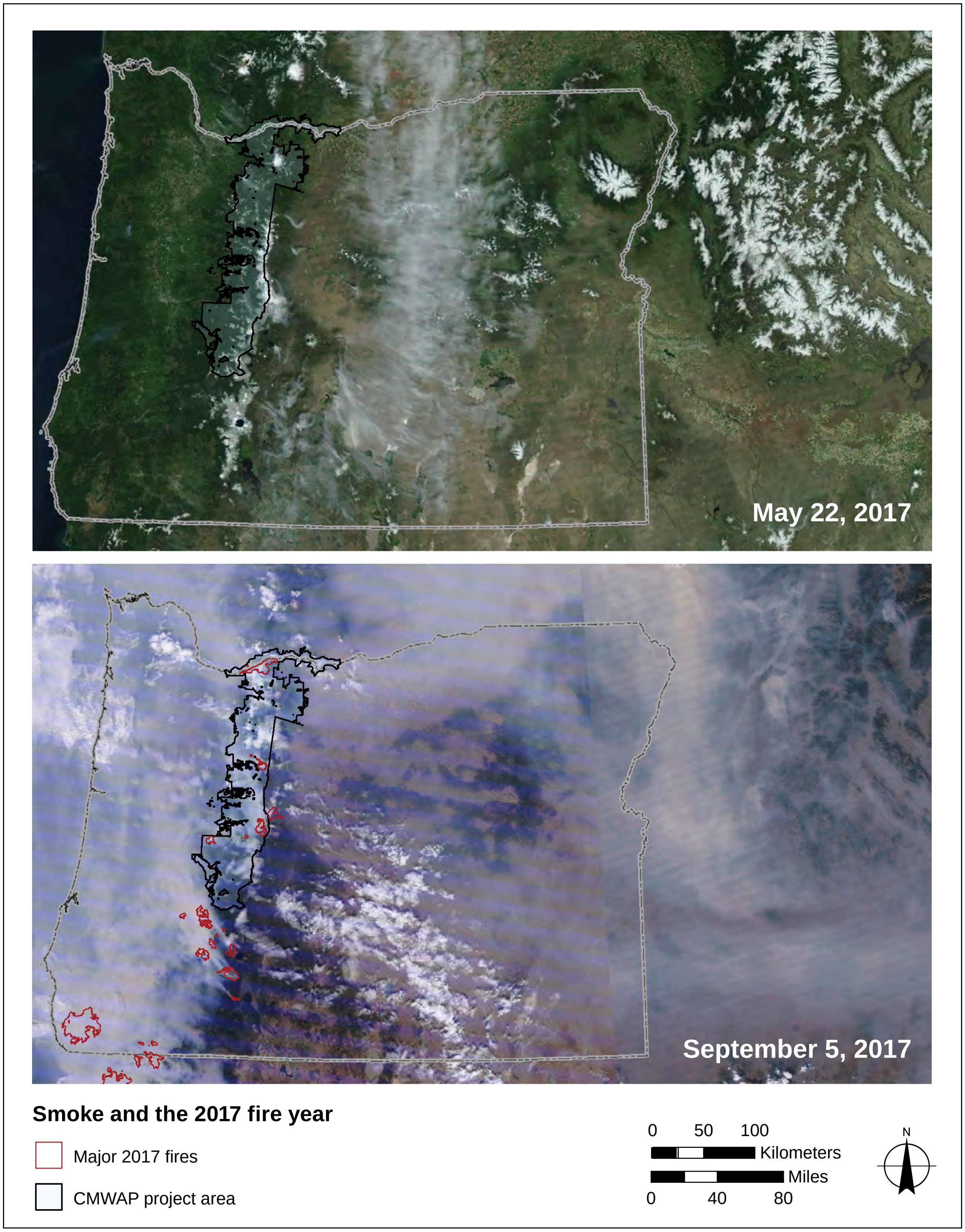


Figure 7.4—Smoke from wildfires has a pervasive influence on air quality and visibility. These images show the spatial extent of smoke during a day with multiple wildfires (lower), compared to a day with no wildfires. Recreation activities were reduced in the assessment area in September 2017 because of poor air quality and restricted access. Moderate Resolution Imaging Spectroradiometer imagery is from the Active Fire Mapping Program, U.S. Forest Service Geospatial Technology and Applications Center; archived images can be found at: https://firms.modaps.eosdis.nasa.gov/usfs/download. CMWAP = Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest Adaptation Partnership assessment area.

Warm-Weather Activities

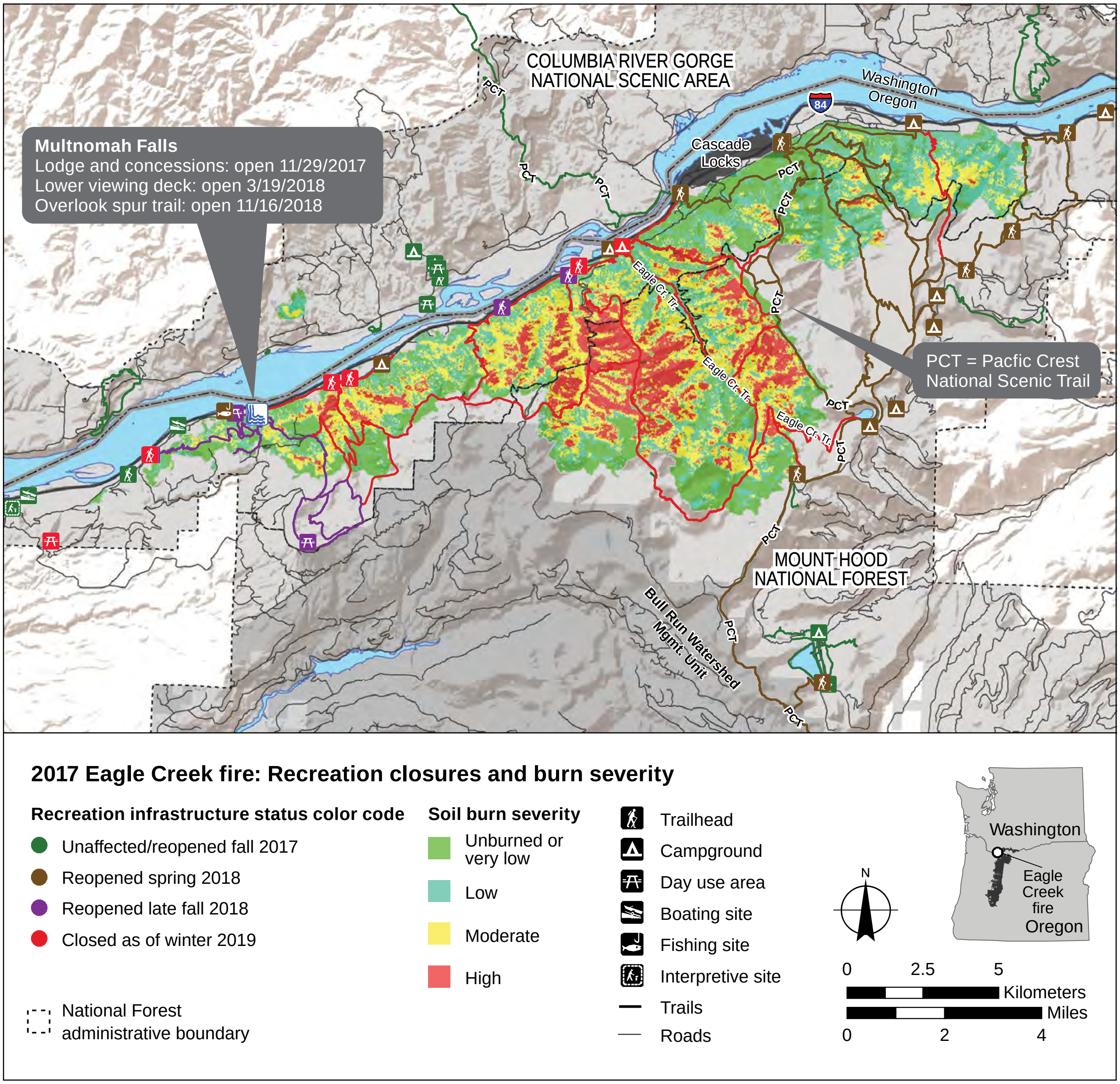
Warm-weather activities, such as hiking, camping, and nature viewing, are the most common form of recreation in the CMWAP assessment area (table 7.3). Warm-weather recreation is sensitive to the availability of snow- and ice-free trails and sites, and the timing and number of days with temperatures within ranges that are comfortable (which may vary with activity type and site). The number of warm-weather days has been shown to be a significant predictor of expected visitation behavior (Richardson and Loomis 2004), and studies of visitation in U.S. national parks show that minimum temperature is a strong predictor of monthly visitation patterns (Albano et al. 2013, Fisichelli et al. 2015, Scott et al. 2007). Recreational activity during warm seasons contributes substantial economic benefits to local communities, especially when considering the large volume of visitation and diverse range of recreation included within this category (White and Stynes 2008).

In addition to temperature, participants are sensitive to site quality and characteristics such as the presence and abundance of wildflowers, conditions of trails, vegetation, and availability of shade. The condition of features that are sensitive to climate change, especially presence of snow, may affect the desirability of certain sites, with snow-free sites being preferred for warm-weather recreation (Scott et al. 2007). Forested areas are positively associated with warm-weather activities, such as camping, backpacking, hiking, and picnicking (Loomis and Crespi 2004); such areas will be sensitive to a warmer climate (USDA FS 2012a).

Wildfire can affect participation in warm-weather activities through closures related to safety as well as changes to site quality and characteristics, including air quality. Wildfires have diverse effects on recreation that do not follow a linear pattern over time (Englin et al. 2001). The presence of recent wildfires has differential effects on the value of hiking trips (positive) and mountain biking (negative), although recent wildfire activity tends to decrease the number of visits (Hesseln et al. 2003, 2004; Loomis et al. 2001). The severity of fire may also matter; high-severity fires are associated with decreased recreation visitation, whereas low-severity fires are associated with slight increases in visitation (Sánchez et al. 2016, Starbuck et al. 2006). Recent fires are associated with initial reductions that weaken over time for camping (Rausch et al. 2010) and backcountry recreation (Englin et al. 1996). Research in Yellowstone National Park showed that visitation tends to be lower following months with high wildfire activity, although there is no discernible effect of previous-year fires (Duffield et al. 2013).

Wildfire can also affect the connectivity of long-distance hiking trails, such as the Pacific Crest Trail that runs through the CMWAP assessment area (fig. 7.5, box 7.6). Furthermore, reduced air quality from wildfire smoke can affect the quality, timing, and location of recreational visits from nonlocal visitors (Sage and

Nickerson 2017) (box 7.7) and can result in reduced participation in outdoor recreation activities by residents (Richardson et al. 2012). Oregon experienced a severe fire season in 2020, with the worst air quality related to wildfire smoke since 2017. During 2017, visitation to Mount Hood and the Columbia River Gorge decreased by more than 4 percent, accompanied by a 2 percent loss in visitor spending associated with wildfires (Ghahramani 2017).



Multnomah Falls
Lodge and concessions: open 11/29/2017
Lower viewing deck: open 3/19/2018
Overlook spur trail: open 11/16/2018

PCT = Pacfic Crest National Scenic Trail

Figure 7.5—The Eagle Creek Fire closed portions of Columbia River Gorge National Scenic Area during 2017 and 2018, and some trails remain closed at the time of writing (2021).

Overall demand for warm-weather activities is expected to increase because of a direct effect of climate change on season length. Temperatures are expected to increase significantly in the assessment area by the year 2100, with an average increase of about 8 °F (chapter 2). This is expected to result in earlier availability of snow- and ice-free sites and an increase in the number of warm-weather days in spring and autumn. Such effects are associated with increased visitation levels in other public lands (Albano et al. 2013, Fisichelli et al. 2015). For example, higher minimum temperatures are associated with an increased number of hiking days (Bowker et al. 2012). Higher maximum summer temperatures are associated with reduced participation in warm-weather activities (Bowker et al. 2012, Scott et al. 2007), so extreme-heat scenarios for climate change are expected to reduce visitation in some cases (Richardson and Loomis 2004). Extreme heat may shift demand to cooler weeks at the beginning or end of the warm-weather season or to alternative sites that are less exposed to extreme temperatures (e.g., at higher elevations, near lakes and rivers). However, overnight use (e.g., camping, backpacking) occurs primarily in summer when most students are not in school, and overnight use may be less affected than day use during other seasons.

Indirect effects of climate change on forested areas may negatively affect warm-weather recreation if site availability and quality are compromised. The overall effect on warm-weather recreation in the CMWAP assessment area will depend on local effects of climate on forest resources. Potential increases in the likelihood of extreme wildfire activity may reduce the supply of warm-weather activities in some years because of degraded site desirability, impaired air quality from smoke, and limited site access caused by fire management activities (fig. 7.6).


U.S. Forest Service

Figure 7.6—The Eagle Creek Fire closed many trails in the Columbia River Gorge National Scenic Area. The fire resulted in damaged recreational infrastructure (bridge on left), and the severity of the fire affected the scenic value of the area (right). Some trails remained closed 3 years after the fire started. Increasing wildfires in a warmer climate may cause safety concerns, reduce access, fragment long-distance trails, and degrade air quality and vistas for hikers.

The assessment area is expected to experience an increase in frequency and extent of wildfire, which tends to negatively affect recreation visitation and benefits derived from recreation (but with some variability as noted above). Shifts in vegetation type and forest cover are likely to occur in wilderness areas over many decades, with subalpine areas decreasing in the assessment area by the end of the century (chapter 5).

Wildfires have economic implications for recreationists and surrounding communities. Suppression and recovery efforts can create short-term jobs (Nielsen-Pincus et al. 2014). However, fire and smoke can damage tourism-dependent businesses, especially when nonlocal recreation declines following wildfire, as documented for Colorado and Montana (Hesseln et al. 2004).

Vegetation shifts may affect recreation indirectly, affecting visitation based on viewing subalpine areas or dependent on forest cover. Loss of forest cover has been associated with a 2 percent decrease in forest-based recreation (Loomis and Crespi 2004). A warm-weather recreation study found that visitors to Rocky Mountain National Park reported viewing alpine scenery as an important part of their decision to visit (Richardson and Loomis 2004). In the same study, recreationists traveling from longer distances were more likely to take fewer trips than those who traveled shorter distances, under climate change scenarios (Richardson and Loomis 2004). Although dynamics might be different in the CMWAP assessment area than those found in the areas discussed above, shifts in forest cover and vegetation type may affect recreationists' decisions to visit the region.

In some cases, adaptive capacity among recreationists may be high because of the large number of potential alternative sites and the ability to alter the timing of visits and capital investments (e.g., appropriate gear). However, benefits derived from recreation may decrease even if substitute activities or sites are available (Loomis and Crespi 2004). For example, some alternative sites may involve higher costs of access (because of remoteness or difficulty of terrain). In addition, limits on ability to alter seasonality of visits may exist (e.g., the timing of scheduled academic breaks). Although the ability of recreationists to substitute sites and activities is well established, how people substitute across time periods or between large geographic regions (e.g., choosing a site in southern Washington or another area of Oregon instead of within the CMWAP assessment area) is poorly quantified (Shaw and Loomis 2008). Climate-altered recreation site access will have varying affects on different socio-economic groups, presenting equity and inclusion dilemmas (Miller et al. 2022). Considering underrepresented populations in the CMWAP assessment area that might be disproportionately affected by such changes is critical in developing equitable adaptation strategies.

In summary, projected climatic changes are expected to result in a moderate increase in warm-weather recreation activities and benefits derived from these activities. Longer warm-weather seasons will increase the number of days when warm-weather activities are viable and increase the number of sites available during shoulder seasons. The effects of a longer season may be offset somewhat by negative influences on warm-weather activities during extreme heat and increased wildfire activity and associated smoke. The likelihood of effects on warm-weather recreation is high because the primary driver of climate-related changes to warm-weather recreation is through direct effects of temperature changes on the demand for warm-weather recreation. However, effects will likely differ for day use versus overnight use, if day use is more adaptable to climate change while overnight use follows more closely with school calendars. The timing and magnitude of climate change projections differ, but they all project rising temperatures (chapter 2). Indirect effects on recreation, primarily those related to wildfire, may be harder to project with certainty and precision (particularly at small spatial scales).

Snow-Based Activities

Snow-based recreation occurs across the CMWAP assessment area, primarily in Mount Hood and Willamette NFs (table 7.3). Downhill skiing accounts for nearly 88 percent of recorded snow-based recreation, with year-round downhill skiing available in some high-elevation ski areas. In some recent years, late and light snowfall have kept lower elevation ski resorts closed year-round (see box 7.4). Cross-country skiing, accessed through Sno-Parks and along roads, accounts for a much smaller portion of snow-based recreation in both Mount Hood NF and Willamette NF, and there is minimal reported snowmobile activity in these forests. Although CRGNSA also hosts snow-based recreation, this was not captured by the NVUM survey. Snow-based recreation accounts for the three most lucrative types of recreation for local communities (White and Stynes 2008). Although far fewer people participate in snowmobiling than skiing (table 7.3), snowmobiling provides important economic benefits to nearby communities (White et al. 2016). Snowmobiling may be more vulnerable than downhill skiing to reduced snowpack in a warmer climate (Scott et al. 2008).

Climate change is expected to have a negative effect on snow-based activities, although a wide range of effects at local scales is possible because of differences across the region in site location and elevation. Warmer projected winter temperatures for the region are expected to reduce the proportion of precipitation as snow, even if the total amount of precipitation does not deviate significantly from historical norms (chapters 2 and 3). The rain-snow transition zone (i.e., where precipitation is more likely to be snow rather than rain for a given time of year) is expected to move to higher elevations, particularly in late autumn and early spring (Klos et al. 2014). This effect places lower elevation sites at risk of shorter or nonexistent snow-based recreation seasons (figs. 7.7 and 7.8; box 7.4).

High-elevation sites are projected to have shorter snow-based recreation seasons, with the season being much shorter at low-elevation sites (fig. 7.6). Large declines

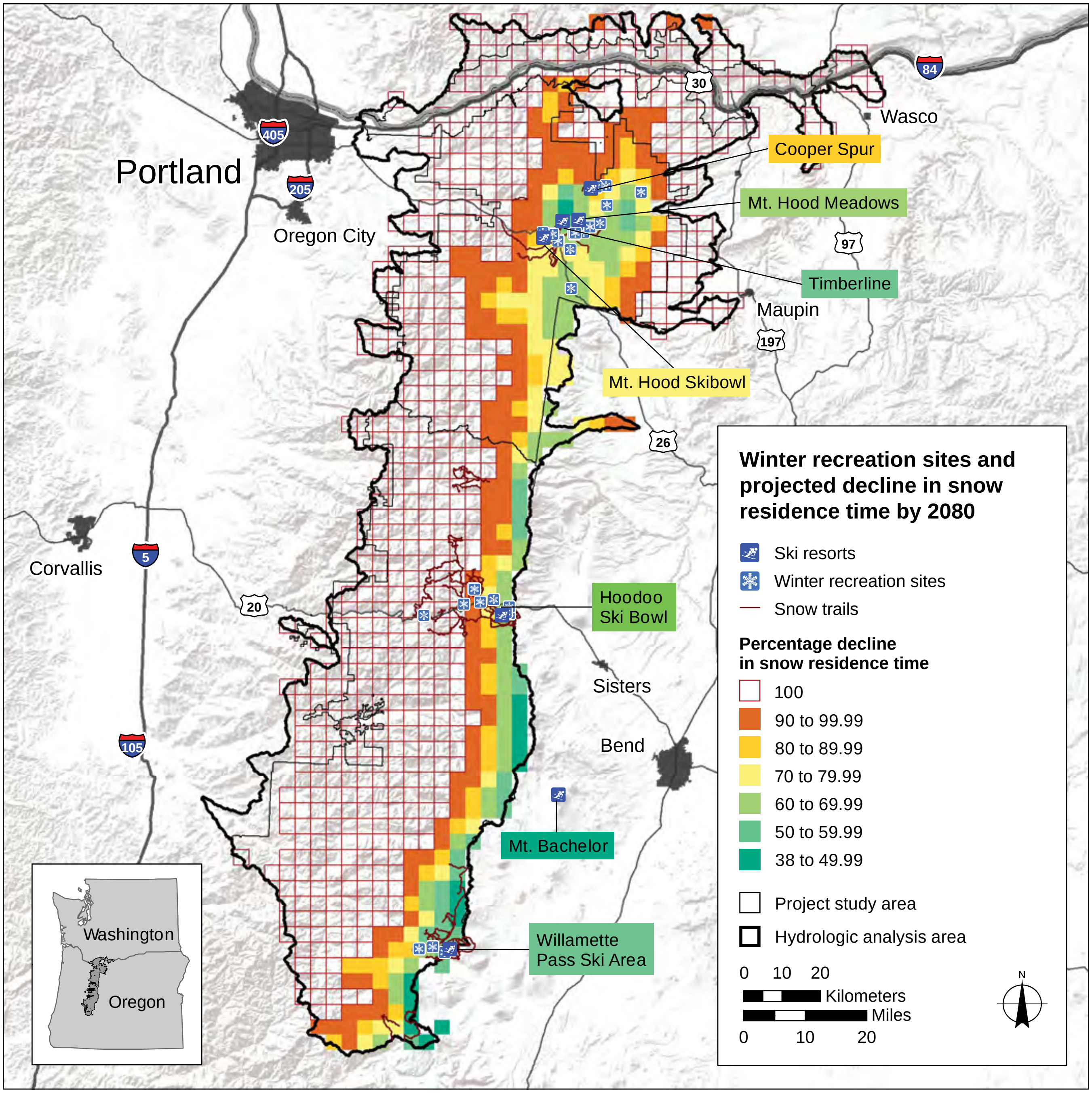


Figure 7.7—Snow-based recreation sites and decline in snow residence time in the Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest Adaptation Partnership assessment area. Sites are indicated by blue boxes with snowflakes, overlaid on percentage decline in snow residence time across the eastern slope of the mountains. The six labeled ski areas are those for which the Pacific Northwest Ski Area Association collects annual visitation data (see fig. 7.9). Ski-area label colors match the percentage decline in snow residence time for their location, as shown in the legend.

in mountain snowpack in the Western United States (Oregon included) observed in recent decades (Mote et al. 2018) will likely have negative effects on snow-based recreation. In some cases, climate-related disturbance (e.g., wildfire and insect outbreaks) can reduce the quality of skiing when the presence of trees is important for the skiing experience (Mote 2013).

Snow-based recreation is highly sensitive to variations in temperature and the amount and timing of precipitation as snow (Wobus et al. 2017). Seasonal patterns of temperature and snowfall determine the likelihood of a given site having a viable season (Scott et al. 2008). Lower temperatures and the presence of new snow are associated with increased demand for skiing and snowboarding (Englin and Moeltner 2004). If participation in snow-based recreation does not substantially decline with decreased supply owing to shorter seasons and smaller snow-covered areas, this may result in a higher concentration of snow-based recreationists in the short term (i.e., mid- to late-century projections) (see fig. 7.7). However, in the longer term (i.e., beyond end-of-century projections), most snow-based recreation areas may disappear from the region altogether.


Jim Cronan

Figure 7.8—Low snowpacks, which are expected to be more common in a warmer climate, can reduce the duration, quality, and safety of skiing in some locations.

Participation in undeveloped skiing and motorized snowsports is generally projected to increase (Cordell 2012). Meanwhile, studies of the ski industry in North America uniformly project negative effects of climate change on these activities (Scott and McBoyle 2007). Overall warming is expected to reduce the season length and the likelihood of reliable snow-based recreation seasons. Climatological projections for the CMWAP assessment area (chapter 2) are consistent with studies of the vulnerability of recreation to climate change in other regions, in which projected effects of climate change on snow-based recreation activities is negative (Dawson et al. 2009, Hamlet 2000, Mote et al. 2008, Scott et al. 2008, Stratus Consulting 2009, Wobus et al. 2017).

For developed downhill skiing in ski resorts, adaptations such as snowmaking and developing new runs at higher elevations are possible (Scott and McBoyle 2007). However, the added costs of these improvements may decrease the profitability of the resorts. Increased precipitation as rain may increase availability of water for snowmaking during winter in the near term, but warmer temperatures may also reduce the number of days per season when snowmaking is viable.

Snow-based recreationists have moderate capacity to adapt to changing conditions, given the number of snow-based recreation sites in the region. For undeveloped or minimally developed site activities (e.g., cross-country skiing, backcountry skiing, snowmobiling, snowshoeing), recreationists may move to higher elevation sites, which have higher likelihoods of viable seasons (Hand and Lawson 2018). One case study found that cross-country skiers whose ski event was cancelled because of a lack of snow and unsafe conditions were more interested in seeking out cross-country ski opportunities in other locations than substituting a different activity (Orr and Schneider 2018).

Snow conditions in the CMWAP assessment area relative to other regions are also an important consideration. If other locations experience relatively large decreases in snow-based recreation, recreationists may view high-elevation sites in Mount Hood NF as a substitute for sites in other locations (Hand and Lawson 2018) (or vice versa), although interregional substitution patterns for recreation activities are poorly understood (Shaw and Loomis 2008). Figure 7.9 shows annual visitation at the six ski areas within the assessment area as well as higher elevation Mount Bachelor. During a low snow year (2014–2015 season), most sites experienced a

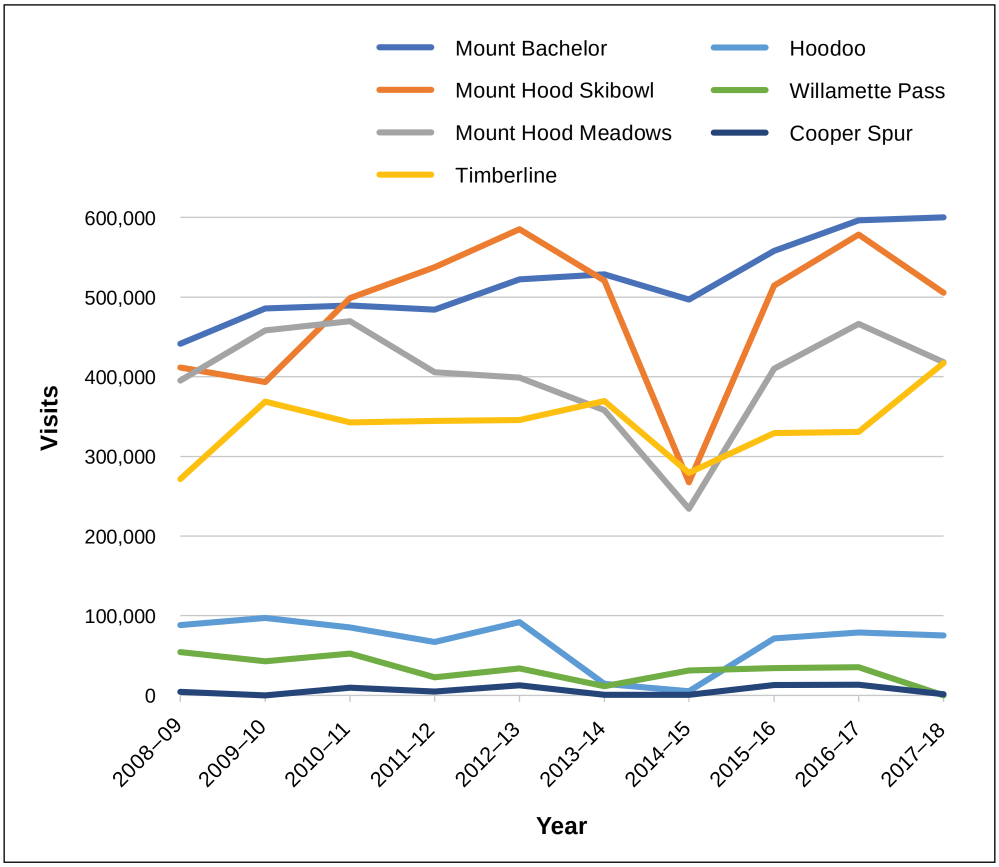


Figure 7.9—Annual visits to ski areas in Oregon (data from Pacific Northwest Ski Area Association 2019). The 2014–2015 decrease in annual visitation corresponds with a low-snow season. Mount Hood Skibowl, with the second lowest elevation of the ski areas listed here, experienced a large drop in visitation during the 2014–2015 season. Two other low-elevation areas had seasons in which they did not operate: Cooper Spur (lowest elevation ski area) in 2009–2010, and Willamette Pass (fourth lowest elevation ski area) in 2017–2018.

substantial decrease in visitation, whereas Mount Bachelor had relatively consistent visitation. Although this is not a measure of substitution, it indicates the possibility of recreationists seeking out snow-based recreation activities at higher elevation sites when these activities are not available owing to climate-related shifts.

In summary, the magnitude of climate-related effects on snow-based activities is expected to be high in Mount Hood and Willamette NFs. Warmer temperatures are likely to shorten snow-based recreation seasons and reduce the likelihood of viable seasons at lower elevation sites, such as Willamette Pass Resort and Hoodoo Ski Area in Willamette NF (box 7.4). Developed sites may have limited ability to adapt to these changes unless additional areas are available and feasible for expanded development. Negative effects are expected to be high for snow-based recreation, although differences across sites are expected because of differences in elevation and local snow conditions. Climate models generally project warming temperatures and a higher elevation rain-snow transition zone, which would expose a larger land area to the risk of shorter seasons.

Wildlife-Related Activities

Terrestrial or aquatic animals are a primary component of the wildlife-related activities experience. Wildlife recreation can involve consumptive (e.g., hunting) or nonconsumptive (e.g., wildlife viewing, birding, catch-and-release fishing) activities. Wildlife-related activities depend on the distribution, abundance, and population health of desired target species. These factors influence activity "catch rates," that is, the likelihood of harvesting or seeing an individual of the target species. Sites with higher catch rates can reduce the costs associated with a wildlife-related activity (e.g., time and effort tracking targets) and enhance overall enjoyment of a recreation day for that activity (e.g., greater number of views of highly valued species). Wildlife-related recreationists contribute substantial economic benefits to local communities, considering both spending per party per trip (White and Stynes 2008) and contributions made through the purchase of hunting and fishing licenses (Cooper et al. 2015). Hunters and fishers are also known to support conservation through other types of environmental behaviors (Cooper et al. 2015).

Fishing is the most popular wildlife-related activity in the CMWAP assessment area, primarily taking place in Mount Hood and Willamette NFs (table 7.3). The most popular species for fishing are rainbow trout (*Oncorhynchus mykiss* Walbaum) and cutthroat trout (*O. clarkia* Richardson), which are present in rivers, reservoirs, and wilderness area high lakes. In addition to these two species, recreational fishers target steelhead (*O. m. irideus* Gibbons) (summer) and Chinook salmon (*O. tshawytscha* Walbaum) (spring) in rivers; bass, walleye (*Sander vitreus* Mitchill), kokanee (*O. nerka* Walbaum), and lake trout (*Salvelinus namaycush* Walbaum in Artedi) in reservoirs; and brook trout (*S. fontinalis* Mitchill) and bass in high lakes. Hunting within this region also takes place primarily in Mount Hood and Willamette NFs, with popular species being black-tailed deer (*Odocoileus hemionus hemionus* Rafinesque), mule deer (*O. hemionus* Rafinesque), and elk (*Cervus elaphus* L.). Wildlife viewing, as a primary recreation activity, occurs across the assessment area. Although wildlife viewing is not a popular primary recreation activity in this region, the presence of wildlife likely has benefits to recreationists participating in a range of activities.

Participation in wildlife-dependent activities is often sensitive to weather-related factors that affect expected catch rates. Catch rates are important determinants of site selection and trip frequency for hunting (Loomis 1995, Miller and Hay 1981), substitution among hunting sites (Yen and Adamowicz 1994), participation and site selection for fishing (Lamborn and Smith 2019, Morey et al. 2002), and participation in nonconsumptive wildlife recreation (Hay and McConnell 1979). Altered habitat, food sources, or streamflows and water temperature (for aquatic species) associated with climate change may alter wildlife abundance and distribution, which in turn influence expected catch rates and participation in wildlife-dependent recreation. Where habitat has been altered by intense fires, wildlife-based recreation will likely shift in response to safety issues and area closures as well as shifts in wildlife species active in these areas.

Wildlife-related recreation may also be sensitive to other direct and indirect effects of climate change. The availability of highly valued target species (e.g., cutthroat trout for coldwater anglers) affects the ability of fishers to obtain desired benefits derived from engaging in fishing (Pitts et al. 2012). On the Yellowstone River in Montana, fishing outfitters and guides reported several ways in which they are already adapting to climate change effects to coldwater fisheries, including (1) altering catch-and-release practices, (2) temporally shifting trips to avoid fishing during the hottest period of the day, (3) spatially shifting trips to fish in cooler waters, (4) avoiding fishing during the hottest part of the year and during droughts, and (5) targeting warm-water species (Lamborn and Smith 2019). Similarly, the diversity of game species present can affect hunt satisfaction (Milon and Clemmons 1991) and enjoyment of nonconsumptive wildlife-dependent activities such as birding (Hay and McConnell 1979).

Temperature and precipitation are related to general trends in participation for multiple wildlife activities (Bowker et al. 2012, Mendelsohn and Markowski 2004), although the exact relationships vary by activity or target species. Warmer temperatures may negatively affect opportunities to participate in activities such as big-game hunting, which is enhanced by cold temperatures and snowfall to aid in field dressing, packing out harvested animals, and tracking. Activities such as wildlife viewing or photography may be influenced by climate change effects in ways similar to warm-weather activities, in which moderate temperatures and snow- and ice-free sites are desirable.

Overall, warming temperatures projected for the CMWAP assessment area are expected to increase participation in terrestrial wildlife activities because of an increased number of days that are desirable for wildlife-dependent outdoor recreation. In general, warmer temperatures are associated with higher participation in and number of days spent hunting, birding, and viewing wildlife (Bowker et al. 2012). However, hunting that occurs during discrete seasons (e.g., elk and deer hunts managed by the Oregon Department of Fish and Wildlife) may depend on weather conditions during a short period within those seasons.

The desirability of hunting during established seasons may decline as warmer weather persists later into fall and early winter and the likelihood of snow cover decreases, reducing harvest rates. This issue is also relevant for outfitters who operate under legal hunting/fishing seasons and may also operate under special-use permits with specific dates and areas. These regulatory constraints could become less aligned with "catch rate" based on climatic conditions. These effects will be felt most in the Willamette NF because there are no commercial hunting guides that operate in the Mount Hood NF or CRGNSA.

The effects of changes in habitat for target species are likely to be ambiguous because of complex relationships among species dynamics, vegetation, climate, and disturbances (primarily wildfire and invasive species) (chapter 5). Overall vegetative productivity may decrease in the future, although this is likely to have a neutral effect on game species populations, depending on the size, composition, and spatial heterogeneity of forage opportunities in the future (chapter 6). Similarly, the effects of disturbances on harvest rates of target species are ambiguous because it is unknown exactly how habitat composition will change in the future.

Higher temperatures are expected to decrease populations of native coldwater fish species (e.g., cutthroat trout), and climate refugia will be confined to higher elevations (chapter 4). This change favors increased populations of fish species that can tolerate warmer temperatures in low-elevation lakes and streams. However, it is unclear whether shifting populations of species (e.g., substituting other fish species for cutthroat trout) will affect catch rates, because relative abundance of fish may not necessarily change.

Reduced snowpack could cause higher peak flows in winter, and lower low flows in summer, creating stress for fish populations during different portions of their life histories (chapters 3 and 4). The largest patches of habitat for coldwater species such as cutthroat trout will be at higher risk of shrinkage and fragmentation. Increased incidence and severity of wildfire may increase the likelihood of erosion events that degrade streams and riparian habitat. These effects could degrade the quality of individual sites in a given year or decrease the desirability of angling as a recreation activity relative to other activities.

An interesting context for the future of hunting and fishing in a warmer climate is an ongoing decrease in hunting participation. Between 1975 and 2013, the number of Oregon residents holding a hunting license decreased from 18.9 to 8.3 percent, and the number holding a fishing license decreased from 34.6 to 17.4 percent (Darling 2014). However, that trend saw a reversal in 2016, with the number of hunting licenses sold in Oregon increasing by 22 percent from 2015 (Aiello 2017). Effects of climate change on both animal populations (chapter 6) and demand for harvesting animals will influence the overall effects on wildlife-related recreation.

In summary, the magnitude of climate-related effects on activities involving wildlife is expected to be moderate for fishing and low for terrestrial wildlife-related activities, although the effects on terrestrial wildlife-related activities are complex and not well understood. Ambiguous effects of vegetative change on terrestrial wildlife populations and distribution suggest that conditions may improve in some areas and deteriorate in others. Overall warming tends to increase participation in wildlife-related recreation but may create timing conflicts for activities with defined regulated seasons (e.g., big-game hunting).

Anglers may experience moderate negative effects of climate change on benefits derived from fishing. As participation in water-based activities such as river floating increases, conflicts between floaters and anglers may increase, such as on the White Salmon River in CRGNSA. Opportunities for coldwater species fishing are likely to be reduced as coldwater refugia become confined to higher elevations and are eliminated in some areas. Coldwater species tend to be high-value targets, indicating that this habitat change will decrease benefits enjoyed by anglers. Warm-water tolerant species may increasingly provide targets for anglers, mitigating reduced populations of coldwater species. Warmer temperatures and longer seasons encourage additional participation, but indirect effects of climate on streamflows and reservoir levels could reduce opportunities in years with low precipitation or snowpack. Uncertainties exist about the magnitude and direction of indirect effects of climate on terrestrial habitat and the degree to which changes in available target species affect participation.

Water-Based Activities (Excluding Fishing)

Water-based activities, aside from fishing, comprise a small portion of primary recreation activity participation in the CMWAP assessment area. Upper reaches of streams and rivers are generally not desirable for boating and floating. Lakes and reservoirs provide opportunities for both motorized and nonmotorized boating and swimming, although boating may commonly be paired with fishing. Existing stressors include the occurrence of drought conditions that reduce water levels and site desirability in some years, and disturbances that can alter water quality (e.g., erosion events following wildfires).

The availability of suitable sites for nonangling, water-based recreation is sensitive to reductions in water levels caused by warming temperatures, increased variability in precipitation, and decreased precipitation as snow. Reductions in surface-water area are associated with decreases in participation in boating and swimming activities (Bowker et al. 2012, Loomis and Crespi 2004, Mendelsohn and Markowski 2004), and streamflow is positively associated with number of days spent rafting, canoeing, and kayaking (Loomis and Crespi 2004, Smith and Moore 2013). Demand for water-based recreation is also sensitive to temperature. Warmer temperatures are generally associated with higher participation in water-based activities (Loomis and Crespi 2004, Mendelsohn and Markowski 2004). Although extreme heat may dampen participation for some activities (Bowker et al. 2012), recreation professionals in the CMWAP assessment area have noted an increase in recreation, especially near water bodies, when residents aim to escape the heat in urban areas.

River recreation, in particular commercial and private rafting, is vulnerable to the climate change effects of drought (e.g., low streamflow) and wildfire (e.g., degraded scenery, reduced access). In the assessment area, whitewater rafting occurs primarily on the Clackamas River during spring and early summer, and on the Lower White Salmon River and the lower portion of the McKenzie River during summer months. River rafters prefer mid-season, intermediate water levels and warm weather over turbulent, cold spring runoff or late-season low water (Yoder et al. 2014). As peak flows are predicted to increase by 10–30 percent in water-based recreation sites around the Clackamas River by mid-century, and by more than 40 percent in many sites by the end of the century (fig. 7.10), the season for white water rafting might shorten. Damage to recreational infrastructure in areas with substantially increased flows might affect access to water-based recreation sites. Additionally, a warmer climate will shorten the period when desirable conditions are available. Quality whitewater rafting requires different conditions than floating the river. This can be a dilemma in locations where whitewater and family float trips are both popular activities and outfitter/guide companies depend on appropriate streamflows for a positive experience (Associated Press 2012).

These issues are compounded when threatened or endangered fish species are present, potentially reducing rafting seasons for commercial river outfitters because low streamflow puts salmon redds (i.e., egg nests in gravel river bottoms) at risk, in addition to reducing the quality of rafting conditions. In some cases, recreationists

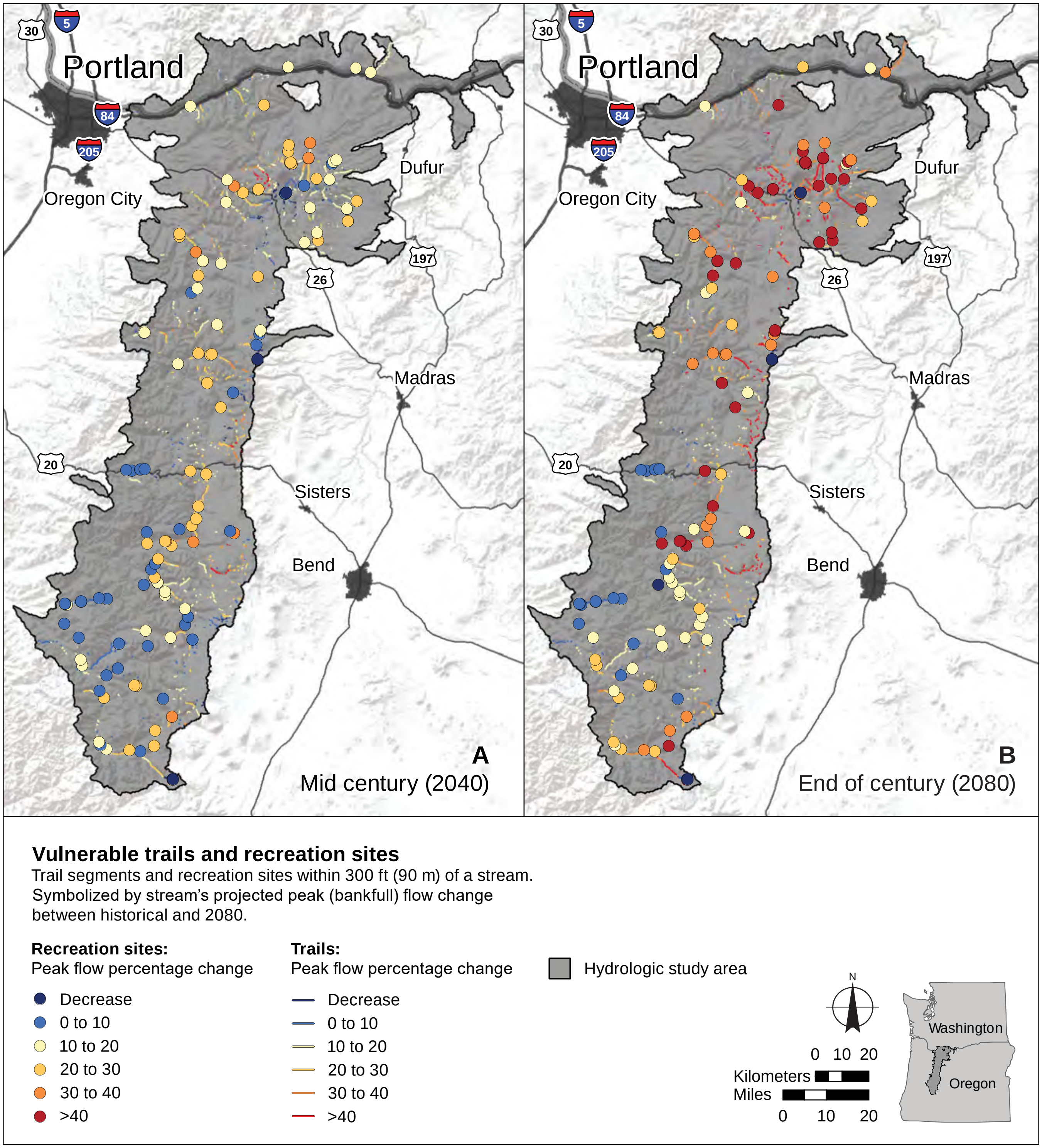


Figure 7.10—Percentage change in peak water flow between historical data and future projections for trail and recreation sites within 90 m of a stream in the Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest Adaptation Partnership assessment area.

may be willing to travel farther to find a suitable location when streamflows are low (Bristow and Jenkins 2018). Although the White Salmon River is spring fed and will likely be less affected by reduced snowpack, other popular whitewater rafting rivers such as the Clackamas and Mackenzie Rivers are likely to have lower flows during the rafting season (chapter 3).

Increasing temperatures, reduced storage of water as snowpack, and increased variability of precipitation are expected to increase the likelihood of reduced water levels and greater variation in water levels in lakes and reservoirs on federal lands (chapter 3). These conditions in turn are associated with reduced site quality and suitability for certain activities (box 7.8). Increased demand for surface water by downstream users may exacerbate reduced water levels in drought years. Warmer temperatures are expected to increase the demand for water-based recreation as the viable season lengthens but can also increase undesirable algal blooms (Gobler 2020, Hand and Lawson 2018). Overall, projections of water-based activities in response to climate change tend to be small compared to the effects of broad population and economic shifts on these activities (Bowker et al. 2012).

In summary, climate change is expected to have a moderate effect on water-based activities. Increasing temperatures and longer warm-weather seasons are likely to increase demand, although the incidence of extreme temperatures may dampen this effect in some years. A higher likelihood of lower streamflows and reservoir levels may also offset increased demand to some extent. Climate model projections tend to agree on a range of warming temperatures and longer seasons, although changes in precipitation are uncertain. Altered timing of snowmelt may increase the likelihood of negative effects to water-based activities (through lower summer streamflows and reservoir levels).

Forest Product Gathering

Forest product gathering accounts for a small portion of primary visit activities in the CMWAP assessment area, although it is more common as a secondary activity. Popular forest products for gathering in this region include Christmas trees and boughs, mushrooms, beargrass (*Xerophyllum tenax* [Pursh] Nutt.), salal (*Gaultheria shallon* Pursh), and berries. A small but avid population of enthusiasts for certain types of products supports a steady demand for gathering as a recreational activity. Small-scale commercial gathering likely competes with recreationists for popular and high-value products such as huckleberries (*Vaccinium* spp.), although resource constraints may not exist at current participation levels. In addition, traditional foods (often called first foods) have high cultural value for American Indians and rural residents. In recent years, seeds collected from native plants are increasingly used for restoration of native vegetation where nonnatives have become prevalent.

Forest product gathering is sensitive primarily to climatic and vegetative conditions that support the distribution and abundance of target species. Participation in forest product gathering is similar to that for warm-weather recreation activities, depending on moderate temperatures and the accessibility of sites where products are typically found. Vegetative change resulting from warming temperatures and increased interannual variation in precipitation may alter the geographic distribution and productivity of some target species over many decades (chapter 5). Increased frequency and extent of wildland fires may eliminate sources of forest products immediately after fire but encourage medium-term productivity for other products (e.g., mushrooms, huckleberries). Long-term changes in vegetation that reduce forest cover may reduce viability of forest product gathering in areas that have a high probability of transitioning to vegetation assemblages with lower abundance and distribution of desirable species.

The projected large increase in growing degree-days (chapter 2) suggests that the availability of some forest products may increase. However, increased drought stress will also influence the availability of these species, primarily at high elevations. Christmas trees and mushrooms might be negatively affected by drought, whereas salal and beargrass are somewhat drought tolerant and may be less affected by a warmer climate.

Recreationists engaged in forest product gathering may have the ability to select different gathering sites as the distribution and abundance of target species changes, although these sites may increase the costs of gathering. Those who engage in gathering as a secondary or tertiary activity may choose alternate activities to complement primary activities. Commercial products serve as an imperfect substitute for some forest products such as Christmas trees.

In summary, the magnitude of climate effects on forest product gathering is expected to be low. This activity is less common than other recreation activities and is typically a secondary activity. Longer warm-weather seasons may expand opportunities for gathering in some locations, although these seasonal changes may not correspond with greater availability of target species. The likelihood of effects is expected to be moderate, although significant uncertainty exists regarding direct and indirect effects on forest product gathering. Vegetative changes caused by climate change and disturbances may alter abundance and distribution of target species, although the magnitude and direction of these effects are unclear.

Summary of Climate Change Vulnerabilities

Several recreation activities are considered highly sensitive to changes to climatic and environmental conditions. However, recreation in the CMWAP assessment area is diverse, and the effects of climate are likely to differ widely among different

Box 7.8

Drought effects on warm-weather recreation

In the Columbia River Gorge National Scenic Area, Mount Hood National Forest (NF), and Willamette NF Adaptation Partnership assessment area, climate change is expected to greatly increase drought stress by the end of the 21st century, doubling historical values of climatic water deficit, a key indicator of drought stress (chapter 3). The largest percentage increase in climatic water deficit is projected for areas above 2100 m elevation in the assessment area, making drought a major concern for high-elevation ski areas, particularly Mount Hood Meadows and Timberline. The season for alpine climbing on Mount Hood appears to be shortening as ice near the peak of the mountain melts earlier in the season.

Resource managers are already experiencing the effects of drought and have reported consequences for recreation in Willamette NF. During periods of drought, fire restrictions are often placed on large areas and can include campgrounds, day-use areas, and trails. Campfires are an important part of the camping experience, facilitating social interaction both historically and today. Campground hosts have reported that the number of campers drops when campfires are banned. People might choose to participate in other activities rather than camping with no campfire.

In summer months, water-based recreation such as swimming, floating, water skiing, and boating are gaining popularity (White et al. 2016). Reservoirs are an important area for water skiing and boating, but keeping reservoirs full can be difficult during times of drought. There may be tradeoffs between providing water for uses such as irrigation versus providing recreation opportunities. Declining water levels in reservoirs used for recreation can compromise the aesthetics of a reservoir by creating “bathtub rings” and mud flats, and by making boat ramps inaccessible. A study conducted in the Willamette River basin found that visitor-days declined by as much as 6-percent-per-meter drop in water level below a full reservoir (Moore 2015). Declines in visitor use were higher in shallower reservoirs with shorter boat ramps, and lower in reservoirs near population centers. Based on an economic analysis, this study suggested that releasing stored water from some reservoirs for downstream needs, while maintaining full reservoirs for recreation in others, would best benefit society (Moore 2015).

In Willamette NF, Detroit Reservoir, which is a popular location for water skiing and boating, has been faced with lowered water levels resulting from drought in recent years. In addition, algal blooms may become more of an issue in Willamette NF in a warmer climate. Rising water temperatures promote harmful algal growth, presenting a health hazard to people who use reservoirs and small lakes (Paerl and Huisman 2008). The U.S. Forest Service monitors developed recreation sites that are known to be susceptible to harmful algal blooms, and posts health advisory signs when toxins are detected, but the areas are not typically closed to the public.

categories of activities and across geographic areas. Although recreationists can adapt to changing opportunities influenced by the effects of climate change, the degree to which different activities and locations are satisfactory substitutes is not well understood.

Overall, participation in climate-sensitive recreation activities is expected to increase, as longer warm-weather seasons make more recreation sites available for longer periods. Participation is also expected to increase owing to increasing population in the assessment area, particularly when new residents are attracted to the area for its outdoor recreation opportunities. Increased participation in warm-weather activities is likely to be offset somewhat by decreased supply of snow-based activities. Receding snow-dominated areas and shorter seasons in the future are likely to reduce the opportunities (in terms of available days and sites) for snow-based recreation.

Beyond these general conclusions, the details of changes to recreation patterns in response to climate changes are complex. Recreation demand is governed by several economic decisions with multiple interacting dependencies on weather and climate. For example, decisions about whether to engage in snow-based recreation, which activity to participate in (e.g., downhill skiing or cross-country skiing), where to ski, how often to participate, and how long to stay for each trip depend to some degree on climatic and environmental characteristics. On the supply side, site availability and quality depend on climate, but the effect may differ greatly from one location to another. Thus, climatic effects on recreation depend on spatial and temporal relationships among sites, environmental conditions, and human decisions.

Uncertainty derives from unknown effects of climate on site quality and characteristics that are important for some recreation decisions (e.g., indirect effects of climate on vegetation, wildlife habitat, and species abundance and distribution). The exact effects of climate on target species or other quality characteristics are difficult to predict and are likely to be diverse across the region, yet these characteristics play a large role in recreation decisions for some activities.

Another source of uncertainty is how people will adapt to changes when making recreation decisions. Substitution behavior between regions and over time is not well understood (Shaw and Loomis 2008, Smith et al. 2016), but more research is focusing on this topic (e.g., Bristow and Jenkins 2018, Lamborn and Smith 2019, Orr and Schnieder 2018). Substitution will be an important adaptation mechanism for recreationists. Some popular activities may have several alternate sites, and the timing of visits may be altered to respond to climate changes. However, spatial and temporal substitution may represent a loss in benefits derived from recreation even if it appears that participation changes little (Loomis and Crespi 2004); the new substitute site may be more costly to access or lower quality than the preferred site before climate change. Furthermore, increased recreational activity in smaller areas may lead to crowding, although not all recreationists will be sensitive to this (e.g., Nickerson 2016, Schultz and Svajda 2017). This represents a decrease in benefits to the recreationist (Miller et al. 2022).

Adapting Recreation Management to Climate Change

Warming temperatures will be the primary driver of climate change effects on recreation. Increasing length of the snow-free season will likely extend the season length for many warm-weather recreation activities. As temperatures increase, timing of peak streamflow will affect the seasonality of whitewater rafting. Riparian and other sensitive areas may see greater use during times of low flow as more people seek shade and cooler sites. As the warm-weather recreation season starts earlier and ends later in the year, human-wildlife interactions will likely change, with recreationists being more prevalent during periods of animal life cycles when animals were previously absent. This might increase the risk of human-wildlife conflict, such as increased interactions between black bears (*Ursus americanus* Pallas) and people. In addition, smaller areas suitable for recreation during the extreme summer and winter seasons might result in crowding for some recreationists and potential conflict between recreational activities.

Climate change effects might lead to new maintenance issues for recreational infrastructure and facilities. Warming will likely extend seasons of use, which may expose sensitive roads and trails, and wildlife habitats that were previously protected from recreational use by snow coverage. Shifting from snow to rain may lead to increased erosion, landslides, and trail failures, which will likely increase the need for road and trail maintenance as well as risks to public safety. Large increases in peak streamflows (fig. 7.10) might damage recreational infrastructure such as trails, bridges, and campgrounds along the course of these water bodies. Recreationists will likely visit infrastructure such as trails and campgrounds outside of the periods during which seasonal staff are in place to maintain them, posing risk to both recreationists and facilities. If recreational use becomes more concentrated in smaller areas during the peak summer and winter seasons, increased effort might be required to keep facilities maintained. However, this might also result in staff being able to focus on smaller areas if recreation is not as widely dispersed. Increased demand during shortened seasons emphasizes the need to address concerns regarding access and use, such as in CRGNSA, where infrastructure such as parking, trails, and lodging already struggle to meet current demand.

Organizational flexibility and responsiveness to changes will help adapt recreation management to climate change in the CMWAP assessment area (Miller et al. 2022), and most adaptation strategies are focused on providing sustainable levels of recreation opportunities (chapter 9). Redirecting recreational use to minimize conflict between users and with wildlife, optimizing recreational opportunities, and protecting vulnerable areas may help maintain the quality of recreational experiences in the future. Public safety may also be of concern as disturbance patterns change. Partnerships with other organizations might provide opportunities to increase flexibility, such as for covering increased search-and-rescue efforts or hiring seasonal staff to cover expanding warm-weather recreation seasons.

Adaptation tactics focus on adjusting the capacity of recreation sites and increasing flexibility of the availability of those sites based on interannual differences in weather conditions. When management capacity cannot be extended, such as through partners, access to some areas may need to be restricted to protect resources, especially when roads, trails, and facilities are not yet open and may not be safe (e.g., when snow melts early). Efforts are needed to identify recreation sites that are likely to incur heavier use in a warmer climate, then ensure that infrastructure and staffing are sufficient to support that use, or alternatively, that access is directed to locations that can sustain more use. Greater flexibility in the seasonality of staffing, permitting, and concessionaire contracts will be needed to adjust to altered recreational demands and opportunities in the future. For a broader summary of outdoor recreation adaptation strategies for public land management agencies, organizations, and participants across the Western United States, refer to Miller et al. (2022).

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Literature Cited

Aiello, D. 2017. Number of Oregon hunters up in 2016, despite fee increases. Statesman Journal. 2 May 2017. https://www.statesmanjournal.com/story/life/2017/05/02/oregon-hunters-up-2016/101177612.

Albano, C.M.; Angelo, C.L.; Strauch, R.L.; Thurman, L.L. 2013. Potential effects of warming climate on visitor use in three Alaskan national parks. Park Science. 30: 37–44.

Associated Press. 2012. Climate change poses challenges for water managers. Times-News. 9 May 2012. https://magicvalley.com/news/state-and-regional/climate-change-poses-challenges-for-water-managers/article_daa1bb68-b85e-5cf9-8efd-0b54b47711ab.html. (7 July 2017).

Bark, R.H.; Colby, B.G.; Dominguez, F. 2010. Snow days? Snowmaking adaptation and the future of low latitude, high-elevation skiing in Arizona, USA. Climatic Change. 102: 467–491.

Baur, J.W.R.; Cerveny, L. 2019. Social impacts of homelessness and long-term occupancy on national forests and grasslands: a national study of U.S. Forest Service law enforcement officers. Landscape and Urban Planning. 184: 69–77.

Bawa, R.S. 2017. Effects of wildfire on the value of recreation in western North America. Journal of Sustainable Forestry. 36: 1–17.

Blahna, D.J.; Cerveny, L.K.; Williams, D.R. [et al.]. 2020. Rethinking “outdoor recreation” to account for the diversity of human experiences and connections to public lands. In: Selin, S.; Cerveny, L.K.; Blahna, D.J.; Miller, A.B., eds. Igniting research for outdoor recreation: linking science, policy, and action. Gen. Tech. Rep. PNW-GTR-987. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 257 p.

Bowker, J.W.; Askew, A.E.; Cordell, H.K. [et al.]. 2012. Outdoor recreation participation in the United States—projections to 2060: a technical document supporting the Forest Service 2010 RPA assessment. Gen. Tech. Rep. GTR-SRS-160. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 34 p.

Bowker, J.M.; Askew, A.E.; Poudyal, N.C. [et al.]. 2013. Climate change and outdoor recreation participation in the Southern United States. In: Vose, J.M.; Klepzig, K.D., eds. Climate change adaptation and mitigation management options: a guide for natural resource managers in the southern forest ecosystems. Boca Raton, FL: CRC Press: 421–450.

Bowler, D.E.; Buyung-Ali, L.M.; Knight, T.M.; Pullin, A.S. 2010. A systematic review of evidence for the added benefits to health of exposure to natural environments. BMC Public Health. 10: 456.

Brandenburg, W.E.; Davis, C.B. 2016. Medical knowledge and preparedness of climbers on Colorado's 14,000-foot peaks. Wilderness & Environmental Medicine. 27: 62–68.

Bristow, R.S.; Jenkins, I. 2018. Travel behaviour substitution for a white-water canoe race influenced by climate induced stream flow. Leisure/Loisir. 42: 25–46.

Clark, R.N.; Stankey, G.H. 1979. The recreation opportunity spectrum: a framework for planning, management, and research. Gen. Tech. Rep. PNW-GTR-098. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 32 p.

Cole, D.N.; Petersen, M.E.; Lucas, R.C. 1987. Managing wilderness recreation use: common problems and potential solutions. Gen. Tech. Rep. INT-230. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 64 p.

Cooper, C.; Larson, L.; Dayer, A. [et al.]. 2015. Are wildlife recreationists conservationists? Linking hunting, birdwatching, and pro-environmental behavior. Journal of Wildlife Management. 79: 446–457.

Cordell, H.K. 2012. Outdoor recreation trends and futures: a technical document supporting the Forest Service 2010 RPA assessment. Gen. Tech. Rep. SRS-150. Asheville, NC: U.S. Department of Agriculture Forest Service, Southern Research Station. 167 p.

Darling, D.J. 2014. Oregon stats show hunting, fishing decline. Bend Bulletin. 29 December 2014. https://www.bendbulletin.com/localstate/oregon-stats-show-hunting-fishing-decline/article_7cb807cc-aef5-59b1-aef3-71edcc35e063.html.

Dawson, J.; Scott, D.; McBoyle, G. 2009. Climate change analogue analysis of ski tourism in the northeastern USA. Climate Research. 39: 1–9.

Duffield, J.W.; Neher, C.J.; Patterson, D.A.; Deskins, A.M. 2013. Effects of wildfire on national park visitation and the regional economy: a natural experiment in the Northern Rockies. International Journal of Wildland Fire. 22: 1155–1166.

Eisenhauer, B.W.; Krannich, R.S.; Blahna, D.J. 2000. Attachments to special places on public lands: an analysis of activities, reason for attachments, and community connections. Society and Natural Resources. 13: 421–441.

Englin, J.; Boxall, P.C.; Chakraborty, K.; Watson, D.O. 1996. Valuing the impacts of forest fires on backcountry forest recreation. Forest Science. 42: 450–455.

Englin, J.; Loomis, J.; González-Cabán, A. 2001. The dynamic path of recreational values following a forest fire: a comparative analysis of states in the Intermountain West. Canadian Journal of Forest Research. 31: 1837–1844.

Englin, J.; Moeltner, K. 2004. The value of snowfall to skiers and boarders. Environmental and Resource Economics. 29: 123–136.

Farnum, J.H.; Hall, T.; Kruger, L.E. 2005. Sense of place in natural resource recreation and tourism: an evaluation and assessment of research findings. Gen. Tech. Rep. PNW-GTR-660. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 59 p.

Fisichelli, N.A.; Schuurman, G.W.; Monahan, W.B.; Ziesler, P.S. 2015. Protected area tourism in a changing climate: Will visitation at U.S. national parks warm up or overheat? PLoS ONE. 10(6): e0128226.

Gergel, D.R.; Nijssen, B.; Abatzoglou, J.T. [et al.]. 2017. Effects of climate change on snowpack and fire potential in the western USA. Climatic Change. 141: 287–299.

Ghahramani, L. 2017. The impacts of the 2017 wildfires on Oregon’s travel and tourism industry. Portland, OR: Oregon Tourism Commission (Travel Oregon). 70 p.

Gobler, C.J. 2020. Climate change and harmful algal blooms: insights and perspective. Harmful Algae. 91: 101731.

Hamilton, L.C.; Hartter, J.; Keim, B.D. [et al.]. 2016. Wildfire, climate, and perceptions in northeast Oregon. Regional Environmental Change. 16: 1819–1832.

Hamlet, A.F. 2000. Effects of climate change scenarios on ski conditions at Snoqualmie Pass, Stevens Pass, Mission Ridge, and Schweitzer Mountain ski areas. Internal report. Seattle, WA: University of Washington, Joint Institute for the Study of Atmosphere and Oceans, Climate Impacts Group.

Hand, M.S.; Lawson, M. 2018. Effects of climate change on recreation in the Northern Rockies Region. In: Halofsky, J.E.; Peterson, D.L.; Hoang, L., eds. Climate change vulnerability and adaptation in the Northern Rocky Mountains [Part 2]. Gen. Tech. Rep. RMRS-GTR-374. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 398–433. Chapter 10.

Hand, M.S.; Peterson, D.L.; Blanchard, B.P. [et al.]. 2019. Climate change and recreation in south-central Oregon. In: Halofsky, J.E.; Peterson, D.L.; Ho, J.J., eds. Climate change vulnerability and adaptation in south-central Oregon. Gen. Tech. Rep. PNW-GTR-974. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 363–402. Chapter 8.

Hand, M.S.; Smith, J.W.; Peterson, D.L. [et al.]. 2018. Effects of climate change on outdoor recreation. In: Halofsky, J.E.; Peterson, D.L.; Ho, J.J., eds. Climate change vulnerability and adaptation in the Intermountain Region [Part 2]. Gen. Tech. Rep. RMRS-GTR-375. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 316–338. Chapter 10.

Hay, M.J.; McConnell, K.E. 1979. An analysis of participation in nonconsumptive wildlife recreation. Land Economics. 55: 460–471.

Hesseln, H.; Loomis, J.B.; González-Cabán, A. 2004. The effects of fire on recreation demand in Montana. Western Journal of Applied Forestry. 19: 47–53.

Hesseln, H.; Loomis, J.B.; González-Cabán, A.; Alexander, S. 2003. Wildfire effects on hiking and biking demand in New Mexico: a travel cost study. Journal of Environmental Management. 69: 359–368.

Irland, L.C.; Adams, D.; Alig, R. [et al.]. 2001. Assessing socioeconomic impacts of climate change on U.S. forests, wood-product markets, and forest recreation. BioScience. 51: 753–764.

Jones, R.; Travers, C.; Rodgers, C. [et al.]. 2013. Climate change impacts on freshwater recreational fishing in the United States. Mitigation and Adaptation Strategies for Global Change. 18: 731–758.

Klos, P.Z.; Link, T.E.; Abatzoglou, J.T. 2014. Extent of the rain-snow transition zone in the Western U.S. under historic and projected climate. Geophysical Research Letters. 41: 4560–4568.

Lamborn, C.C.; Smith, J.W. 2019. Human perceptions of, and adaptations to, shifting runoff cycles: a case-study of the Yellowstone River (Montana, USA). Fisheries Research. 216: 96–108.

Loomis, J. 1995. Four models for determining environmental quality effects on recreational demand and regional economics. Ecological Economics. 12: 55–65.

Loomis, J.B.; Crespi, J. 2004. Estimated effects of climate change on selected outdoor recreation activities in the United States. In: Mendelsohn, R.; Neumann, J.E., eds. The impact of climate change on the United States economy. Cambridge, United Kingdom: Cambridge University Press: 289–314.

Loomis, J.B.; Richardson, R.B. 2006. An external validity test of intended behavior: comparing revealed preference and intended visitation in response to climate change. Journal of Environmental Planning and Management. 49: 621–630.

Loomis, J.; González-Cabán, A.; Englin, J. 2001. Testing for differential effects of forest fires on hiking and mountain biking demand and benefits. Journal of Agricultural and Resource Economics. 26: 508–522.

Manning, R. 2010. Studies in outdoor recreation: search and research for satisfaction. 3rd ed. Corvallis, OR: Oregon State University Press. 448 p.

Matzarakis, A.; de Freitas, C.R. 2001. Proceedings of the first international workshop on climate, tourism, and recreation. Milwaukee, WI: International Society of Biometeorology, University of Wisconsin-Milwaukee. 150 p.

Mendelsohn, R.; Markowski, M. 2004. The impact of climate change on outdoor recreation. In: Mendelsohn, R.; Neumann, J., eds. The impact of climate change on the United States economy. Cambridge, United Kingdom: Cambridge University Press: 267–288.

Miller, A.B.; Winter, P.L.; Sanchez, J.J. [et al.] 2022. Climate change and recreation in the western United States: effects and opportunities for adaptation. Journal of Forestry. https://doi.org/10.1093/jofore/fvab072.

Miller, J.R.; Hay, M.J. 1981. Determinants of hunter participation: duck hunting in the Mississippi flyway. American Journal of Agricultural Economics. 63: 401–412.

Milon, J.W.; Clemmons, R. 1991. Hunters' demand for species variety. Land Economics. 67: 401–412.

Moore, K.M. 2015. Optimizing reservoir operations to adapt to 21st century expectations of climate and social change in the Willamette River Basin, Oregon. Corvallis, OR: Oregon State University. 183 p. Ph.D. dissertation.

Morey, E.R.; Breffle, W.S.; Rowe, R.D.; Waldman, D.M. 2002. Estimating recreational trout fishing damages in Montana's Clark Fork River basin: summary of a natural resource damage assessment. Journal of Environmental Management. 66: 159–170.

Morris, S.; Walls, M. 2009. Climate change and outdoor recreation resources. Backgrounder Rep. Washington, DC: Resources for the Future. 28 p.

Mote, P.W. 2013. Climate change in the Northwest. The Long View. Winter 2013: 6–8.

Mote, P.W.; Casson, J.; Hamlet, A.; Reading, D. 2008. Sensitivity of Northwest ski areas to warming. In: McGurk, B., ed. Proceedings of the 75th western snow conference. Soda Springs, CA: Western Snow Conference: 63–67.

Mote, P.W.; Li, S.; Lettenmaier, D.P. [et al.]. 2018. Dramatic declines in snowpack in the Western U.S. Climate and Atmospheric Science. 1: 2.

Nickerson, N.P. 2016. What we know about crowding and visitor experiences. Res. Pub. 340. Missoula, MT: University of Montana, Institute for Tourism and Recreation. 6 p.

Nielsen-Pincus, M.; Moseley, C.; Gebert, K. 2014. Job growth and loss across sectors and time in the Western U.S.: the impact of large wildfires. Forest Policy & Economics. 38: 199–206.

Njus, E. [N.d.] Oregon 9th fastest-growing state; Idaho leads pack. The Oregonian/ OregonLive. https://www.oregonlive.com/business/2017/12/oregon_9th_fastest-growth_stat.html. (18 April 2019).

O'Toole, D.; Brandt, L.A.; Janowiak, M.K. [et al.]. 2019. Climate change adaptation strategies and approaches for outdoor Recreation. Sustainability. 1(24): 7030. https://doi.org/10.3390/su11247030.

Orr, M.; Schneider, I. 2018. Substitution interests among active-sport tourists: the case of a cross-country ski event. Journal of Sport and Tourism. 22: 315–332.

Pacific Crest Trail Association [PCTA]. 2019. 2,600 miler list. https://www.pcta.org/discover-the-trail/thru-hiking-long-distance-hiking/2600-miler-list. (10 December 2019).

Paerl, H.W.; Huisman, J. 2008. Blooms like it hot. Science. 320: 57–58.

Pitts, H.M.; Thacher, J.A.; Champ, P.A.; Berrens, R.P. 2012. A hedonic price analysis of the outfitter market for trout fishing in the Rocky Mountain West. Human Dimensions of Wildlife. 17: 446–462.

Procter, E.; Brugger, H.; Burscher, M. 2018. Accidental hypothermia in recreational activities in the mountains: a narrative review. Scandinavian Journal of Medicine and Science in Sports. 28: 2464–2472.

Rausch, M.; Boxall, P.C.; Verbyla, A.P. 2010. The development of fire-induced damage functions for forest recreation activity in Alberta, Canada. International Journal of Wildland Fire. 19: 63–74.

Richardson, L.A.; Champ, P.A.; Loomis, J.B. 2012. The hidden costs of wildfires: economic valuation of health effects of wildfire smoke exposure in southern California. Journal of Forest Economics. 18: 14–35.

Richardson, R.B.; Loomis, J.B. 2004. Adaptive recreation planning and climate change: a contingent visitation approach. Ecological Economics. 50: 83–99.

Rudzitis, G. 1999. Amenities increasingly draw people to the rural West. Rural Developmental Perspectives. 14: 9–13.

Sachdeva, S. 2020. Using social media for research and monitoring the changing landscape of public land use. In: Selin, S.; Cerveny, L.K.; Blahna, D.J.; Miller, A.B., eds. Igniting research for outdoor recreation: linking science, policy, and action. Gen. Tech. Rep. PNW-GTR-987. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 257 p. Chapter 17.

Sage, J.L.; Nickerson, N.P. 2017. The Montana expression 2017: 2017's costly fire season. Res. Pub. 363. Missoula, MT: University of Montana, Institute for Tourism and Recreation. 17 p.

Sánchez, J.J.; Baerenklau, K.; Gonzalez-Caban, A. 2016. Valuing hypothetical wildfire impacts with a Kuhn-Tucker model of recreation demand. Forest Policy and Economics. 71: 63–70.

Schultz, J.; Svajda, J. 2017. Examining crowding among winter recreationists in Rocky Mountain National Park. Tourism Recreation Research. 42: 84–95.

Scott, D.; Dawson, J.; Jones, B. 2008. Climate change vulnerability of the U.S. Northeast winter recreation-tourism sector. Mitigation and Adaptation Strategies for Global Change. 13: 577–596.

Scott, D.; Jones, B.; Konopek, J. 2007. Implications of climate and environmental change for nature-based tourism in the Canadian Rocky Mountains: a case study of Waterton Lakes National Park. Tourism Management. 28: 570–579.

Scott, D.; McBoyle, G. 2007. Climate change adaptation in the ski industry. Mitigation and Adaptation Strategies for Global Change. 12: 1411–1431.

Seekamp, E.; Cerveny, L.K.; McCreary, A. 2011. Institutional, individual, and socio-cultural domains of partnerships: a typology of USDA Forest Service recreation partners. Environmental Management. 48: 615–630.

Shaw, D.; Loomis, J. 2008. Frameworks for analyzing the economic effects of climate change on outdoor recreation and selected estimates. Climate Research. 36: 259–269.

Smith, J.W.; Davenport, M.A.; Anderson, D.H.; Leahy, J.E. 2011. Place meanings and desired management outcomes. Landscape and Urban Planning, 101: 359–370.

Smith, J.W.; Moore, R.L. 2013. Social-psychological factors influencing recreation demand: evidence from two recreational rivers. Environment and Behavior. 45: 821–850.

Smith, J.W.; Seekamp, E.; McCreary, A. [et al.]. 2016. Shifting demand for winter outdoor recreation along the North Shore of Lake Superior under variable rates of climate change: a finite-mixture modeling approach. Ecological Economics. 123: 1–13.

Starbuck, C.M.; Berrens, R.P.; McKee, M. 2006. Simulating changes in forest recreation demand and associated economic impacts due to fire and fuels management activities. Forest Policy Economics. 8: 52–66.

Stedman, R. 2003. Sense of place and forest science: toward a program of quantitative research. Forest Science. 49: 822–829.

Stratus Consulting. 2009. Climate change in Park City: an assessment of climate, snowpack, and economic impacts. Report prepared for The Park City Foundation. Boulder, CO: Stratus Consulting, Inc. https://parkcitycf.org/wp-content/uploads/2015/11/Park.City_.Climate.Change.Assessment.9.29.2009.pdf. (7 July 2017).

Thompson Coon, J.; Boddy, K.; Stein, K. [et al.]. 2011. Does participating in physical activity in outdoor natural environments have a greater effect on physical and mental well-being than physical activity indoors? A systematic review. Environmental Science and Technology. 45: 1761–1772.

Timberline Lodge. 2019. Historical snow data. https://www.timberlinelodge.com/mountain/historical-snow-data. (14 March 2019).

U.S. Department of Agriculture, Forest Service [USDA FS]. 1990. ROS primer and field guide. Washington, DC: Recreation staff.

U.S. Department of Agriculture, Forest Service [USDA FS]. 2010. Connecting people with America's great outdoors: a framework for sustainable recreation. http://www.fs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb5346549.pdf. (7 July 2017).

U.S. Department of Agriculture, Forest Service [USDA FS]. 2012a. Future of America's forest and rangelands: Forest Service 2010 Resources Planning Act assessment. Gen. Tech. Rep. WO-87. Washington, DC: U.S. Department of Agriculture, Forest Service. 198 p.

U.S. Department of Agriculture, Forest Service [USDA FS]. 2012b. National Forest System land management planning. 36 CFR Part 219. RIN 0596-AD02. Federal Register. 77(68): 21162–21276.

U.S. Department of Agriculture, Forest Service [USDA FS]. [N.d.]. Timeline of the Eagle Creek Fire. https://usfs.maps.arcgis.com/apps/Cascade/index.html?appid=d2a772ec2fb14555a51a0ac0a08a1116. (14 March 2019).

White, E.M.; Bowker, J.M.; Askew, A.E. [et al.]. 2016. Federal outdoor recreation trends: effects on economic opportunities. Gen. Tech. Rep. PNW-GTR-945. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 46 p.

White, E.M.; Stynes, D.J. 2008. National forest visitor spending averages and the influence of trip-type and recreation activity. Journal of Forestry. 116: 17–24.

Wobus, C.; Small, E.E.; Hosterman, H. [et al.]. 2017. Projected climate change impacts on skiing and snowmobiling: a case study of the United States. Global Environmental Change. 45: 1–14.

Yen, S.T.; Adamowicz, W.L. 1994. Participation, trip frequency and site choice: a multinomial-Poisson hurdle model of recreation demand. Canadian Journal of Agricultural Economics. 42: 65–76.

Yoder, J.K.; Ohler, A.M.; Chouinard, H.H. 2014. What floats your boat? Preference revelation from lotteries over complex goods. Journal of Environmental Economics and Management. 67: 412–430.

Chapter 8: Climate Change Effects on Ecosystem Services

Robert W. Hoyer, Nikola M. Smith, Steven A. Acker, Cheryl A. Friesen,
Duncan C. McKinley, and Rebecca A. Gravenmier[1]

Introduction

Ecosystem services are the benefits people receive from nature. They are critical building blocks of human societies. A global analysis of human dependence on natural systems known as the Millennium Ecosystem Assessment found that 60 percent of these goods and services are declining faster than they can recover (MEA 2005). This is partly because relationships between ecological conditions and flows of benefits are poorly understood or inadequately considered in resource decision making. The Millennium Ecosystem Assessment drew attention to these critical goods and services by highlighting their importance in four primary categories: (1) **provisioning services** such as food, fiber, energy and water; (2) **regulating services** such as erosion and flood control, water and air purification, and temperature regulation; (3) **cultural services** such as spiritual connections with the land, history, heritage, and recreation; and (4) **supporting services** or the foundations of systems such as soil formation, nutrient cycling, and pollination.

Climate change will affect key goods and services, such as water availability and quality, flow regulation, pollinator-plant interactions, and forest products (Montoya and Raffaelli 2010, Mooney el al. 2009). Higher incidences of environmental extremes (e.g., droughts, floods, fires) could hinder the ability of an ecosystem to provide vital services to human populations. Understanding the underlying biophysical interactions that produce ecosystem services can inform actions that mitigate negative impacts, increase resilience, and facilitate adaptation over time (Seidl et al. 2016).

There have been increased efforts to integrate the concept of ecosystem services into U.S. Department of Agriculture, Forest Service (Forest Service) policy and practice. In 2013, the Forest Service chartered the National Ecosystem Services Strategy Team. This team, made up of scientists and resource managers within the National Forest System, State and Private Forestry, and the Pacific Northwest

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[1] **Robert W. Hoyer** is a climate change program associate, Pacific Northwest Region and Pacific Northwest Research Station, Forestry Sciences Laboratory, 1220 SW 3rd Avenue, Portland, OR 97204; **Nikola M. Smith** is the regional partnership coordinator, Pacific Northwest Region, 1220 SW 3rd Avenue, Portland, OR 97204; **Steve A. Acker** is an ecologist (retired), Pacific Northwest Region, Area Ecology Program, 16400 Champion Way, Sandy, OR 97055; **Cheryl A. Friesen** is a science liaison, Willamette National Forest, McKenzie River Ranger District, 57600 McKenzie Highway, McKenzie Bridge, OR 97413; **Duncan C. McKinley** is a program specialist, Office of Sustainability and Climate Change, 201 14th Street SW, Washington, DC 20250; **Rebecca A. Gravenmier** (retired) is a science coordinator and regional climate change coordinator, Pacific Northwest Research Station and Pacific Northwest Region, 1220 SW 3rd Avenue, Portland, OR 97204.

Research Station, was tasked with finding opportunities to incorporate ecosystem services into Forest Service programs and operations. Recommendations were published in a report in Deal et al. (2017).

The Forest Service 2012 Planning Rule (36 CFR 219) requires national forests to take ecosystem services into consideration when revising land management plans. This chapter highlights the priority climate change effects on ecosystem services that may be considered during forest planning. Climate change vulnerability assessments inform the land management plan revision process by analyzing potential climate change effects relevant to land management. By including ecosystem services in climate change vulnerability assessments, the information gathered can be more easily incorporated once plan revision begins.

This chapter analyzes several key ecosystem services: forest products, livestock grazing, forest carbon, pollinator services, cultural services valued by tribes and recreationists, and water. These were chosen in consultation with staff at Columbia River Gorge National Scenic Area (CRGNSA), Mount Hood National Forest (NF), and Willamette NF, hereafter referred to as the CMWAP. This informal process identified services known to be valued by forest user groups and the public at large. By focusing on a limited selection of important services, the assessment aims to provide the most salient information on climate change effects on key ecosystem services for the CMWAP assessment area. This mirrors the criteria outlined in the 2012 Planning Rule directives, which advises resource managers to focus on key ecosystem services in forest plan revision that are (1) important outside the planning area and (2) can be affected by Forest Service decision making. Ecosystem services covered in this chapter are representative of all four categories (provisioning, regulating, cultural, supporting), thus providing a broad perspective on potential resource benefits.

Forest Products

One of the management objectives of the Forest Service is to ensure a sustainable supply of forest products. Willamette NF (684 000 ha) and Mount Hood NF (411 000 ha) supply significant volumes of wood products, including timber, biomass, posts and poles, and firewood (figs. 8.1 and 8.2). The volumes taken from both forests, however, do not reach the probable sale quantity, or estimates of maximum annual sustainable harvest levels that were developed for the Northwest Forest Plan (USDA and USDI 1994). State and private forest lands in the CRGNSA (118 000 ha) also produce a notable volume of forest products. The CRGNSA land base managed by the National Forest System is smaller (40 500 ha) and is generally not managed for timber; its output is attributed to Mount Hood or Gifford Pinchot NFs depending on which side of the Columbia River a harvest takes place.

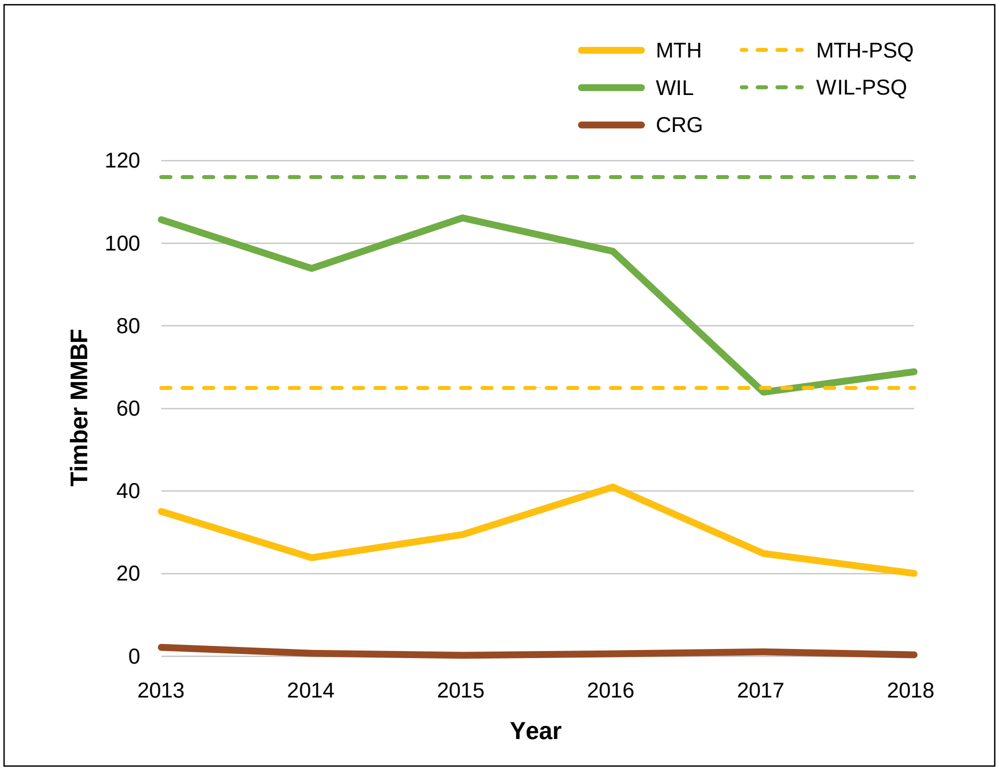

Figure 8.1—Annual cut of sawtimber in million board feet (MMBF) for Mount Hood National Forest (MTH), Willamette National Forest (WIL), and Columbia River Gorge National Scenic Area (CRG) from 2013 to 2018. Probable sale quantity (PSQ) is the estimate of annual sustainable harvest for the unit developed for the Northwest Forest Plan.

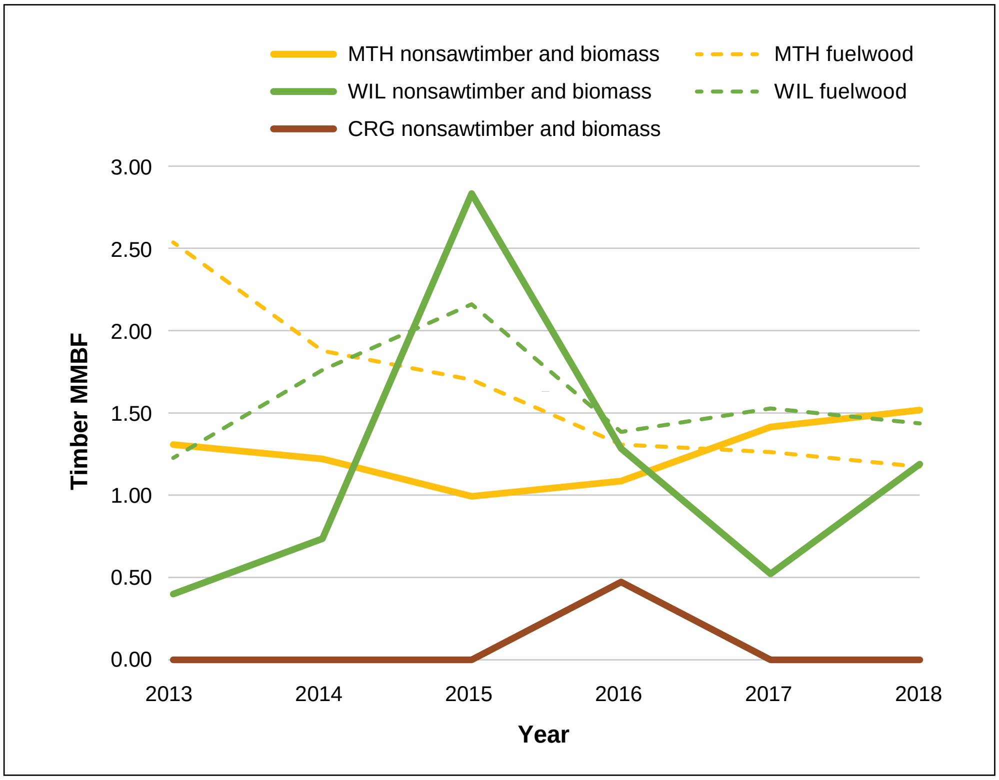

Figure 8.2—Annual output of nonsawtimber wood products in million board feet (MMBF) for Mount Hood National Forest (MTH), Willamette National Forest (WIL), and Columbia River Gorge National Scenic Area (CRG) from 2013 to 2018.

Climate change is expected to affect timber and forest products by altering vegetation productivity and disturbance regimes. Increased levels of carbon dioxide (CO_2) may increase forest productivity, particularly in moist forests with adequate water supply (chapter 5). The MC2 dynamic global vegetation model projected increases in vegetation productivity by the end of the 21st century across most of the CMWAP assessment area, with the exception of the drier, eastern portion of CRGNSA (see chapter 5). These productivity increases may result in increased timber production for some forests. However, water limitations with increasing temperatures may limit or negate this increased productivity (MC2 does not fully account for potential effects of water limitation), potentially reducing the amount of merchantable timber and other harvested forest products.

The greatest effects of climate change on forest management may come from changes in disturbance regimes rather than changes in forest productivity (Kirilenko and Sedjo 2007). Increased frequency or severity of drought-induced disturbances, such as insect outbreaks (Hicke et al. 2006) and wildfire (McKenzie et al. 2004), are anticipated to cause widespread tree mortality (see chapter 5). These disturbances are likely to lead to losses in available green timber as well as a potential shift to more dead material harvested through salvage or biomass sales. Fuels reduction projects could also increase timber harvest. For example, the "bump" in biomass seen in figure 8.2 in 2015 on the Willamette NF was related to a fuels reduction project in the Hoodoo wildland-urban interface. More fuels reduction and salvage harvest activity may occur in the future with climate change.

Biophysical changes in forest vegetation will have implications for local and regional socioeconomic conditions, affecting industries and communities that are dependent on timber and nontimber forest products. Climate change is expected to alter supply and demand of timber products in the global market, with cascading effects on prices (Kirilenko and Sedjo 2007). New technologies may help communities adapt to changing conditions through better use of timber resources and a more diverse timber market in the future.

Timber

Generation of forest products in the CMWAP assessment area differs by unit. For timber volume sold between fiscal years 2013 and 2018, Willamette NF had the highest production of any national forest in Oregon and Washington, averaging 74.3 million board feet (MMBF) per year. Mount Hood NF is more representative of other national forests in the region, averaging 33.7 MMBF per year. Management of National Forest System lands in CRGNSA emphasizes conservation and recreation, with timber volume averaging 0.1 MMBF (Huber-Stearns et al. 2016). Local unit reporting for the fiscal years 2013–2018 illustrates the variability among CMWAP units for sawtimber, nonsawtimber, and firewood (figs. 8.1 and 8.2).

Nontimber Forest Products

A national assessment of nontimber forest products (NTFPs) in the United States under changing climate conditions concluded that disturbances, such as drought, wildfires, and insect outbreaks, are affecting habitat quality and access to valued NTFPs in the Pacific Northwest (Chamberlain et al. 2018). Residents of the Pacific Northwest harvest hundreds of NTFPs for cultural, subsistence, recreational, craft, and commercial purposes (Hansis et al. 2001). In some areas, increased awareness of opportunities for commercial harvest have created conflict and competition among some harvester groups. Mount Hood and Willamette NFs have permit programs for harvest of NTFPs (CRGNSA does not). Commonly harvested NTFPs are listed in table 8.1, and recent trends in the harvest of NTFPs for each CMWAP unit are in figures 8.3 through 8.10.

As climate change affects vegetation in the assessment area, the availability of and access to NTFPs will also change, affecting those who derive benefits from them. Each plant species that provides these products will respond individually to climate change, affecting the quantity, quality, and seasonality of plant materials. The magnitude and rate of changes are uncertain, and spatial and temporal patterns are likely to be obscured by interannual variation. In many cases, desired qualities, spatial distribution, and abundance of NTFP species are associated with a particular forest seral stage, time since disturbance, or severity of the disturbance. Challenges will likely arise around the temporal and spatial periodicity of NTFPs based on disturbances and integrity of habitats. Suitable habitat for some NTFPs is

Table 8.1—Primary nontimber forest products harvested in the Northwest

Category	Products
Basketry	California hazelnut (*Corylus cornuta* ssp. *californica* [A. DC.] A.E. Murray), Sitka spruce (*Picea sitchensis* [Bong.] Carrière), western redcedar (*Thuja plicata* Donn ex D. Don), Alaska cedar (*Callitropsis nootkatensis* [D. Don] D.P. Little), pines (*Pinus* spp.), beargrass (*Xerophyllum tenax* [Pursh] Nutt.), dyes from lichens and berries
Poles, unique branches	Subsistence fishing and hunting construction materials, carvings, crafts
Food	Huckleberries (*Vaccinium* spp.), salmonberry (*Rubus spectabilis* Pursh), thimbleberry (*R. parviflorus* Nutt.), western raspberry (*R. leucodermis* Douglas ex Torr. & A. Gray), trailing blackberry (*R. ursinus* Cham. & Schltdl.), Pacific serviceberry (*Amelanchier alnifolia* [Nutt.] Nutt. ex M. Roem.), western chokecherry (*Prunus virginiana* var. *demissa* [Nutt.] Torr.), silver buffaloberry (*Shepherdia argentea* [Pursh] Nutt.), roots (e.g., camas [*Camassia quamash* {Pursh} Greene], lilies (*Lillium* spp. L.)), mosses and ferns, mushrooms
Medicinal	Foliage, bark rots of shrubs and trees
Floral industry	Salal (*Gaultheria shallon* Pursh), branches, cones
Transplants, trees	Christmas trees, small conifers, ferns, various shrubs

Source: Chamberlain et al. 2018.

anticipated to remain the same, but as the environment changes, so will the ranges of many species (Fettig et al. 2013). The capacity of NTFP harvesters to anticipate when and where NTFPs will occur across the landscape in response to climate-associated disturbances remains to be seen (Chamberlain et al. 2018).

Access to NTFPs may also be affected by shifting human demography and recreation patterns (chapter 7), as well as climate change effects on road access (chapter 3). The human population in the CMWAP region is expected to continue to experience growth over the next 50 years (PRC PSU 2020), and with population growth, there will be more users of federal lands and likely more demand for NTFPs. User group conflicts, particularly in years of low production of products for which demand is high, could arise in some locations if yields are low for several consecutive years. Shifting recreation patterns (chapter 7) will also likely affect NTFP gathering. This could mean more intense gathering in the shoulder (spring and fall) seasons when staffing and infrastructure might not be in place to support those activities.

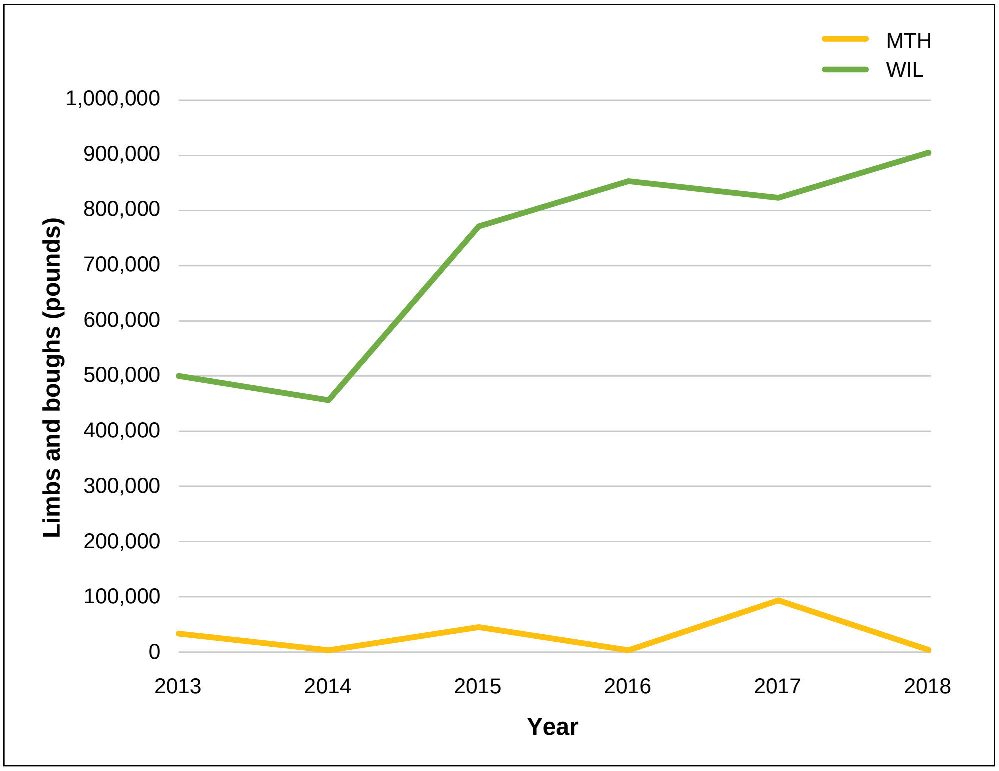

Figure 8.3—Annual output of limbs and boughs in pounds for Mount Hood National Forest (MTH) and Willamette National Forest (WIL) from 2013 to 2018 (Columbia River Gorge National Scenic Area does not have a permitting program and does not collect data on limbs and boughs harvesting).

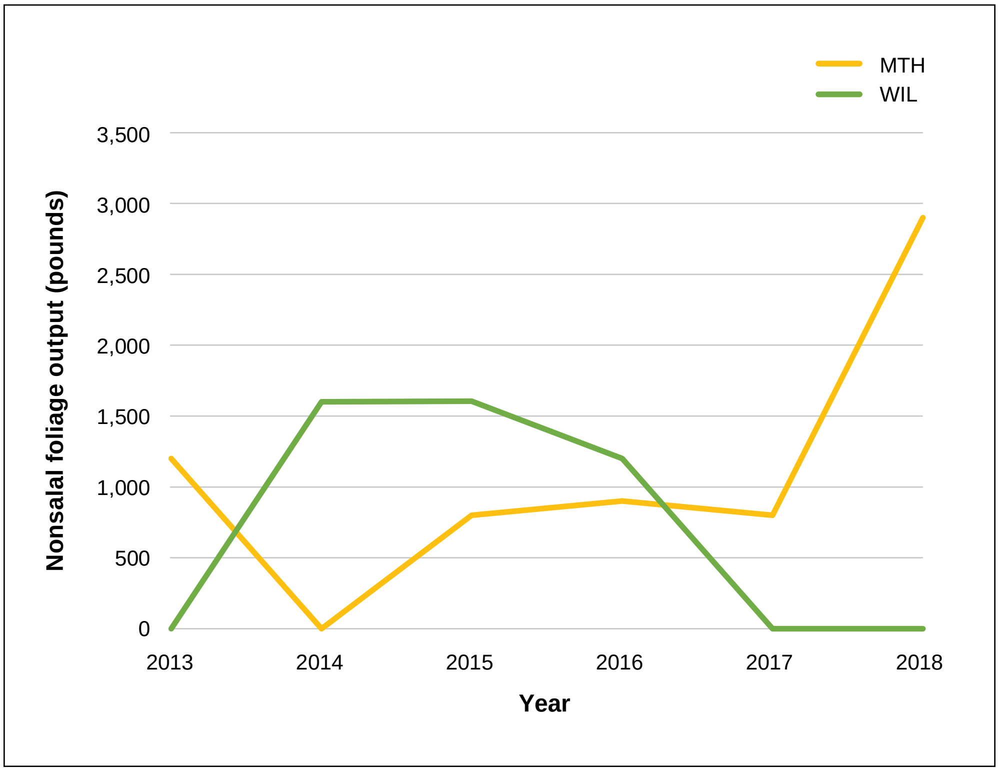

Figure 8.4—Annual output of nonsalal (*Gaultheria shallon* Pursh) foliage in pounds for Mount Hood National Forest (MTH) and Willamette National Forest (WIL) from 2013 to 2018 (Columbia River Gorge National Scenic Area does not have a permitting program and does not collect data on nonsalal foliage harvesting).

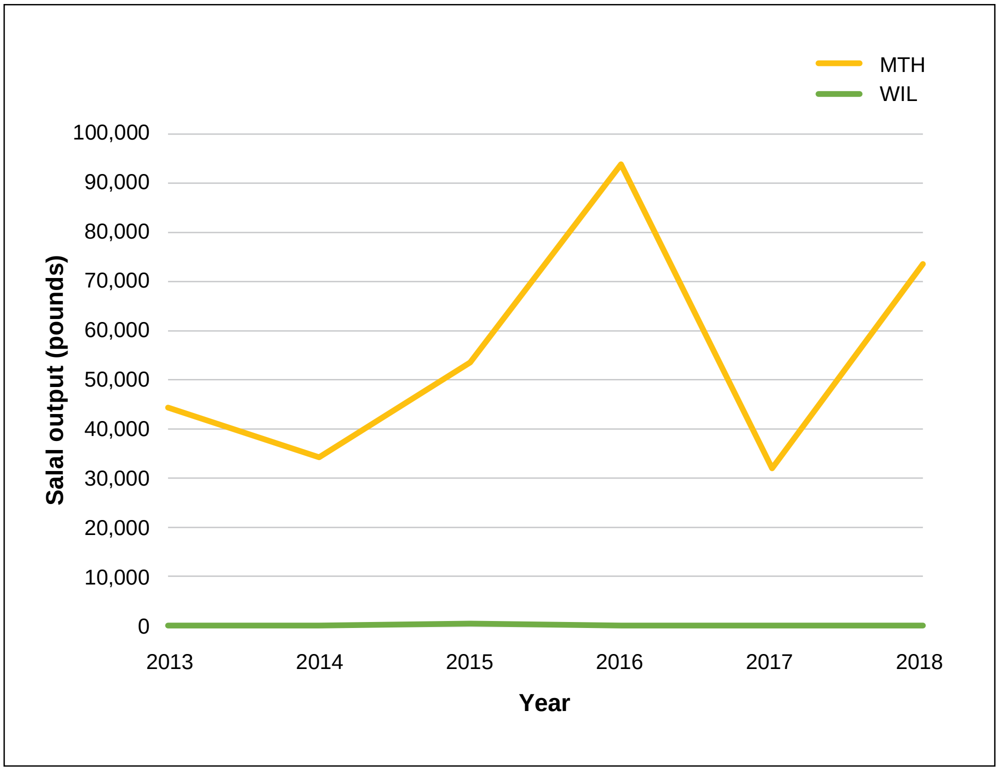

Figure 8.5—Annual output of salal (*Gaultheria shallon* Pursh) in pounds for Mount Hood National Forest (MTH) and Willamette National Forest (WIL) from 2013 to 2018 (Columbia River Gorge National Scenic Area does not have a permitting program and does not collect data on salal harvesting).

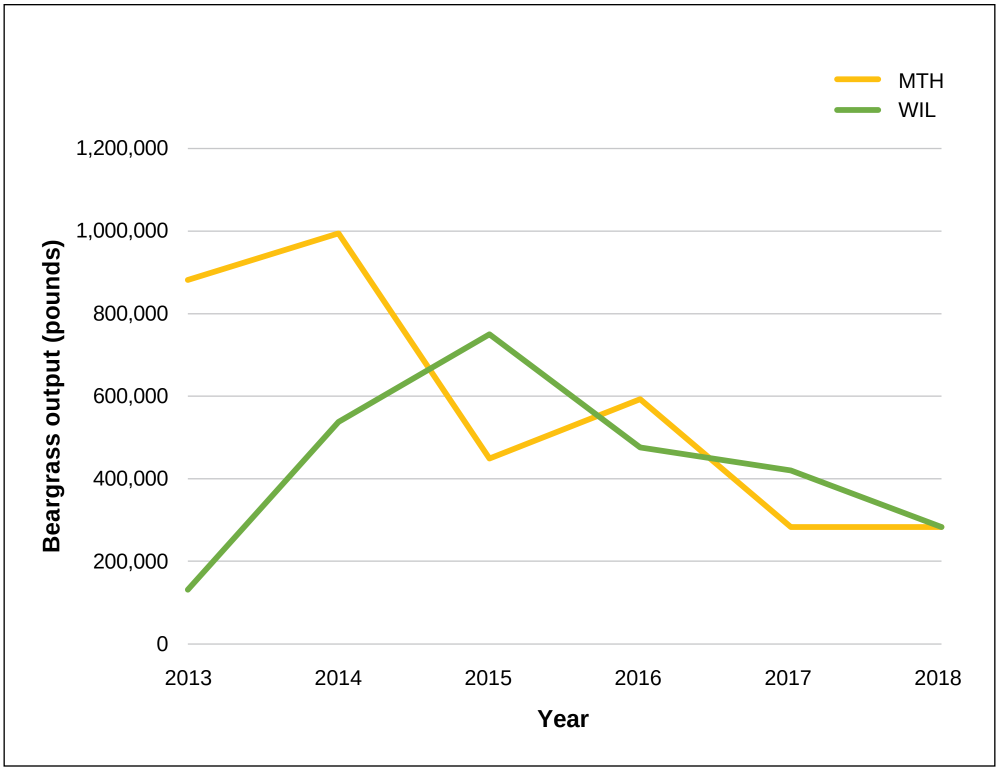

Figure 8.6—Annual output of beargrass (*Xerophyllum tenax* [Pursh] Nutt.) in pounds for Mount Hood National Forest (MTH) and Willamette National Forest (WIL) from 2013 to 2018 (Columbia River Gorge National Scenic Area does not have a permitting program and does not collect data on beargrass harvesting).

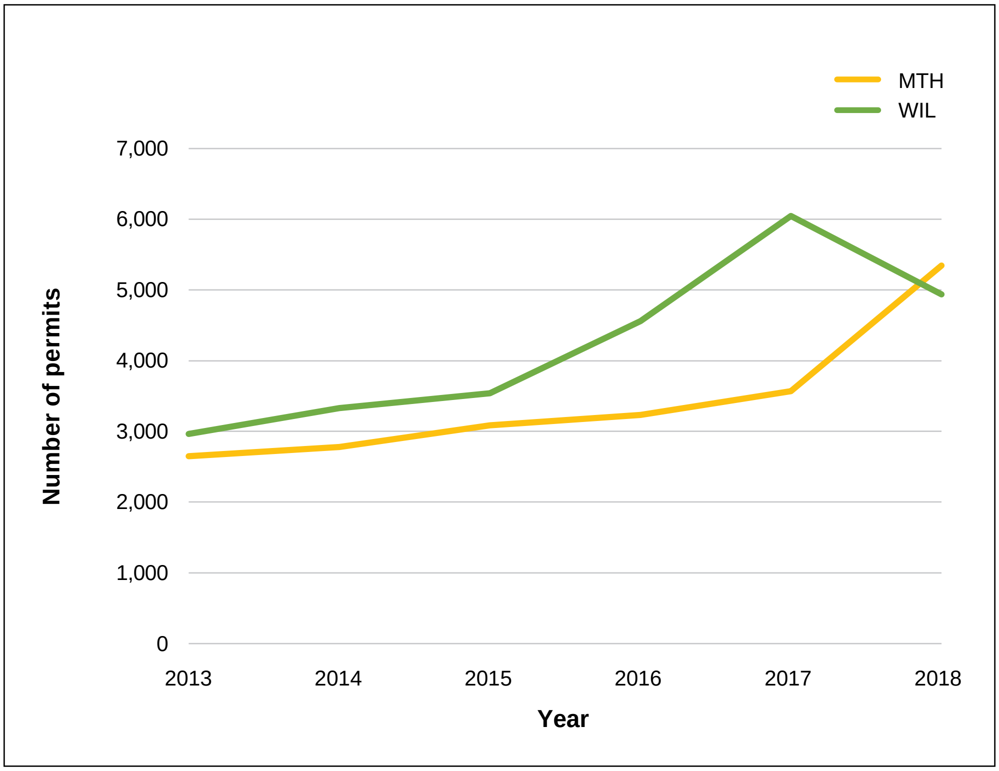

Figure 8.7—Annual permits issued for Christmas trees for Mount Hood National Forest (MTH) and Willamette National Forest (WIL) from 2013 to 2018 (Columbia River Gorge National Scenic Area does not have a permitting program and does not collect data on Christmas tree harvesting).

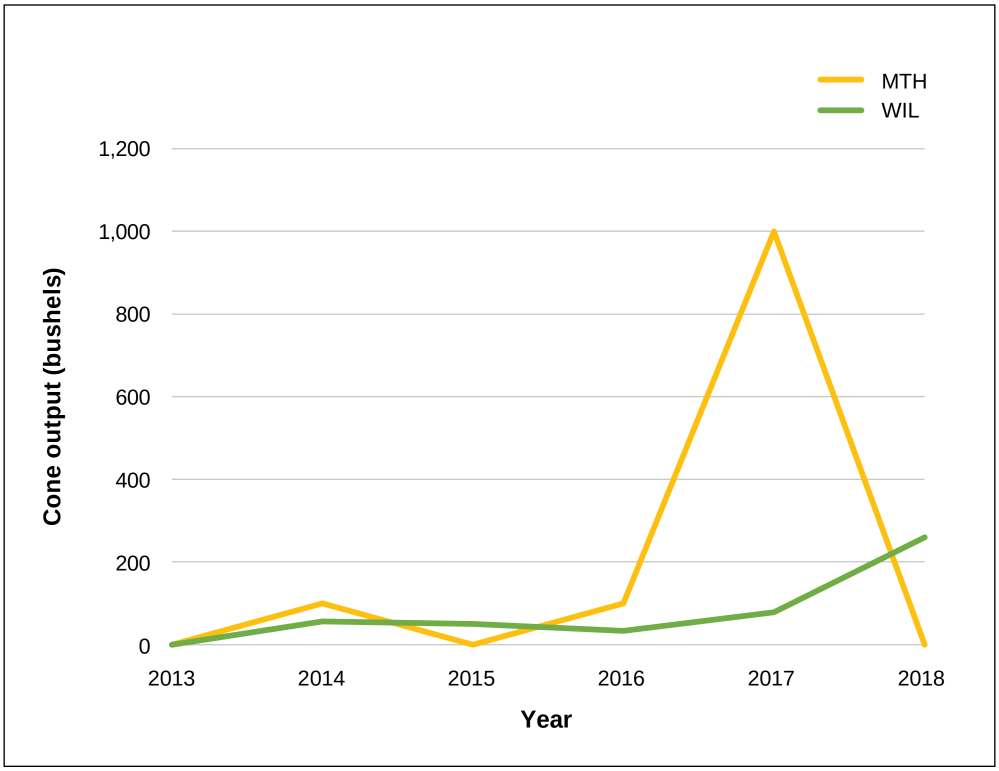

Figure 8.8—Annual output of cones in bushels for Mount Hood National Forest (MTH) and Willamette National Forest (WIL) from 2013 to 2018 (Columbia River Gorge National Scenic Area does not have a permitting program and does not collect data on cone harvesting).

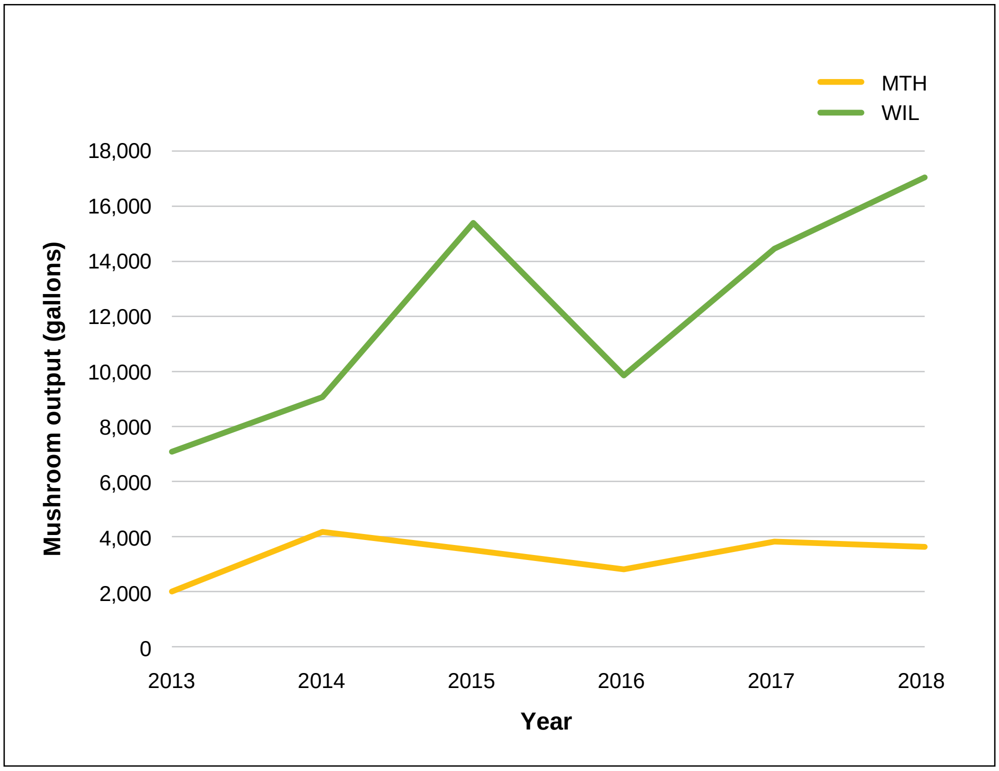

Figure 8.9—Annual output of mushrooms in gallons for Mount Hood National Forest (MTH) and Willamette National Forest (WIL) from 2013 to 2018 (Columbia River Gorge National Scenic Area does not have a permitting program and does not collect data on mushroom harvesting).

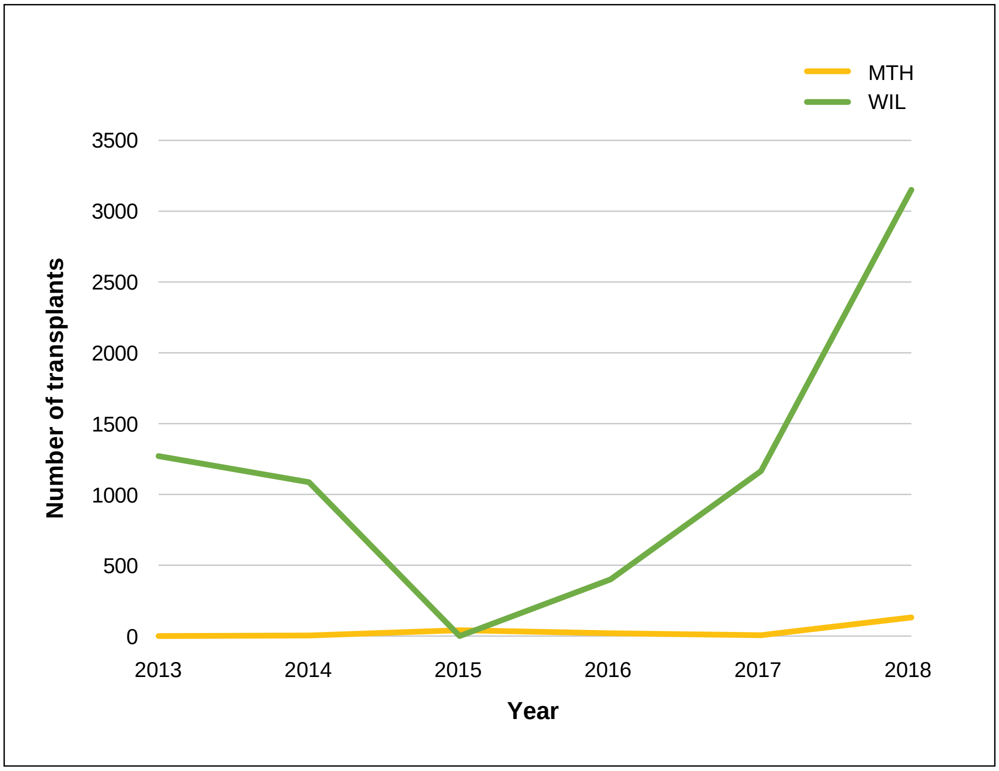

Figure 8.10—Annual output of transplants for Mount Hood National Forest (MTH) and Willamette National Forest (WIL) from 2013 to 2018 (Columbia River Gorge National Scenic Area does not have a permitting program and does not collect data on transplant harvesting).

Livestock Grazing

Livestock forage is a minor ecosystem service in the CMWAP assessment area (table 8.2). Counties served by the CMWAP units (Clackamas, Hood River, Klickitat, Lane, Linn, Marion, Multnomah) represented just over 8 percent of cattle and calves in Oregon in 2018 (USDA 2018).

Altered winter and spring precipitation could translate into effects on rangeland vegetative species composition and distribution (chapter 5), with implications for forage availability and quality. Unmanaged or excessive grazing, as well as other historical activities, have been associated with the spread and dominance of nonnative grasses in some locations. Cheatgrass (*Bromus tectorum* L.), medusahead (*Taeniatherum caput-medusae* [L.] Nevski), and North Africa grass (*Ventenata dubia* [Leers] Coss.) are invaders that alter fire regimes and disrupt ecosystem structure and function. Cheatgrass has been associated with higher fine fuel quantities, greater fuel continuity, and lower fuel moisture, increasing the burn flammability (Davies and Nafus 2013). In a warmer climate, it is possible that cheatgrass and other invasive annual grasses will increase in extent (chapter 5).

Rangeland managers may need to shift the duration and timing of grazing as conditions change. Some studies suggest that dormant season (winter) grazing could reduce the spread of nonnative grasses and wildfire probability (Davies et al.

Table 8.2—Grazing head months (HMs) and animal unit months (AUMs) and allotments for the Columbia River Gorge National Scenic Area (NSA), Mount Hood National Forest (NF), and Willamette NF Adaptation Partnership assessment area[a]

Forest/district	Class	Livestock permitted (cow/calf pairs)	HMs permitted	AUMs permitted
Mount Hood NF	Cattle	330	1,369	1,807
Columbia River Gorge NSA	Cattle	34	89	117
Willamette NF	None			

	Allotments			
	Active	Vacant	Closed	Combined
Mount Hood NF	2	4	0	0
Columbia River Gorge NSA	1	0	20	0
Willamette NF	None			

[a] Fiscal year 2017 data from the U.S. Forest Service INFRA database, in consultation with local staff.

2015). On drier sites, more fire and decreased forest density may lead to increased grass abundance, though some species may be invasive (chapter 5). Refinement of ecological site descriptions could help managers adapt grazing management to changing conditions by evaluating land use suitability, responding to different management activities or disturbance processes, and sustaining productivity over the long term (USDA NRCS 2020). Adaptive management will be necessary to manage sites that become more sensitive to climate change (e.g., riparian areas, wetlands, and groundwater-dependent ecosystems).

Forest Carbon

Carbon sequestration refers to the long-term uptake and storage of carbon by forests in biomass and soils. The cycling of carbon through a forest ecosystem is a dynamic process, involving carbon uptake via photosynthesis and growth and carbon release via respiration, decomposition, and disturbance. As a regulating ecosystem service, carbon sequestration by forests helps to maintain or reduce atmospheric CO_2 concentrations, with climate implications (USDA FS 2015).

Currently, forests of North America, including most forests on National Forest System lands, are a net carbon sink, meaning they are taking up and storing more carbon than they are releasing (Pan et al. 2011). The carbon taken up by U.S. forests is equivalent to about 11.5 percent of total annual CO_2 emissions (US EPA 2018), making forests the country's largest terrestrial carbon sink. The National Forest System accounts for 20 percent of all forest land area in the United States and about 25 percent of all carbon stored in U.S. forests (excluding interior Alaska) (USDA FS 2015).

In a changing climate, forests will be increasingly affected by factors such as multiyear droughts, insect outbreaks, wildfires, and severe storms (Cohen et al. 2016, Westerling et al. 2006). For example, over the past few decades, the assessment area has experienced several extensive, severe wildfires, including the 2017 Eagle Creek Fire (20 000 ha) and the large fires that occurred on the west side of the Cascade Range in 2020. Natural and human-caused disturbances can cause both immediate and gradual changes in forest structure, which in turn affect forest carbon dynamics by transferring carbon between different ecosystem carbon pools and the atmosphere.

Management activities that restore and maintain healthy forest structure and composition (e.g., hazardous fuels reduction and thinning) typically represent a short-term loss of carbon from the ecosystem through removal or burning of biomass (Birdsey and Pan 2015, Nunery and Keeton 2010). However, these short-term losses may help to maintain forest carbon sequestration over the long term by reducing the risks of larger and more severe disturbances (e.g., wildfires) and improving overall forest health (Stephens et al. 2012). Furthermore, when forests are disturbed through natural processes or management activities, the carbon that is initially removed is eventually replaced as forests recover and continue to take up and store carbon overtime. However, a drier, warmer climate is expected to lead to increased fire frequency as well as challenges to tree regeneration. In some places, this could lead to transitions to nonforest alternatives that could store substantially less carbon (Serra-Diaz et al. 2018).

Harvested wood, especially timber used for durable structures, can be reservoirs of long-term carbon storage (Bergman et al. 2014). These durable wood products can also be used in place of other emission-intensive building materials such as concrete and steel (Gustavasson et al. 2006, Lippke et al. 2011). Harvested wood and residues may also be used as bioenergy, displacing the use of fossil fuel sources (Miner et al. 2014) (fig. 8.11). Emissions associated with forest harvests and product use are eventually recovered as forests regrow (fig. 8.11). In response to a growing need for guidance on carbon management and stewardship, the Forest Service created a set of “carbon principles” (USDA FS 2015):

- Emphasize ecosystem function and resilience.
- Recognize carbon sequestration as one of many ecosystem services.
- Support a diversity of approaches.
- Consider system dynamics and scale in decision making.
- Use the best information and analysis methods.

These general principles are intended to assist all Forest Service programs and authorities with carbon stewardship. The second principle recognizes the importance of considering carbon sequestration in the context of other ecosystem

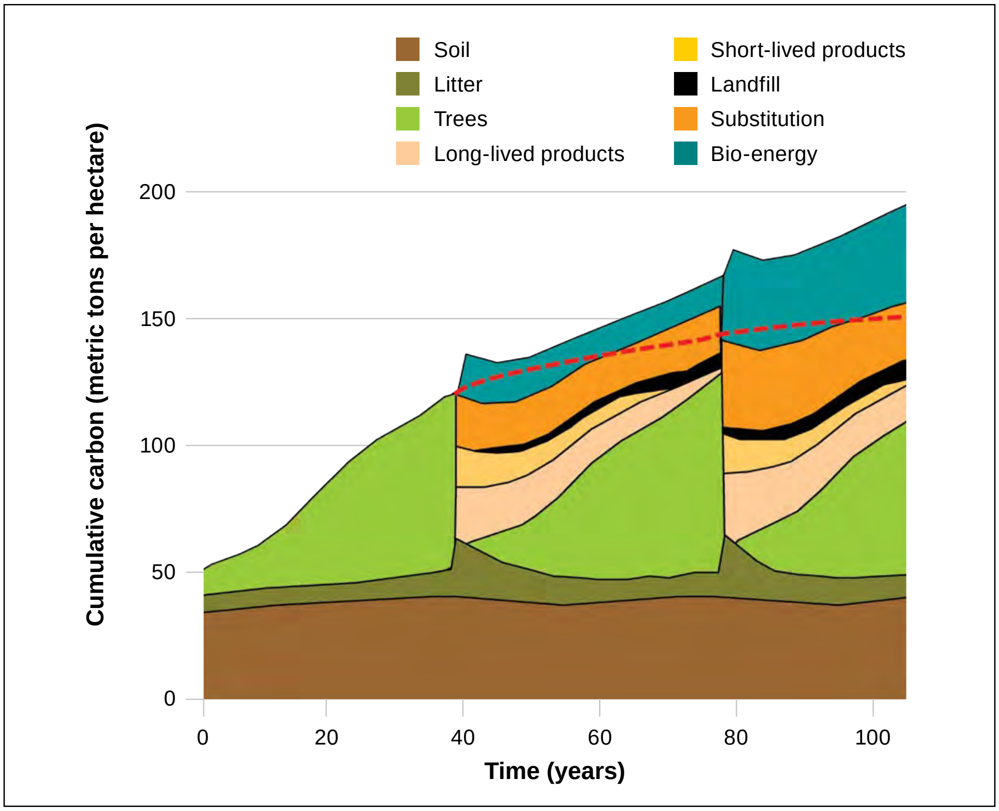

Figure 8.11—Carbon balance from a hypothetical forest management project in which the forest is harvested roughly every 40 years from land that started with low forest carbon stocks. This figure illustrates how harvested forests can continue to accrue carbon over time when accounting for forest regrowth, carbon stored in wood products in use and landfills, and product and biomass energy substitution (also counted as stored carbon). From McKinley et al. (2011).

services (USDA FS 2015). The Forest Service promotes integration of climate adaptation and mitigation, and balancing carbon uptake and storage with a wide range of public benefits. The goal is to maintain and enhance net sequestration across all carbon pools and forest age classes. This includes protecting existing carbon stocks, as well as building resilience through adaptation, restoration, and reforestation. Carbon estimates are useful for understanding patterns and trends at large spatial scales. At the scale of a national forest, these estimates are useful for context but not useful for project-scale applications.

U.S. Forest Service Baseline Estimates of Forest Carbon

The Forest Service has developed a nationally consistent assessment framework for reporting carbon components in each national forest. Estimates of total ecosystem carbon and stock change (flux) have been produced at the scale of national forests across the entire country, using a consistent methodology based on the Carbon Calculation Tool (Smith et al. 2007), which summarizes plot-scale data from the Forest Inventory and Analysis program (USDA FS 2015).

Baseline estimates produced by the Forest Service Office of Sustainability and Climate, Forest Service Research and Development, and other collaborators include carbon stocks and trends for the period 2005–2013 for seven ecosystem carbon pools in national forests: aboveground live tree, belowground live tree, standing dead, understory, down dead wood, forest floor, and soil organic carbon, as well as storage in harvested wood products where data are available. Although other carbon calculation approaches are available (Battles et al. 2018), the Forest Service uses a standardized national approach for National Forest System carbon accounting (Smith et al. 2007, USDA FS 2015).

Figure 8.12 displays carbon stock trends for CRGNSA, Willamette NF, and Mount Hood NF. Carbon (C) storage on Willamette NF increased from 243 teragrams (Tg) C in 2005 to 248 Tg C in 2013. During this period, total forest ecosystem carbon on Mount Hood NF increased from 142 Tg C in 2005 to 145 Tg C in 2013. Forest inventory plots in CRGNSA were sampled only once during this period, so it was not possible to detect changes in total ecosystem carbon stocks.

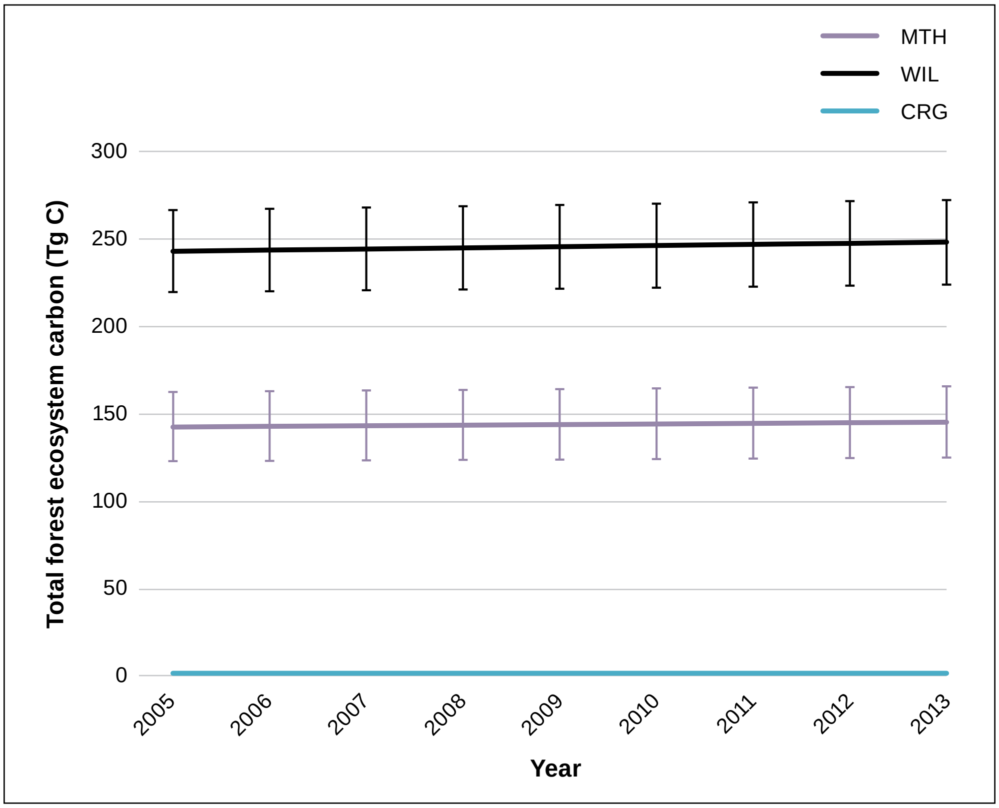

Figure 8.12—Estimated total forest ecosystem carbon in teragrams (Tg C) for the baseline period of 2005 to 2013 for Willamette National Forest (WIL) and Mount Hood National Forest (MTH); data are not available for Columbia River Gorge National Scenic Area. Estimates are bounded by 95 percent confidence intervals.

Carbon density is an estimate of forest carbon stocks per unit area. Carbon density on Willamette NF increased by 3.6 percent from 388 tonnes C ha^{-1} in 2005 to 402 tonnes C ha^{-1} in 2013 (fig. 8.13). Carbon density for Mount Hood NF increased by 2.3 percent, from 341 tonnes C ha^{-1} in 2005 to 349 tonnes C ha^{-1} in 2013, whereas in CRGNSA, carbon densities were 327 tonnes C ha^{-1} for the only year sampled. It is important to note that these estimates of carbon storage are derived from datasets and modeling with considerable uncertainty.

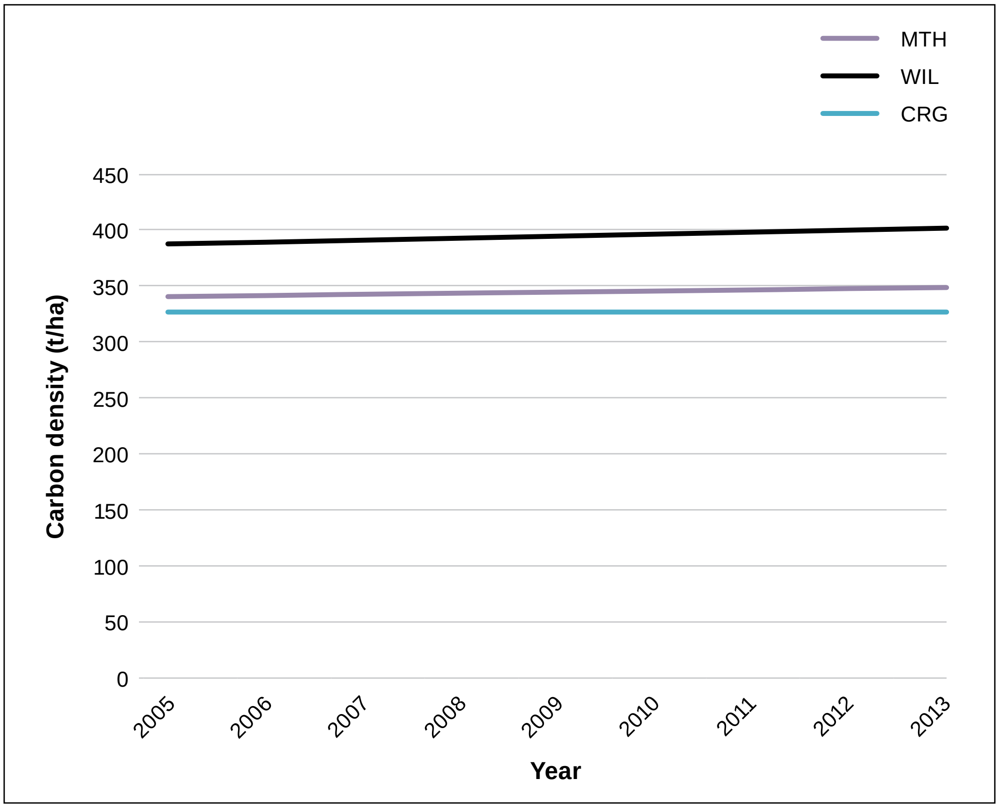

Figure 8.13—Carbon density of Willamette National Forest (WIL), Mount Hood National Forest (MTH), and Columbia River Gorge National Scenic Area (CRG) from 2005 to 2013.

Carbon Storage in U.S. Forest Service Harvested Wood Products

Although timber harvesting transfers carbon out of the forest ecosystem, most of that carbon is not lost or emitted directly to the atmosphere. Rather, harvested wood products (HWP) (e.g., lumber, panels, paper) can account for a significant amount of offsite carbon storage. Estimates of this contribution are important for both national-level accounting and regional reporting (Bergman et al. 2014, Skog 2008). Wood products can be substituted for other products, such as concrete and steel, which emit more greenhouse gases in manufacturing, thus lowering net emissions and creating a substitution effect. Harvested wood and residues may also be burned to produce heat or electrical energy, or converted to liquid transportation fuels and chemicals that would otherwise come from fossil fuels, also resulting in a substitution effect. In addition, much of the carbon removed onsite from harvesting can be recovered through regrowth.

The Forest Service baseline assessment of forest ecosystem carbon (USDA FS 2015) also contains an assessment of carbon storage in HWPs across all national forests in Oregon and Washington from 1909 to 2012.[2] Carbon accounting for HWPs was conducted by incorporating national forests harvest data documented in cut-and-sold reports within a production accounting system (Skog 2008). This accounting approach was used to track the entire life cycle of carbon from harvest to timber products to primary wood products to end use and disposal (see footnote 2). HWP carbon pools include both products in use and products that have been discarded to solid waste disposal sites (SWDS), such as landfills and dumps.

Historical timber harvesting trends can help forest managers contextualize the importance of sequestration through wood production. As more forests are harvested and more commodities are produced and stay in use, the amount of carbon stored in products accumulates (fig. 8.14). Furthermore, although products may be retired in SWDS, they decompose slowly, so carbon continues to be stored for many decades.

In national forests in the Pacific Northwest Region, annual harvest levels remained low (below 0.75 Tg C yr^{-1}) until after the start of World War II in the late 1930s and early 1940s, when they began to increase, and eventually peaked at 8.3 Tg C yr^{-1} in 1973 (fig. 8 in USDA FS 2015). This increase in timber harvesting also caused a steady increase in the amount of carbon stored in products in use and SWDS (fig. 8.11). Harvest levels fluctuated during the following decade, but then declined significantly in the early 1990s. As a result, carbon storage in products in use peaked in 1992 at 97.6 Tg C yr^{-1} and has since declined with continued low levels of harvesting, which have remained below 1 Tg C yr^{-1} since 2001.

Despite the decline in harvesting, carbon storage in SWDS has increased as products continue to be retired. Total carbon storage in HWPs (products in use and SWDS) reached a peak in 1994 at 144 Tg C but declined to about 131 Tg C in 2013. This decline in total HWP carbon storage indicates that the contribution of national forest timber harvests to the HWP carbon pool is less than the decay of retired products, causing the HWP pool to be a net source of atmospheric carbon

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[2] **Butler, E.; Stockmann, K.; Anderson, N. [et al.]. 2014.** Estimates of carbon stored in harvested wood products from the U.S. Forest Service Pacific Northwest Region, 1909–2012. 28 p. Unpublished report. On file with: USDA Forest Service, Rocky Mountain Research Station, Madison, WI 53726.

since the mid-1990s. HWP carbon stocks in the Pacific Northwest Region represent 5.25 percent of total forest sector carbon storage (both ecosystem and HWP carbon) associated with national forests in 2012 (USDA FS 2015).

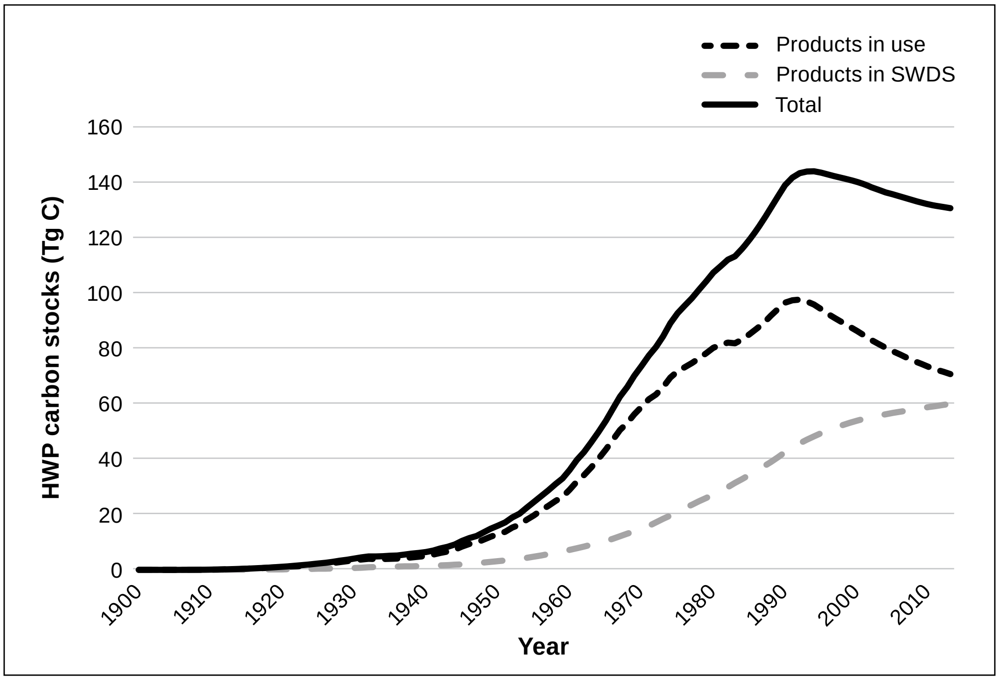

Figure 8.14—Cumulative total carbon stored (Tg C) in harvested wood products (HWP) manufactured from timber from 16 national forests and one national scenic area in the U.S. Forest Service Pacific Northwest Region. Carbon in HWP includes products that are still in use and carbon stored in solid waste disposal sites (SWDS), including landfills and dumps (Butler et al. 2014).

Factors Influencing U.S. Forest Service Forest Carbon Storage

The Forest Service expanded on the baseline assessments by developing unit-scale assessments of the influences of disturbances (fire, insects, abiotic), management activities, climate variability, atmospheric CO_2, and nitrogen deposition on forest carbon stocks and flux (Birdsey et al. 2019, Dugan et al. 2017, Healey et al. 2014, Raymond et al. 2015). Like the baseline assessments, these expanded assessments (Birdsey et al. 2019) rely on Forest Inventory and Analysis data but also integrate high-resolution disturbance maps based on Landsat satellite imagery (Healey et al. 2018), monthly climate observations, and data on atmospheric CO_2. Given the application of different datasets, modeling approaches, and parameters, there may be discrepancies between trends documented in baseline assessments and these expanded assessments (Dugan et al. 2017).

In Willamette NF, fire was the dominant disturbance type, affecting a total of 2.8 percent of the forested area from 1990 to 2011. Although there were several relatively large and severe wildfires in Willamette NF, including those in 1997, 2004, and 2010, these fires each affected less than 1 percent of the forested area (fig. 8.15; note that this figure does not include the large 2020 fires). Future fire projections indicate a potential increase in annual area burned in the Western United States owing to a warming climate (Kitzberger et al. 2017, McKenzie et al. 2004) and in some forest types, highly dense forests resulting from decades of fire exclusion (e.g., Perry et al. 2011).

Timber harvesting was also common on Willamette NF, affecting a small but consistent amount of area of forest annually. Likewise, timber harvest was the dominant disturbance type detected in Mount Hood NF from 1990 to 2011 in terms of the total percentage of forested area disturbed over the period (fig. 8.16). However, on both Willamette and Mount Hood NFs, timber harvests generally affected <0.5 percent of the forested area annually.

The Forest Carbon Management Framework (ForCaMF) model estimates how much more carbon would be on each national forest if the disturbances and harvests from 1990 to 2011 had not occurred. ForCaMF simulates the effects of disturbance and management on only nonsoil carbon stocks (i.e., vegetation, dead wood, forest floor). Forest carbon losses associated with disturbances and harvesting have been small compared to the total amount of carbon stored in the forests. The model results indicated that by 2011, Willamette NF contained about 1.4 percent less nonsoil carbon owing to fires and harvests each since 1990, as compared to a hypothetical undisturbed scenario (fig. 8.16). Harvests had a relatively small effect on forest carbon on Mount Hood NF, resulting in the loss of only 0.9 percent of nonsoil carbon over the 21-year period. The ForCaMF model was not run for CRGNSA.

The ForCaMF analysis was conducted over a relatively short period. After a forest is disturbed, it will eventually regrow and recover the carbon removed or released from the ecosystem. However, several decades may be needed to recover the carbon lost, depending on the type of the disturbance or harvest (e.g., clearcut versus partial cut), as well as the conditions before the disturbance (e.g., forest type and amount of carbon). The time required for a forest to reach predisturbance levels generally increases with both increased removal of biomass and the amount of predisturbance aboveground live-tree carbon. Likewise, the effects of the few large fire years on Willamette NF may be felt beyond the year that each fire occurred, as there is a gradual release of carbon from fire-killed biomass, partially offsetting the carbon gained through regrowth (Raymond et al. 2015).

In addition to directly affecting carbon stocks and emissions in the short term, disturbances also affect forest age structures, and in turn, longer term carbon trends. For instance, stand-age distributions in 2011 (fig. 8.17) indicate that about two-thirds of Willamette NF and 57 percent of Mount Hood NF forested stands are

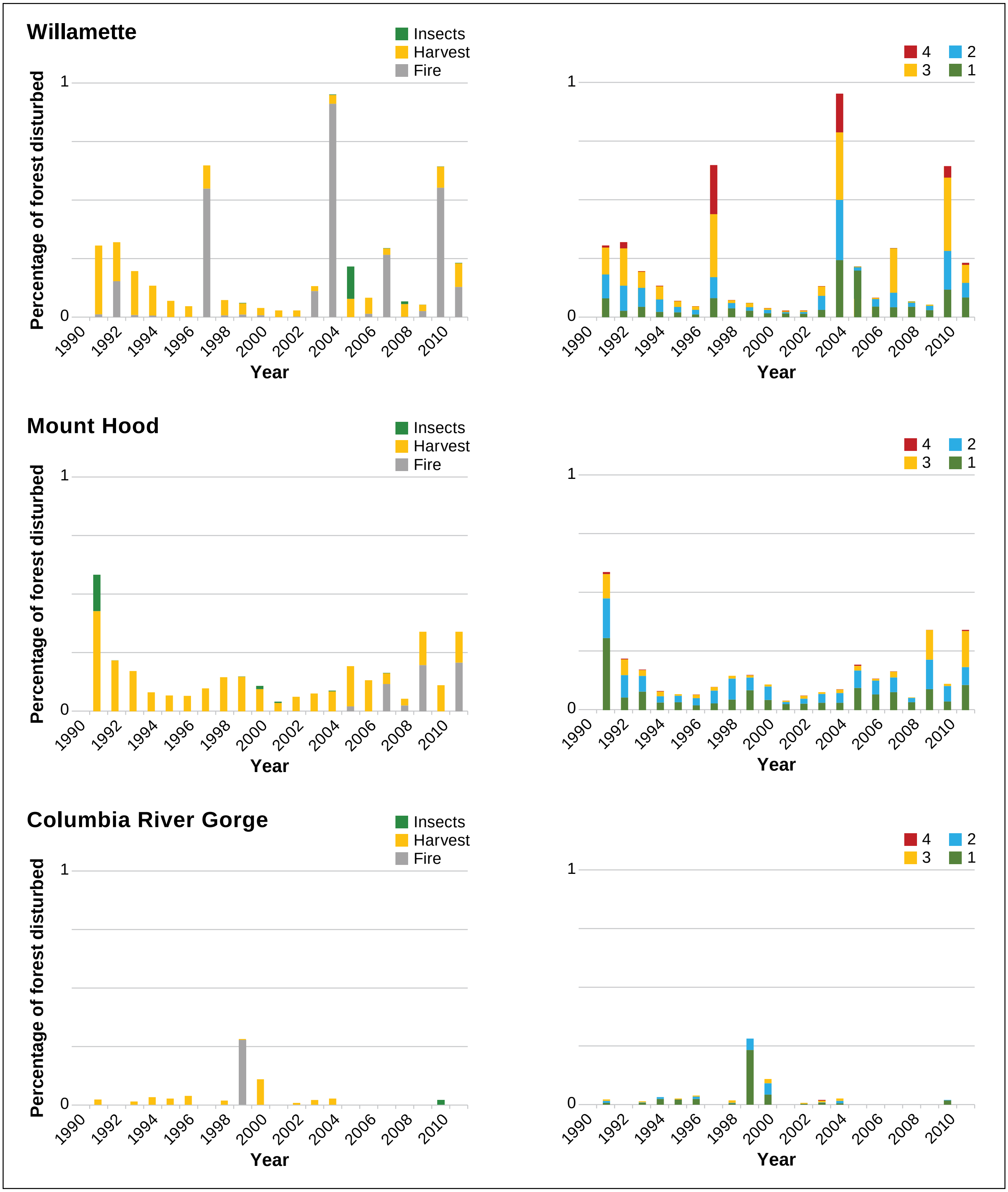

Figure 8.15—Percentage of forest area disturbed from 1991 to 2011 in Willamette National Forest, Mount Hood National Forest, and Columbia River Gorge National Scenic Area by disturbance types (graphs on left); and magnitude classes (graphs on right), characterized by percentage change in canopy cover as follows: (1) 0 to 25 percent, (2) 25 to 50 percent, (3) 50 to 75 percent, and (4) 75 to 100 percent.

greater than 100 years old. Forests are generally most productive when they are young to middle aged, then productivity declines or stabilizes as the forest canopy closes and as the stand experiences increased respiration and mortality of older trees. As forests continue to age and their productivity declines, the uptake of CO_2 can slow, suggesting that the rate of forest carbon accumulation in the Willamette and Mount Hood NFs may already be declining. On the other hand, the 2011 age structure for the CRGNSA has some older forests (about one-third of the forest is greater than 100 years old), but also shows a large peak of middle-aged stands, that may still be growing at an elevated rate of productivity.

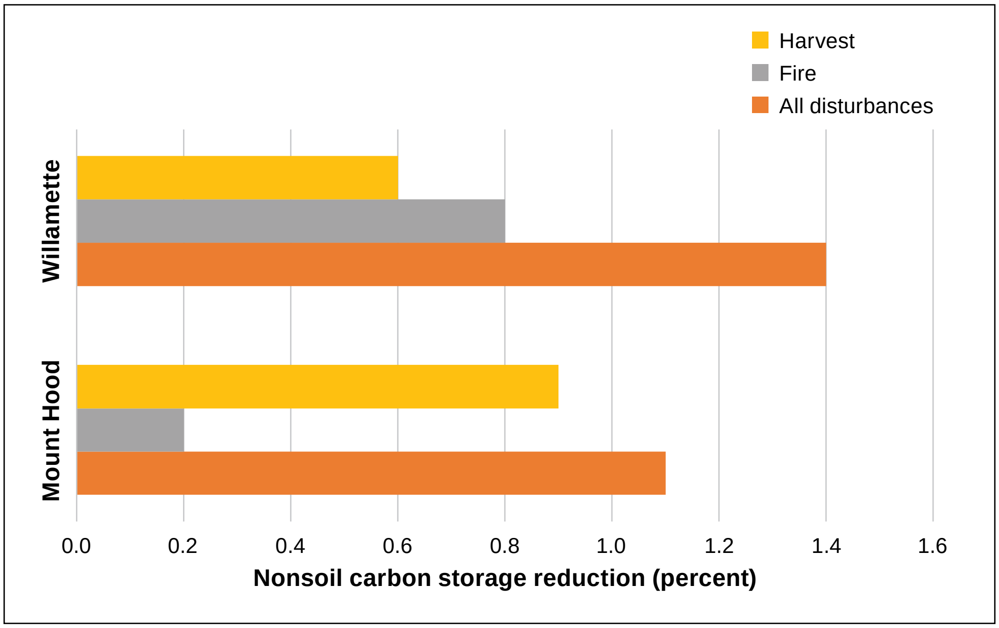

Figure 8.16—The degree to which 2011 carbon storage on each national forest was reduced by disturbances occurring from 1990 to 2011. Results were derived through the ForCaMF system (Healey et al. 2014), and include all nonsoil ecosystem pools. Modeling was not conducted for Columbia River Gorge National Scenic Area.

Pollinator Services

Globally, pollinators are responsible for the reproduction of 65 percent of the world's wild plants and about 35 percent of crops (Klein et al. 2007, Wratten et al. 2012). Pollination services are generally provided by insects, birds, and mammals. Honeybees (*Apis mellifera* L.) in particular provide most pollination services in agricultural landscapes (USDA NRCS 2008), adding more than $15 billion in value annually to agricultural crops in the United States (Pollinator Health Task Force 2015). Some wild insects that primarily occupy natural habitats, such as forestlands, often forage in adjacent agricultural landscapes, enhancing pollination services by improving crop quantity and quality (Garibaldi et al. 2013, 2014; Rader et al.

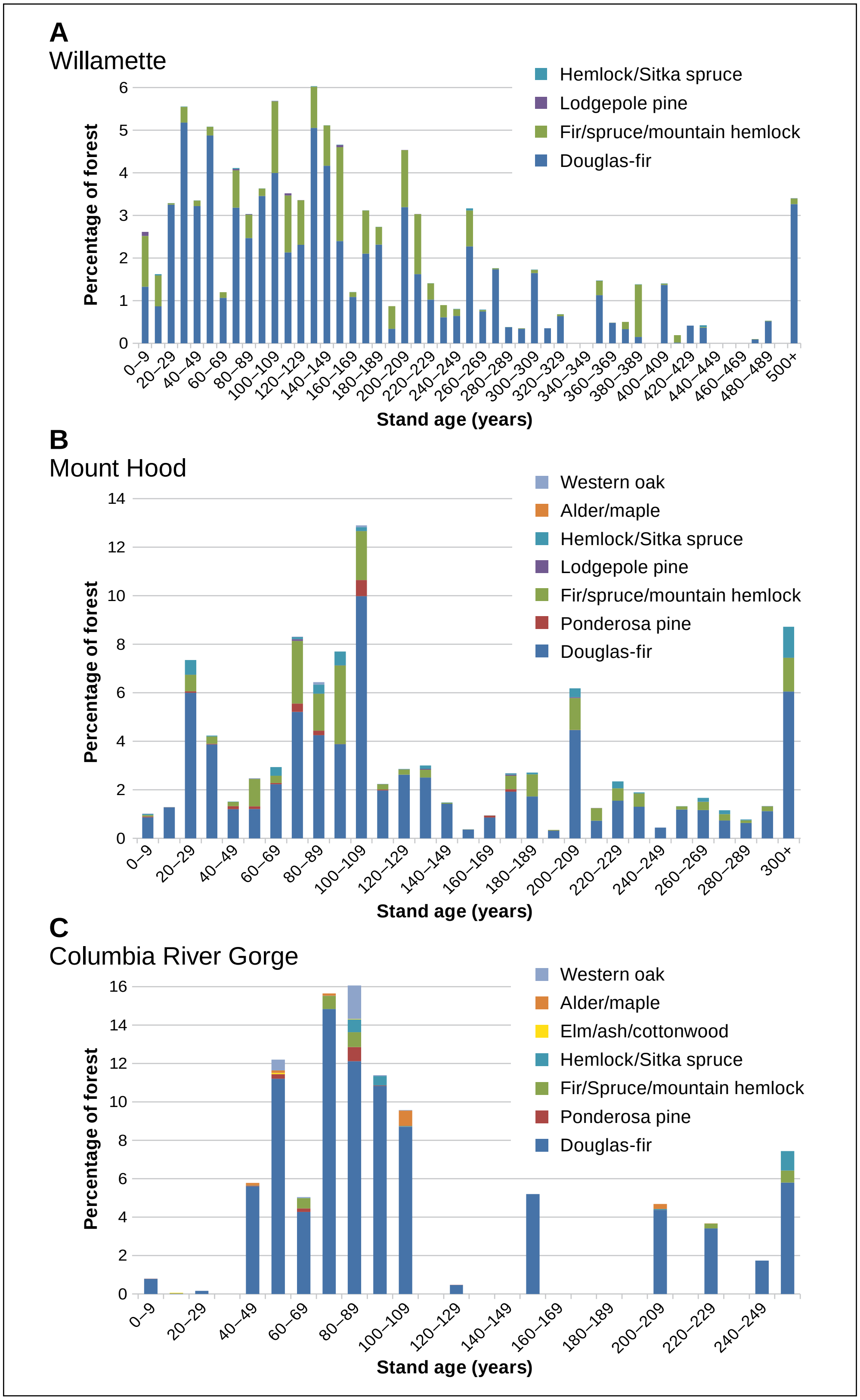

Figure 8.17—Age class distribution in 2011, showing the area of each forest type in 10-year age classes for (A) Willamette National Forest, (B) Mount Hood National Forest, and (C) Columbia River Gorge National Scenic Area.

2016; Ricketts 2004). Federal lands play an important role in pollinator habitat because private lands are subject to development, resulting in fragmented habitats. Pollinator value to natural systems is hard to ascertain because their contributions through maintenance of plant communities means they often serve as a keystone species for a variety of ecosystem services (Warziniack et al. 2018).

Pollination services also have significant cultural value. For example, pollinators help sustain NTFPs, which include first foods and medicinal plants. Spurred by the "…critical importance of pollinators to the economy, including to agricultural production and general ecosystem services," a presidential memorandum on pollinator health was released in 2014, leading to creation of the Pollinator Health Task Force led by the U.S. Environmental Protection Agency and U.S. Department of Agriculture (Pollinator Task Force 2015). One goal of this task force was to restore or enhance 2.8 million ha of land for pollinators through federal actions and public-private partnerships. A critical component of pollinator habitat enhancement involves increasing native vegetation through application of

Box 8.1

Excerpts from the 2014 Presidential memorandum on pollinators

Section 3A: Federal agencies will enhance pollinator habitat on managed lands and facilities through increased native vegetation (integrated vegetation and pest management) with application of pollinator-friendly best management practices and pollinator-friendly seed mixes.

Section 3B: Federal agencies will evaluate permit and management practices on power line, pipeline, utility, and other rights-of-way and easements, and consistent with applicable law, make necessary and appropriate changes to enhance pollinator habitat on federal lands through the use of integrated vegetation and pest management and pollinator-friendly best management practices, and by supplementing existing agreements and memoranda of understanding with rights-of-way holders, where appropriate, to establish and improve pollinator habitat.

Section 3C: Federal agencies will incorporate pollinator health as a component of all future restoration and reclamation projects as appropriate, including all annual restoration plans.

Section 3F: Federal agencies will establish a reserve of native seed mixes, including pollinator-friendly plants, for use on postfire rehabilitation projects and other restoration activities.

Section 3G: The U.S. Department of Agriculture will substantially increase both the acreage and forage value of pollinator habitat in the department's conservation programs, including the Conservation Reserve Program, and provide technical assistance, through collaboration with the land-grant university-based cooperative extension services to executive departments and agencies; state, local and tribal governments; and other entities and individuals, including farmers and ranchers, in planting the most suitable pollinator-friendly habitats.

pollinator-friendly seed mixes in revegetation, rehabilitation, and restoration of aquatic and terrestrial ecosystems (boxes 8.1 through 8.3) and creating conditions where natural processes promote recolonization by native species.

Box 8.2

The 2015 National Strategy to Promote the Health of Honeybees and Other Pollinators

From Pollinator Health Task Force (2015)

Goals:

- Reduce honeybee colony losses to economically sustainable levels.
- Increase monarch butterfly numbers to protect the annual migration.
- Restore or enhance 7 million ac (2.8 ha) of land for pollinators over the next 5 years through federal actions and public/private partnerships.

The strategy addresses four themes central to the June 2014 Presidential Memorandum "Creating a federal strategy to promote the health of honeybees and other pollinators":

- Conduct research to understand, prevent, and recover from pollinator losses.
- Expand public education programs and outreach.
- Increase and improve pollinator habitat.
- Develop public-private partnerships across all these activities.

Box 8.3

Building organizational capacity to improve pollinator habitat

Management of pollinator decline is based on avoiding or reducing the spread of new and existing diseases and pathogens, reducing pesticide use, and improving the resistance and resilience of native plant communities by encouraging or planting a wider variety of regionally appropriate pollinator-friendly plant species. The following action items are encouraged:

- Assign a point of contact for pollinators and native plant materials development on each unit.
- Plant pollinator gardens to raise awareness about pollinator decline for the public, decisionmakers, and resource specialists.
- Interpret/improve best management practices for pollinators.
- Assess pollinator issues of greatest need for different locations.
- Develop revegetation guidelines, including seed mixes by habitat type and seed transfer zones; include this document in updated plans.
- Assess the need for increased seed supply by species.
- Focus seed collection and material development on areas anticipated to have the greatest need.
- Actively engage in outreach and education about pollinator declines and climate change.
- Identify appropriate areas for apiary (honeybee colony) permits.
- Improve and maintain pollinator habitat through appropriate grazing management.

Climate Change Effects

Human actions and climate-induced stressors, including introduction of nonnative species, overgrazing by livestock, altered wildfire regimes, habitat modification, and land use, affect native plant communities and species that depend on them, including both native and managed pollinators (USDI BLM 2016. Novel ecosystems may develop in a warmer climate (see chapter 5), resulting in the loss, degradation, or fragmentation of basic pollinator habitat requirements, such as floral resources (nectar, pollen), and other basic needs such as nesting sites (GBNPP 2020).

Climate change is expected to affect pollinator populations both directly and indirectly (Vanbergen and the Insect Pollinators Initiative 2013). Temperature shifts could alter insect physiology (e.g., altered body size and lifespan) and behavior (e.g., altered foraging behavior) (Scaven and Rafferty 2013). The timing and amount of precipitation will interact with temperature thresholds to potentially alter the structure and function of plant communities and ecosystems. The ability of pollinators to track these changes will have implications for plant-pollinator mutualisms.

Climate change is also expected to affect the phenology of some plant species (Miller-Rushing and Primack 2008, Panchen et al. 2012). Potential mismatches in timing of flower and pollinator emergence can affect plant reproduction, especially when either the flowers or pollinators are short lived (Fagan et al. 2014). Specifically, critical nectar resources may become unavailable at key times during pollinator life stages. Pollinators will be most sensitive to altered plant phenology at the beginning and end of their flight seasons.

Native bees, as opposed to honeybees, may be more capable of shifting their phenology to compensate for warming temperatures, keeping pace with host-plant flowering (Bartomeus et al. 2011). Native bees may also be able to shift their range to find new food sources. However, such migration may be impeded in areas of low habitat connectivity, potentially reducing population sizes and increasing the likelihood of local extinction (Vanbergen and the Insect Pollinators Initiative 2013).

Research on pollinator networks in meadows on the H.J. Andrews Experimental Forest (HJA) (on Willamette NF) is helping to guide future restoration efforts. For example, Jones et al. (2019) documented a meadow community with a total of 178 flowering plant species, where they observed 688 flower-visitor species and 137,916 interactions. The resultant network mapping from this and previous work highlighted the complexity of the ecosystem service that pollinators provide for maintaining the health of increasingly rare meadow communities. Although larger meadows contained more species, an important finding highlighted the value of maintaining a mix of patch sizes to provide landscape diversity and connectivity.

In 2016, an HJA study analyzed the effect of climate change on wild pollinators in montane meadows (Young 2016). As mentioned in chapter 5, warming temperatures have resulted in some plants flowering earlier each spring, which can cause temporal mismatches with pollinator species. Asynchronies can hinder plant reproduction and limit the food resources necessary for pollinator survival. At this HJA study site, springtime temperatures rose significantly from 2011 to 2015, and the snowpack melted from the ground consistently earlier over the 5 years. In response to this climatic variability, the median date of peak flower abundance and the median date of peak plant-pollinator interactions both shifted earlier by about 5 weeks between 2011 and 2015. Despite sustained synchrony between the plants and pollinators, median flower abundance declined by 68 percent, and median number of interactions declined by 73 percent. Although the data suggest that the wild pollinators are trying to adapt to shifts in timing of flowering, the dwindling interaction counts indicate that the populations may have experienced adverse effects (Young 2016).

Ecological Restoration and Pollinators

Landscapes that retain functionality in a warmer and potentially drier climate will have greater capacity to survive natural disturbances and extreme events. Ecological restoration addresses composition, structure, pattern, and ecological processes in terrestrial and aquatic ecosystems, typically with a focus on long-term sustainability relative to desired social, economic, and ecological conditions. Including pollinators as a consideration in climate change adaptation will assist restoration goals related to genetic conservation, biological diversity, and production of habitat for endemic species. Increasing the capacity of federal agencies to mitigate current damage to pollinator populations and facilitate improvement of habitat will contribute to both restoration and climate change adaptation.

Strategies for sustaining pollinator habitat in the face of climate change and other stressors include habitat creation and enhancement, restoration of open areas such as meadows, and connectivity routes (roadside, right-of-ways, and riparian habitat). There is also a need to incorporate mitigation actions specific to pollinators in land management projects, such as timing, duration, and scale of activities.

Leveraging scarce resources through partnerships is critical to implementing and monitoring projects that enhance pollinator habitat. In the CMWAP assessment area, over 20 organizations have worked together to improve thousands of hectares of pollinator habitat.

Expanding understanding of pollinator distribution has also been a priority in the CMWAP assessment area. For example, previously unknown populations of western bumblebee (*Bombus occidentalis* Greene) have been documented in the

CMWAP assessment area through substantial efforts in the past several years. A previously unknown population of monarch butterfly (*Danaus plexippus* L.) was recently found in Willamette NF. Recent work also has shown the potential for combining restoration of native shrub-steppe vegetation with vineyard management in the Columbia Gorge and elsewhere to benefit native butterfly species (James et al. 2015). Through projects like the Bee Atlas, Walama Restoration Project, and Mount Hood Pollinator Garden, partnerships are being developed, information on pollinators and native plants is being collected, and restoration projects and tools are being implemented.

Cultural Values

Cultural services include connections between people and the land that may be intangible, such as spiritual enrichment, heritage, identity, and aesthetic values. Cultural services are connected with each other as well as with provisioning and regulating services (FAO 2020). Cultural services also include practices such as harvesting of first foods (native plants that American Indian tribes have traditionally harvested), rituals in sacred places, recreation activities, and sense of place. People and communities can develop connections to specific locations, features, or landscapes. Memories, interactions, and history play a role in visitor and resident attachment to the land (Eisenhauer et al. 2000, Kruger and Jakes 2003). The attraction of these places and experiences can influence where people live, work, and recreate (Smith et al. 2011).

The effects of climate change on ecological structures, processes, and functions will affect culturally important resources, places, and traditions, as well as connections between people and landscapes (Hess et al. 2008, Lynn et al. 2011). Disruptions to hydrologic processes (chapter 3), increased vulnerability to insects, shifts in plant species composition (chapter 5), and changes in pollinator patterns may affect related habitats, products, and cultural uses of forests. American Indian tribes and recreationists use National Forest System lands for cultural services. This section covers potential climate change effects on cultural services of concern to these groups.

Tribal Values

Some tribal populations may be more affected by climate change than others because of geographic location, degree of association to climate-sensitive environments, and specific cultural, economic, or political characteristics (Lynn et al. 2011). American Indian tribes may be particularly vulnerable to climate shifts because of their cultural connections with ecosystems and specific plant and animal species, as well as their dependence on resources for subsistence (Cordalis and Suagee 2008, Lynn et al. 2011).

The Northwest Forest Plan science synthesis provides an overview of tribal ecocultural resources in a region encompassing the CMWAP assessment area (Long et al. 2018). Changes in climate can potentially jeopardize resources valued by tribes, and the well-being of tribal communities more generally, by exacerbating droughts, extreme storms and runoff events, as well as wildfires and insect outbreaks. Such changes threaten the availability of traditional foods, medicines, and materials to tribes, which can affect diets, health, and other dimensions of community well-being (Bennett et al. 2014, Lynn et al. 2013). The CMWAP assessment area contains hundreds of locations of traditional uses, including camps, harvesting and hunting areas, trails, and places with mythical and spiritual significance.

Harvesting of first foods represents an ongoing relationship between Native peoples and ecosystems in the assessment area. Iconic examples of first foods include salmon, berries (especially huckleberries [*Vaccinium* spp.]), roots (e.g., common camas [*Camassia quamash* {Pursh} Greene]), and large mammals. The abundance and accessibility of these foods may shift with climate change (Chamberlain et al. 2018). Salmon have spiritual and economic value for many Pacific Northwest tribes. Climate change is expected to reduce some salmon populations, especially at lower elevations, because of increased stream temperatures and altered streamflows (chapter 4).

Huckleberries are sacred to many tribes in the Pacific Northwest, which regard berry gathering as a religious and social activity. August is the preferred month for huckleberry collection, and collection is accompanied by social gatherings and trading. Black huckleberry (*V. membranaceum* Douglas ex Torr.) has been the most important of the huckleberry species gathered by indigenous people in the Pacific Northwest (Richards and Alexander 2006). Climate-envelope models have recently been used to project the likely geographic range and habitat suitability for black huckleberry under modeled climates for the middle and end of the 21st century (Prevéy et al. 2020). The range of black huckleberry is expected to no longer include lower elevations of the CMWAP assessment area, which are mostly outside of the boundaries of National Forest System lands. Within the boundaries of the two national forests and CRGNSA, suitability of habitat for black huckleberry is projected to decline (Prevéy et al. 2020). The study also considered potential changes in timing of flowering and fruiting, both of which may advance by one to several weeks by the end of the 21st century. Such changes could require tribes to alter traditional patterns of huckleberry harvest and associated cultural events (Prevéy et al. 2020). However, this kind of modeling does not consider species plasticity or physiology in determining plant response to climate change, and thus the changes in the extent of huckleberry distribution may not be as large as implied in this study.

Fire frequency plays a key role in sustainability of plants like camas and huckleberry (Chamberlain et al. 2018). Changing fire regimes in the CMWAP assessment area may result in more fires and larger areas of open forest canopy, which are beneficial to light-loving plant species like camas and huckleberry. However, prolonged droughts may create stress for both species.

As the CMWAP assessment area gets warmer, large mammals like black-tailed deer (*Odocoileus hemionus hemionus* [Rafinesque]), elk (*Cervus elaphus* L.), and black bear (*Ursus americanus* Pallas) may benefit from early-seral conditions created by more frequent fires. However, prolonged droughts may stress these populations as water sources decline on the landscape. Many preferred forage species become less palatable under drought conditions, which could be expressed in declining reproduction of these animals. There are also unknown future influences of parasites that might expand their range and impacts.

A concerning indirect effect of climate change is the disruption of archaeological evidence from increasingly large wildfires. Archaeological evidence is often buried in duffs and woody material in the productive forests of the CMWAP assessment area. Archaeologists are increasingly observing exposure of materials as fires burn over and around artifacts, exposed further by subsequent erosion.[3] This increased visibility can lead to vandalism and illegal collecting. Effects of fire on the integrity of cultural resources are well described in Ryan et al. (2012). The risk of damage or illegal removal is a reality, although artifact exposure may aid in understanding and documenting historical tribal uses.

A long history of harvest of plants and animals by Americans Indians forms the basis of “traditional ecological knowledge.” Longstanding connections with the land will undoubtedly inform tribal adaptation as conditions change. Such knowledge can help tribes respond adaptively to reduced salmon populations and habitat quality (Lynn et al. 2013). Western scientific knowledge can be linked to tribal knowledge to better project and anticipate changes in resource availability (Turner et al. 2011) and to identify possible refugia (Carroll et al. 2010, Olson et al. 2012).

Various tree species that have tribal importance have been studied to assess their vulnerability to projected changes in climate. Drought- and fire-resistant species are likely to be less vulnerable. Tribal members often depend upon large, long-lived trees with particular characteristics to obtain nuts and special wood products, but there is much uncertainty about how individual tree species will respond to climate change. Existing vulnerability assessments conducted by tribes in the CMWAP assessment area can contribute to effective adaptation strategies (see box 8.4).

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[3] Kelly, C. 2019 Personal communication. Archaeologist, Willamette National Forest, Detroit Ranger District, 44125 North Santiam Highway Southeast, Detroit, OR 97342.

Box 8.4

Climate change vulnerability assessments completed by American Indian tribes represented within the assessment area

- **Clearwater River Subbasin (ID) Climate Change Adaptation Plan**
  http://www.mfpp.org/wp-content/uploads/2012/03/ClearwaterRiver-Subbasin_ID_Forest-and-Water-Climate-Adaptation-Plan_2011.pdf
- **Columbia River Basin Tribes Climate Change Capacity Assessment**
  https://www.sciencebase.gov/catalog/item/56abb786e4b0403299f463db
- **Columbia River Inter-Tribal Fish Commission Climate Change Needs Assessment Survey**
  https://www.critfc.org/wp-content/uploads/2019/01/CRITFC-CC-Survey.pdf
- **Confederated Tribes of the Umatilla Indian Reservation Climate Change Vulnerability Assessment**
  http://static1.squarespace.com/static/50c23e29e4b0958e038d6bd6/t/57b4c5af6a496315610b2d86/1471464889144/CTUIR+Vulnerability+Assessment+Technical+Report+FINAL.pdf
- **Climate and Health Perspectives; Voices of the Confederated Tribes of Warm Springs**
  https://www.oregon.gov/oha/PH/HEALTHYENVIRONMENTS/CLIMATECHANGE/Pages/perspectives.aspx
- **Climate Adaptation Plan for the Territories of the Yakama Nation**
  https://www.critfc.org/wp-content/uploads/2016/05/Yakama-Nation-Climate-Adaptation-Plan-.pdf
- **Cowlitz Indian Tribe; Focal Landscapes and Species**
  https://www.cowlitz.org/focal-landscapes-and-species.html

Recreation

National Forest System lands provide outdoor recreation opportunities that impart many benefits to human well-being (chapter 7). Outdoor recreation in natural settings is highly valued and is often a key driver of where people choose to live, work, and travel. Climate change will alter the supply and demand for recreational activities, causing changes in location and timing of visitation. People perceive the areas where they choose to recreate as more than just a commodity that can be easily replaced or substituted. Attachments to particular places can influence sense of self and lead to strongly held notions about appropriate use and acceptable experiences (Williams 2008). Feelings of distress and psychological damage can occur when places are perceived to be negatively transformed (Albrecht et al. 2007, Dodgen et al. 2016, Doherty and Clayton 2011), such as following the 2017 Eagle Creek Fire in CRGNSA. Numerous media accounts documented the sense of loss and grief people felt after a beloved place was indelibly changed (e.g., Bakall 2017).

Glacier recession in the CMWAP assessment area may affect recreation and sense of place (chapter 3). One of the most direct and visible manifestations of climate change, glacier loss engenders a spectrum of emotions dependent on the relationship people hold with glaciers themselves and the lands that contain them (Brugger et al. 2013). For many forest visitors, their sense of place at least partly depends on the presence of snow and ice, whether the snow and ice are used directly such as in winter sports activities, or indirectly such as for aesthetic quality. For example, the Mazamas mountaineering organization, based in Portland, Oregon, makes climbing to the summit of a glaciated peak a prerequisite to membership (Mazamas 2017). It is uncertain what the emotional response of forest visitors and nearby residents will be to the gradual loss of ice and snowpack and how it will affect their attitudes and sense of place in the future.

Water

Clean and abundant water is critical for the social, economic, and cultural life of populations within and adjacent to the CMWAP assessment area. Ecosystems managed by CMWAP units provide water supplies for human use and aesthetic values from the rivers and lakes. The three units are major contributors to the supply of drinking water used by the surrounding population centers. CRGNSA provides water to 721,000 people, Mount Hood NF provides water to 936,000 people, and Willamette NF provides water to 343,000 people (USDA FS 2019a). Hydrologic services include the quantity, quality, location, and timing of water supply (Brauman et al. 2007), with quality and timing the most likely to be affected by climate change (chapter 3). Increasing stream temperatures, higher peak flows, and lower summer streamflows all have the potential to strain water infrastructure, particularly as a result of increasing frequency and extent of extreme events.

Ensuring safe drinking water is likely to become more challenging, such as in the Bull Run Reservoir, which supplies water to the greater Portland area (chapter 3, box 3.1). Lower summer streamflows could affect the performance of municipal wastewater systems, making pollutant discharge requirements more difficult to attain (Kormos et al. 2016). A changing hydrologic regime affects the function of reservoirs in relation to hydropower, water storage, and recreation (May et al. 2018) (chapters 3 and 7).

Snowpack loss can create or amplify the mismatch between streamflow availability and need. With more winter rain and faster snowmelt, early streamflow will outstrip reservoir capacity. Most of the “early water” will pass into the ocean before it can be used by irrigators during the growing season. A current estimate of the value of lost snow-water storage in the Western United States alone is in the trillions of dollars (Sturm et al. 2017). This does not factor in the potential costs associated with increased risk of flood events from early water. Effects on both quality and timing will have consequences for the composition and productivity of aquatic ecosystems. A key management challenge will be maintaining the ecosystem processes that support a sustainable flow of hydrologic services in the future.

Summary of Ecosystem Services Across Units

Since the publication of the Millennium Ecosystem Assessment (MEA 2005), there has been considerable debate on how to best show the linkage between ecosystem structure and function and the benefits humans receive from nature (de Groot et al. 2012, Häyhä and Franzese 2014). Quantification and valuation of ecosystem services (Daily et al. 2000) enable the assessment of tradeoffs when making management decisions; estimates of quantified stocks, flows, and monetary values of ecosystem services can be useful for communicating about climate change with stakeholders (Deal et al. 2017). This approach is not meant to turn ecosystem services into tradeable commodities (Costanza et al. 2014, de Groot et al. 2012).

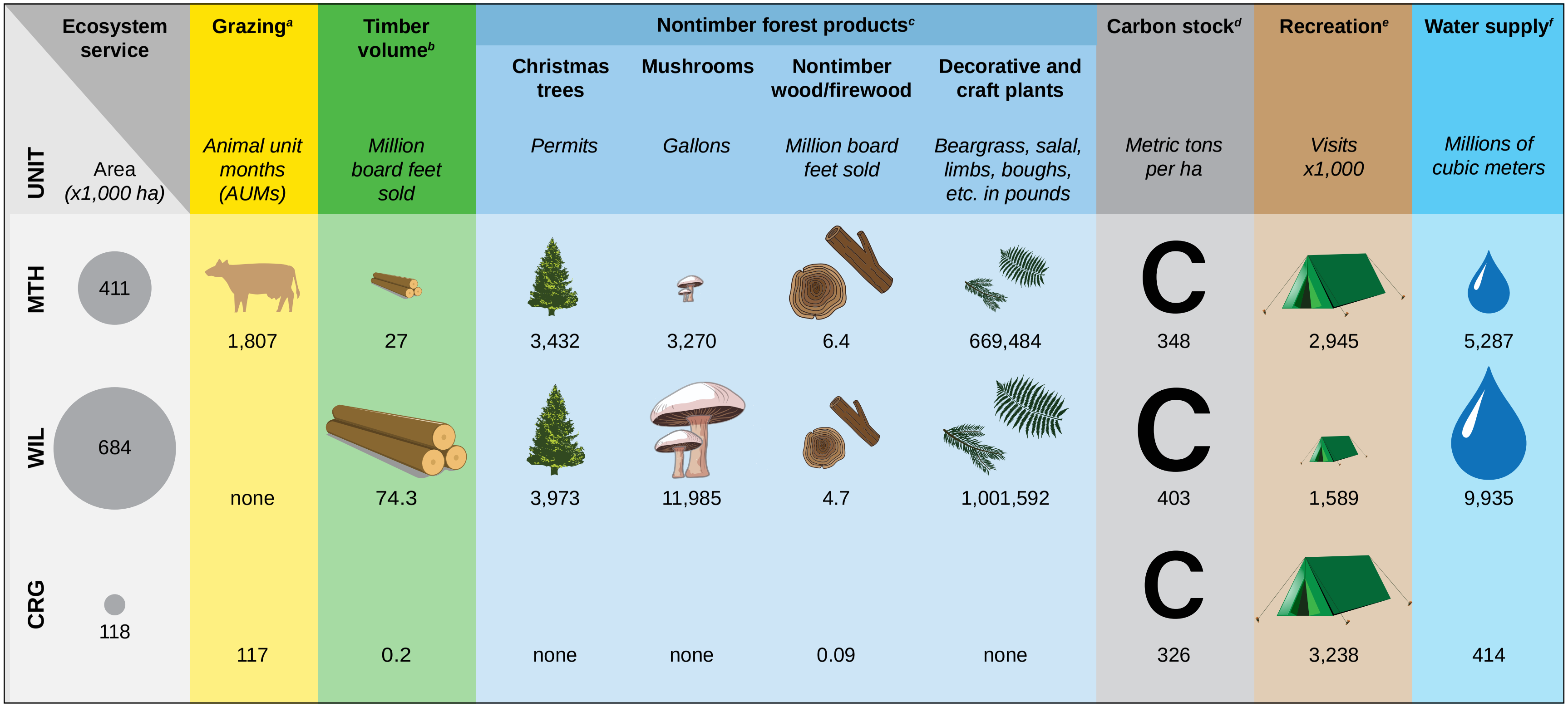
Table 8.3 summarizes a selection of quantifiable ecosystem goods and services provided by CMWAP units and is useful for characterizing a portion of each unit's ecosystem service portfolio under its current management regime. The numbers in the table are influenced by factors that control the supply of goods and services, land base, and distribution of ecosystem types, as well as by factors that control the demand for them (e.g., management regulations and accessibility to human populations). From a regional perspective, the CMWAP units make significant contributions in several ecosystem service categories, including water, carbon, sawtimber, and recreation (fig. 8.18). These categories serve as the foundation for the economic activity derived from National Forest System lands (box 8.5). Although a snapshot, the information provided in table 8.3 illustrates at least some ecosystem services that may be at risk from climate change.

Quantification and Valuation Challenges

Although the information presented in table 8.3 allows for some conclusions about what types of ecosystem services are currently being produced by the units within the assessment area, it does not capture all of them. Some ecosystem services (e.g., water and air purification, nutrient cycling, wildlife habitat, preservation of traditions, spiritual needs) typically lack a market price but assessing the monetary value of these services is beyond the scope of this report.

CRGNSA is a special case relative to other units in the National Forest System. The numbers in tables 8.3 and 8.4 apply only to National Forest System lands and thus do not fully capture the ecosystem services provided by this unit. Given the mix of land uses, land ownerships, infrastructure, development, and human activities within its boundary, it can be difficult to represent CRGNSA outputs and ecosystem services using metrics typically applied to national forests. For example, although little timber is harvested from federal lands in the CRGNSA, there is a considerable amount of timber output from state and private forest land.

Table 8.3—Summary of metrics describing selected ecosystem services in Mount Hood National Forest (MTH), Willamette National Forest (WIL), and Columbia River Gorge National Scenic Area (CRG)



UNIT	Ecosystem service	Grazing[a]	Timber volume[b]	Nontimber forest products[c]				Carbon stock[d]	Recreation[e]	Water supply[f]
				Christmas trees	Mushrooms	Nontimber wood/firewood	Decorative and craft plants			
	Area (x1,000 ha)	*Animal unit months (AUMs)*	*Million board feet sold*	*Permits*	*Gallons*	*Million board feet sold*	*Beargrass, salal, limbs, boughs, etc. in pounds*	*Metric tons per ha*	*Visits x1,000*	*Millions of cubic meters*
MTH	411	1,807	27	3,432	3,270	6.4	669,484	348	2,945	5,287
WIL	684	none	74.3	3,973	11,985	4.7	1,001,592	403	1,589	9,935
CRG	118	117	0.2	none	none	0.09	none	326	3,238	414

AUM = animal unit month; ha = hectares.

Graphics used are public domain; tent graphic designed by Brgfx/http://www.freepick.com; water drop graphic from http://www.vexels.com.

[a] From U.S. Forest Service INFRA inventory data for fiscal year 2017.

[b] Timber volume is the 2013–2018 annual average reported by the U.S. Forest Service Pacific Northwest Region.

[c] Nontimber forest products metrics are annual averages for 2013–2018, as reported by the U.S. Forest Service Pacific Northwest Region.

[d] Carbon stocks are for 2013, as reported in USDA FS (2015).

[e] From U.S. Forest Service National Visitor Use Monitoring (NVUM) program (CRG and MTH data from 2016, WIL data from 2017). NVUM data only covers national forest lands and does not fully capture the Columbia River Gorge National Scenic Area, which hosts recreation opportunities and infrastructure on state and private ownerships.

[f] Estimate of mean annual renewable water supply is for the period 1981–2010 from Brown et al. (2016).

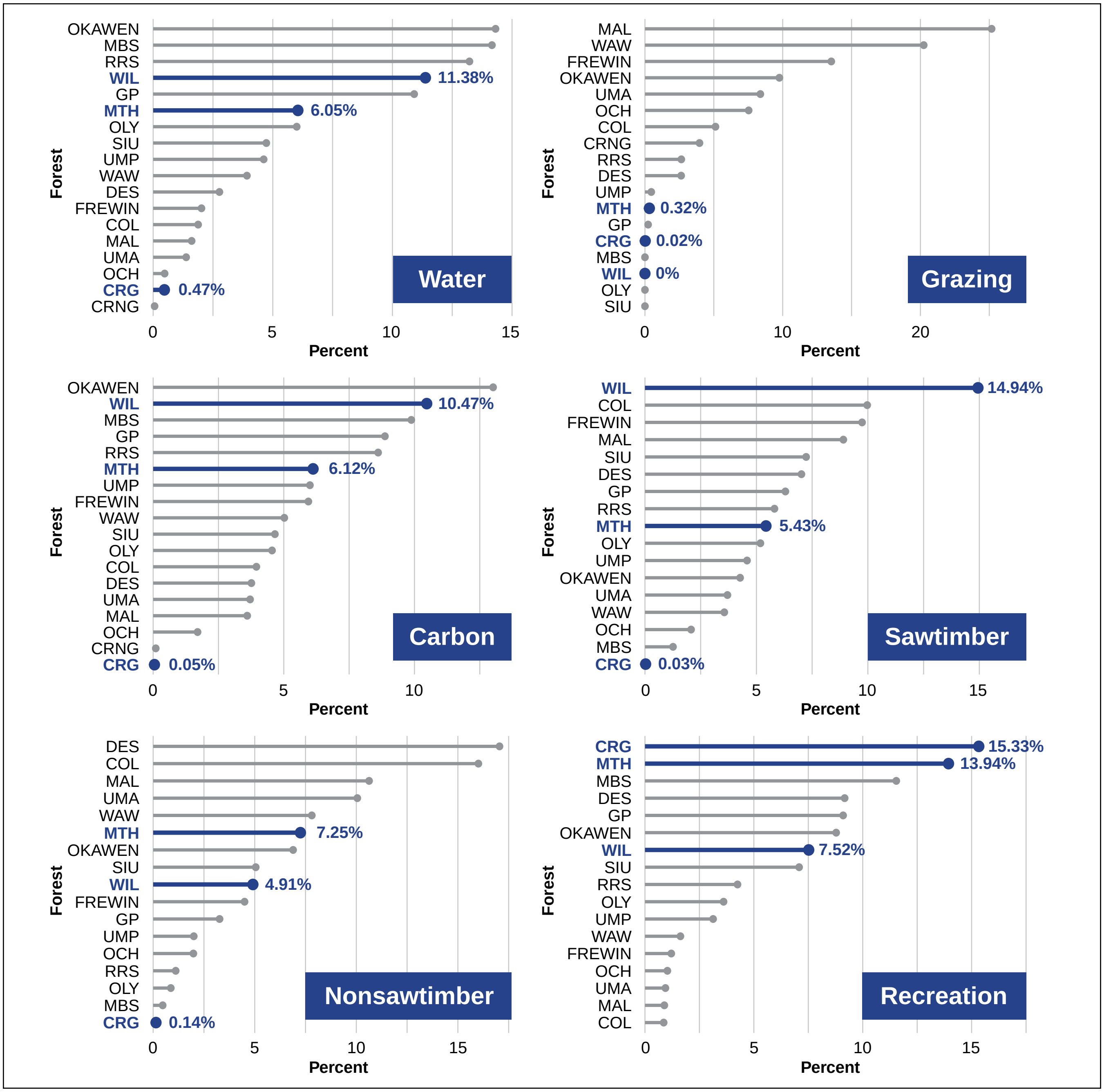


Figure 8.18—Rankings for select ecosystem services in the U.S. Forest Service Pacific Northwest Region, highlighting units in the Columbia River Gorge Scenic Area, Mount Hood National Forest, and Willamette National Forest Adaptation Partnership assessment area. Percentages are calculated from the regionwide total for a given ecosystem service. Ecosystem services are (1) mean annual water runoff volume, 1981–2020 (Brown et al. 2016); (2) grazing in animal unit months, based on 2017 data from the U.S. Forest Service INFRA database; (3) carbon stocks as of 2013, based on estimates from U.S. Forest Service (2015); (4) timber, based on timber volume sold, 2013–2018 (from U.S. Forest Service Pacific Northwest Region data), (5) nonsawtimber, based on timber volume sold, 2013–2018 (from U.S. Forest Service Pacific Northwest Region data); and (6) recreation, based on data from the U.S. Forest Service National Visitor Use Monitoring (NVUM) program (2017 multiforest regional estimates, data collected between 2010 and 2017 [NVUM data cover only national forest lands and do not fully capture Columbia River Gorge National Scenic Area recreation activities]). U.S. Forest Service units are abbreviated as follows (national forest = NF): Columbia River Gorge National Scenic Area (CRG), Colville NF (COL), Deschutes NF (DES), Fremont-Winema NF (FREWIN), Gifford Pinchot NF (GP), Malheur NF (MAL), Mount Hood NF (MTH), Mount Baker-Snoqualmie (MBS), Ochoco NF (OCH), Okanogan-Wenatchee NF (OKAWEN), Olympic NF (OLY), Rogue River-Siskiyou NF (RRS), Siuslaw NF (SIU), Umatilla NF (UMA), Umpqua NF (UMP), Wallowa-Whitman NF (WAW), and Willamette NF (WIL).

Box 8.5

Employment and labor income supported by national forests

(Source: USDA FS 2019b)

Public lands contribute to economic activity in the areas surrounding them by providing recreational opportunities, forest products, and water supplies, as well investments in restoration, among many other benefits. The U.S. Forest Service estimates its contributions to employment in terms of jobs (full time, part time, temporary, seasonal) and income (wages, salaries and benefits for wage earners plus income to sole business proprietors). Although these estimates do not capture all of the economic contributions provided by ecosystem services, they are a conservative approximation of how the agency brings work to local communities.

In 2016, the Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest Adaptation Partnership assessment area, supported nearly 6,400 jobs and approximately $313,728,000 in labor income in local communities. Recreation and forest products contribute the highest percentage of wages and benefits. Total spending by visitors at Mount Hood National Forest alone is about $125.6 million annually. The effects of climate change on timber species and recreation opportunities will have cascading effects on socioeconomic benefits.

Relative to other national forest units, especially in relation to its size, the CRGNSA receives high recreation and tourist use, both on and off public lands. The private agricultural land base includes thousands of hectares of orchards, vineyards, and livestock grazing, and supports agricultural production, added-value products such as wine and cider, and an agricultural tourism industry. The Columbia River is a critical migration route for anadromous salmonids and plays a central role for tribal fisheries. Potential climate change vulnerabilities for the CRGNSA need to include consideration of these human, social, and economic factors.

Fortunately, defensible valuations are not necessary for assessing climate change risk or forest planning evaluation of ecosystems services. The process of identification and characterization of key ecosystem services and the subsequent development of descriptive narratives about the levels of ecosystem service production can accomplish much of what quantification and valuation does, as well as capture the benefits of ecosystems services that are difficult to value monetarily. These can then be used to communicate public benefits and assess tradeoffs among management alternatives in forest planning (Kline and Mazzotta 2012, Jaworski et al. 2018). Methods of ecosystem quantification and valuation will improve over time, but they are not essential for meeting Forest Service planning and management objectives.

Table 8.4—Summary of anticipated responses to climate change for selected ecosystem services in Mount Hood National Forest (MTH), Willamette National Forest (WIL), and Columbia River Gorge National Scenic Area (CRG)[a]

Ecosystem service	Anticipated response to climate change	Sources of uncertainty	Where most applicable?
Grazing	↑↓ Plant community shifts to dry forest and woodland vegetation types could increase understory grass, although past management practices, warmer temperatures, and wildfire favor invasives that reduce forage availability and quality, particularly nonnative annual grasses	Disturbance size and severity, rate of invasive spread	Grazing allotments, east side of CRG and MTH
Timber	↑↓ Direct effects—temperature-driven productivity gains that increase with elevation, but potentially offset by increased summer water deficits and drought stress mortality, and reduced regeneration ↓ Indirect effects—increase in disturbance events and interactions among disturbance types	CO_2 fertilization, phenology, species interactions, invasives, model results	MTH and WIL
Christmas trees	↓ Loss of moist forest conifer species and encroachment of hardwoods in seasonally accessible areas; the popular species noble fir in particular will likely experience an upward range shift	Model results (MC2 and GCMs), disturbance, changes in desired traits/quality	Low-/mid-elevation areas on MTH and WIL
Mushrooms	↓ Habitat loss and fragmentation, decline of tree species necessary for mycorrhizal associations, potential for drier and hotter spring and fall seasons, increased demand and access ↑ Increases in species associated with dead wood and wildfires (e.g., morels)	Disturbance size and severity, precipitation patterns	MTH and WIL
Nontimber wood	↑↓ Increased disturbance and drought-related mortality may reduce availability of green wood, but provide potential for increased salvage and biomass operations	Disturbance, productivity (warming vs. water deficit)	MTH and WIL
Decorative and craft plants	↑↓ Disturbance-related effects on habitat quality and species composition, but some species may benefit from more disturbance; habitat fragmentation could limit migration to suitable areas ↓ Increasing demand and potential for increased access (roads open earlier)	Individual species response, phenology, invasives, changes in quality/valued traits	MTH and WIL
Carbon	↑↓ Dependent on balance of productivity gains to increased temperature and water deficit, amount and severity of disturbances, distribution of communities resilient to disturbance, changes in species composition, and changes to cycling within and transfer among forest carbon pools	Disturbance, precipitation patterns, decay rates, CO_2 fertilization, nutrient cycling	All units
Recreation	↑ Warm-weather activities—increased length of shoulder seasons ↓↓ Snow-based activities—loss of snowpack and decreased snow residence time — Wildlife-, water-, and forest gathering-based activities	Extreme heat, fire/smoke effects on warm-weather and other activities	All units, MTH and WIL for snow-based activities
Water	↑↓ Timing and quantity: increase in extremes—floods and droughts ↓ Quality: higher temperatures and sedimentation stresses on fish and aquatic habitat, impacts on roads and developments, drinking water and stormwater/wastewater systems, reservoirs	Model results (VIC and GCMs), precipitation patterns	All units, mid-/high-elevation streams, large tributaries

[a] Up arrow indicates positiver effect; down arrow indicates negative effects; bar indicates neutral effects.

Conclusions

Lines of scientific evidence support both positive and negative outcomes, and considerable uncertainty, regarding the quantity, quality, and timing of the potential effects of climate change on ecosystem services. For example, it is uncertain how longer growing seasons and increased summer water deficits will affect vegetation productivity and distribution and abundance of plant species. We have high confidence that the frequency and extent of disturbances will increase in future decades, although timing and interactions among disturbances that may affect vegetation are difficult to project (chapters 2 and 5). As shown in table 8.4, other factors (e.g., phenology, invasive species) also affect ecosystem services provided by vegetation, creating additional complexity in inferring climate change effects.

Expectations for ecosystem services will increase as human populations in the CMWAP assessment area grow. Societal values and cultural attitudes will evolve, leading to changes in demand that may be difficult to anticipate. As ecological and human systems change, some products and services will be “winners” and others “losers,” and some may have both positive and negative outcomes. The coronavirus pandemic demonstrated how quickly things can change in response to a social perturbation, creating a surge in demand for some types of outdoor recreation in the Pacific Northwest (Hewitt 2020) while at the same time having many facilities closed to protect human health.

Ecosystem services elevate and support the benefits that people derive from public lands. Although the concept of ecosystem services is relatively new compared to other aspects of resource management and planning, it is now a well-established component of sustainable management in the Forest Service, providing an interface for social valuation with natural and cultural resources. The potential effects of climate change described in this assessment can be used by the Forest Service and other agencies and organizations to (1) anticipate how ecosystem services might change in the coming decades, (2) develop options for adapting to these changes, and (3) inform plans, programs, and projects. Monitoring and continual learning will be essential for tracking climate change effects and the effectiveness of adaptation actions, informing all aspects of sustainable management related to ecosystem services.

Literature Cited

Albrecht, G.; Sartore, G-M.; Connor, L. [et al.]. 2007. Solastalgia: the distress caused by environmental change. Australian Psychiatry. 15: S95–S98.

Bakall, S. 2017. 'The Gorge will never be the same': Oregonians grieve as Eagle Creek Fire burns. Oregon Live. 6 September 2017. https://www.oregonlive.com/wildfires/2017/09/the_gorge_will_never_be_the_sa.html. (9 April 2019).

Bartomeus, I.; Ascher, J.S.; Wagner, D. [et al.]. 2011. Climate-associated phenological advances in bee pollinators and bee-pollinated plants. Proceedings of the National Academy of Sciences, USA. 108: 20645–20649.

Battles, J.J.; Bell, D.M.; Kennedy, R.E. [et al.]. 2018. Innovations in measuring and managing forest carbon stocks in California. California's fourth climate change assessment. Pub. CCCA4-CNRA2018-014. Sacramento, CA: California Natural Resources Agency. 99 p.

Bennett, T.; Maynard, N.; Cochran, P. [et al.]. 2014. Indigenous peoples, lands, and resources. In: Melillo, J.; Richmond, T.; Yohe, G., eds. Climate change impacts in the United States: the third national climate assessment. Washington, DC: U.S. Global Change Research Program: 297–317.

Bergman, R.; Puettman, M.E.; Taylor, A.; Skog, K.E. 2014. The carbon impacts of wood products. Forest Products Journal. 64: 220–231.

Birdsey, R.A.; Dugan, A.J.; Healey, S.P. [et al.]. 2019. Assessment of the influence of disturbance, management activities, and environmental factors on carbon stocks of U.S. national forests. Gen. Tech. Rep. RMRS-GTR-402. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 116 p.

Birdsey, R.A.; Pan, Y. 2015. Trends in management of the world's forests and impacts on carbon stocks. Forest Ecology and Management. 355: 83–90.

Brauman, K.A.; Daily, G.C.; Duarte, T.K.; Mooney, H.A. 2007. The nature and value and ecosystem services: an overview highlighting hydrologic services. Annual Review of Environment and Resources. 32: 6.1–6.32.

Brugger, J.; Dunbar, K.W.; Jurt, C.; Orlove, B. 2013. Climates of anxiety: comparing experience of glacier retreat across three mountain regions. Emotion, Space and Society. 6: 4–13.

Carroll, C.; Dunk, J.R.; Moilanen, A. 2010. Optimizing resiliency of reserve networks to climate change: multispecies conservation planning in the Pacific Northwest, USA. Global Change Biology. 16: 891–904.

Chamberlain, J.J.; Emery, M.R.; Patel-Weynand, T., eds. 2018. Assessment of nontimber forest products in the United States under changing conditions. Gen. Tech. Rep. GTR-SRS-232. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 260 p.

Cohen, W.B.; Yang, Z.; Stehman, S.V. [et al.]. 2016. Forest disturbance in the conterminous US from 1985–2012: the emerging dominance of forest decline. Forest Ecology and Management. 360: 242–252.

Cordalis, D.; Suagee, D.B. 2008. The effects of climate change on American Indian and Alaska Native tribes. Natural Resources and Environment. 22: 45–49.

Costanza, R.; de Groot, R.; Sutton, P. [et al.]. 2014. Changes in the global value of ecosystem services. Global Environmental Change. 26: 152–158.

Daily, G.C.; Söderqvist, T.; Aniyar, S. [et al.]. 2000. The value of nature and the nature of value. Science. 289: 395–396.

Davies, K.W.; Boyd, C.S.; Bates, J.D.; Hulet, A. 2015. Dormant season grazing may decrease wildfire probability by increasing fuel moisture and reducing fuel amount and continuity. International Journal of Wildland Fire. 24: 849–856.

Davies, K.W.; Nafus, A.M. 2013. Exotic annual grass invasion alters fuel amounts, continuity and moisture content. International Journal of Wildland Fire. 22: 353–358.

de Groot, R.; Brander, L.; ver der Ploeg, S. [et al.]. 2012. Global estimates of the value of ecosystems and their services in monetary units. Ecosystem Services. 1: 50–61.

Deal, R.; Fong, L.; Phelps, E., tech. eds. 2017. Integrating ecosystem services into national Forest Service policy and operations. Gen. Tech. Rep. PNW-GTR-943. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 87 p.

Dodgen, D.; Donata, D.; Kelly, N. [et al.]. 2016. Mental health and well-being. In: Crimmins, A.; Balbus, J.; Gamble, J.L. [et al.], eds. The impacts of climate change on human health in the United States: a scientific assessment. Washington, DC: U.S Global Change Research Program: 217–246.

Doherty, T.J.; Clayton, S. 2011. The psychological impacts of global climate change. American Psychologist. 66: 265–276.

Dugan, A.J.; Birdsey, R.; Healey, S.P. [et al.]. 2017. Forest sector carbon analyses support land management planning and projects: assessing the influence of anthropogenic and natural factors. Climatic Change. 144: 207–220.

Eisenhauer, B.W.; Krannich, R.S.; Blahna, D.J. 2000. Attachments to special places on public lands: an analysis of activities, meanings and community connections. Society and Natural Resources. 13: 421–441.

Fagan, W.F.; Bewick, S.; Cantrell, S. [et al.]. 2014. Phenologically explicit models for studying plant-pollinator interactions under climate change. Theoretical Ecology. 7: 289–297.

Fettig, C.J.; Reid, M.L.; Bentz, B.J. [et al.]. 2013. Changing climates, changing forests, a western North American perspective. Journal of Forestry. 111: 214–228.

Food and Agriculture Organization [FAO]. 2020. Ecosystem service and biodiversity: cultural service. http://www.fao.org/ecosystem-services-biodiversity/background/cultural-services/en. (17 April 2020).

Garibaldi, L.A.; Carvalheiro, L.G.; Leonhardt, S.D. [et al.]. 2014. From research to action: enhancing crop yield through wild pollinators. Frontiers in Ecology and the Environment. 12: 439–447.

Garibaldi, L.A.; Steffan-Dewenter, I.; Winfree, R. [et al.]. 2013. Wild pollinators enhance fruit set of crops regardless of honey bee abundance. Science. 339: 1608–1611.

Great Basin Native Plant Project [GBNPP]. 2020. http://www.greatbasinnpp.org. (15 December 2017).

Gustavsson, L.; Pingoud, K.; and Sathre, R. 2006. Carbon dioxide balance of wood substitution: comparing concrete-and wood-framed buildings. Mitigation and Adaptation Strategies for Global Change. 11: 667–691.

Hansis, R.; Jones, E.T.; McLain, R.J. 2001. Recent trends: nontimber forest product pickers in the Pacific Northwest. Journal of Sustainable Forestry. 13: 141–148.

Häyhä, T.; Franzese, P.P. 2014. Ecosystem services assessment: a review under an ecological-economic and systems perspective. Ecological Modelling. 289: 124–132.

Healey, S.P.; Urbanski, S.P.; Patterson, P.L.; Garrard, C. 2014. A framework for simulating map error in ecosystem models. Remote Sensing of Environment. 150: 207–217.

Hess, J.J.; Malilay, J.N.; Parkinson, A.J. 2008. Climate change: the importance of place. American Journal of Preventive Medicine. 35: 469–478.

Hewitt, L. 2020. In Pacific Northwest, camping on rise amid coronavirus. The Columbian. 12 July 2020. https://www.columbian.com/news/2020/jul/12/in-pacific-northwest-camping-on-rise-amid-coronavirus. (20 January 2021).

Hicke, J.A.; Logan, J.A.; Powell, J.; Ojima, D.S. 2006. Changing temperatures influence suitability for modeled mountain pine beetle (*Dendroctonus ponderosae*) outbreaks in the Western United States. Journal of Geophysical Research-Biogeosciences. 111: G02019.

Huber-Stearns, H.; Moseley, C.; Ellison, A. [et al.]. 2016. The Forest Service and communities: the relationships between land and people in the Pacific Northwest Region. Ecosystem Workforce Program Working Pap. 72. Eugene, OR: University of Oregon. 66 p.

James, D.G.; Seymour, L.; Lauby, G.; Buckley, K. 2015. Beauty with benefits: butterfly conservation in Washington State, USA, wine grape vineyards. Journal of Insect Conservation. 19: 341–348.

Jaworski, D.; Kline, J.D.; Miller, C. [et al.]. 2018. Evaluating ecosystem services as management outcomes in national forest and grassland planning assessments. Gen. Tech. Rep. PNW-GTR-968. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 38 p.

Jones, J.A.; Hutchinson, R.; Moldenke, A. [et al.]. 2019. Landscape patterns and diversity of meadow plants and flower-visitors in a mountain landscape. Landscape Ecology. 34: 997–1014.

Kirilenko, A.P.; Sedjo, R.A. 2007. Climate change impacts on forestry. Proceedings of the National Academy of Sciences, USA. 104: 19697–19702.

Kitzberger, T.; Falk, D.A.; Westerling, A.L.; Swetnam, T.W. 2017. Direct and indirect climate controls predict heterogeneous early-mid 21st century wildfire burned area across western and boreal North America. PLoS ONE. 12(12): e0188486.

Klein, A.; Vaissiere, B.E.; Cane, J.H. [et al.]. 2007. Importance of pollinators in changing landscapes for world crops. Proceedings of the Royal Society of London B: Biological Sciences. 274: 303–313.

Kline, J.D.; Mazzotta, M.J. 2012. Evaluating tradeoffs among ecosystem services in the management of public lands. Gen. Tech. Rep. PNW-GTR-865. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 38 p.

Kormos, P.R.; Luce, C.H.; Wenger, S.J.; Berghuijs, W.R. 2016. Trends and sensitivities of low streamflow extremes to discharge timing and magnitude in Pacific Northwest mountain streams. Water Resources Research. 52: 4990–5007.

Kruger, L.E.; Jakes, P.J. 2003. The importance of place: advances in science and application. Forest Science. 49: 819–821.

Lippke, B.; Oneil, E.; Harrison, R. [et al.]. 2011. Life cycle impacts of forest management and wood utilization on carbon mitigation: knowns and unknowns. Carbon Management. 2: 303–333.

Long, J.; Lake, F.K.; Lynn, K.; Viles, C. 2018. Tribal ecocultural resources and engagement. In: Spies, T.A.; Stine, P.A.; Gravenmier, R.; Long, J.W.; Reilly, M.J., tech. coords. Synthesis of science to inform land management within the Northwest Forest Plan area. Gen. Tech. Rep. PNW-GTR-966. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 851–917.

Lynn, K.; Daigle, J.; Hoffman, J. [et al.]. 2013. The impacts of climate change on tribal traditional foods. Climatic Change. 120: 545–556.

Lynn, K.; MacKendrick, K.; Donoghue, E.M. 2011. Social vulnerability and climate change: synthesis of literature. Gen. Tech. Rep. PNW-GTR-838. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 56 p.

May, C.; Luce, C.; Casola, J. [et al.]. 2018. Northwest. In: Reidmiller, D.R., Avery, C.W.; Easterling, D.R. [et al.], eds. Impacts, risks, and adaptation in the United States: fourth national climate assessment. Volume II. Washington, DC: U.S. Global Change Research Program: 1036–1100.

Mazamas. 2017. About us. https://mazamas.org/about. (9 April 2019).

McKenzie, D.; Gedalof, Z.; Peterson, D.L.; Mote, P. 2004. Climatic change, wildfire, and conservation. Conservation Biology. 18: 890–902.

McKinley, D.C.; Ryan, M.G.; Birdsey, R.A. [et al.]. 2011. A synthesis of current knowledge on forests and carbon storage in the United States. Ecological Applications. 21: 1902–1924.

Millennium Ecosystem Assessment [MEA]. 2005. Ecosystems and human well-being. Synthesis. Washington, DC: Island Press. 24 p.

Miller-Rushing, A.J.; Primack, R.B. 2008. Global warming and flowering times in Thoreau's Concord: a community perspective. Ecology. 89: 332–341.

Miner, R.A.; Abt, R.C.; Bowyer, J.L. [et al.]. 2014. Forest carbon accounting considerations in US bioenergy policy. Journal of Forestry. 112: 591–606.

Montoya, J.; Raffaelli, D. 2010. Climate change, biotic interactions and ecosystem services. Philosophical Transactions of the Royal Society B. 365: 2013–2018.

Mooney, H.; Larigauderie, A.; Cesario, M. [et al.]. 2009. Biodiversity, climate change and ecosystem services. Current Opinion in Environmental Sustainability. 1: 46–54.

Nunery, J.S.; Keeton, W.S. 2010. Forest carbon storage in the northeastern United States: net effects of harvesting frequency, post-harvest retention, and wood products. Forest Ecology and Management. 259: 1363–1375.

Olson, D.; DellaSala, D.A.; Noss, R.F. [et al.]. 2012. Climate change refugia for biodiversity in the Klamath-Siskiyou ecoregion. Natural Areas Journal. 32: 65–74.

Pan, Y.; Birdsey, R.A.; Fang. J. [et al.]. 2011. A large and persistent carbon sink in the world’s forests. Science. 333: 988–993.

Panchen, Z.A.; Primack, R.B.; Anisko, T.; Lyons, R.E. 2012. Herbarium specimens, photographs, and field observations show Philadelphia area plants are responding to climate change. American Journal of Botany. 99: 751–756.

Perry, D.A.; Hessburg, P.F.; Skinner, C.N. [et al.]. 2011. The ecology of mixed severity fire regimes in Washington, Oregon, and northern California. Forest Ecology and Management. 262: 703–717.

Pollinator Health Task Force, The White House. 2015. The national strategy to promote the health of honey bees and other pollinators. https://obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/Pollinator Health Strategy 2015.pdf. (4 November 2021).

Prevéy, J.S.; Parker, L.E.; Harrington, C.A. [et al.]. 2020. Climate change shifts in habitat suitability and phenology of huckleberry (*Vaccinium membranaceum*). Agricultural and Forest Meteorology. 280: 107803.

Rader, R.; Bartomeus, I.; Garibaldi, L.A. [et al.]. 2016. Non-bee insects are important contributors to global crop pollination. Proceedings of the National Academy of Sciences, USA. 113: 146–151.

Raymond, C.L.; Healey, S.; Peduzzi, A.; Patterson, P. 2015. Representative regional models of post-disturbance forest carbon accumulation: integrating inventory data and a growth and yield model. Forest Ecology and Management. 336: 21–34.

Richards, R.T.; Alexander, S.J. 2006. A social history of wild huckleberry harvesting in the Pacific Northwest. Gen. Tech. Rep. PNW-GTR-657. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 113 p.

Ricketts, T. 2004. Tropical forest fragments enhance pollinator activity in nearby coffee crops. Conservation Biology. 18: 1262–1271.

Ryan, K.C.; Jones, A.T.; Koerner, C.L.; Lee, K.M., tech. eds. 2012. Wildland fire in ecosystems: effects of fire on cultural resources and archaeology. Gen. Tech. Rep. RMRS-GTR-42-vol. 3. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 224 p.

Scaven, V.L.; Rafferty, N.L. 2013. Physiological effects of climate warming on flowering plants and insect pollinators and potential consequences for their interactions. Current Zoology. 59: 418–426.

Seidl, R.; Spies, T.A.; Peterson, D.L. [et al.]. 2016. Searching for resilience: addressing the impacts of changing disturbance regimes on forest ecosystem services. Journal of Applied Ecology. 53: 120–129.

Serra-Diaz, J.M.; Maxwell, C.; Lucash, M.S. [et al.]. 2018. Disequilibrium of fire-prone forests sets the stage for a rapid decline in conifer dominance during the 21st century. Scientific Reports. 8: 1–12.

Skog, K.E. 2008. Sequestration of carbon in harvested wood products for the United States. Forest Products Journal. 58: 56–72.

Smith, J.E.; Heath, L.S.; Nichols, M.C. 2007. U.S. forest carbon calculation tool: forest-land carbon stocks and net annual stock change. Gen. Tech. Rep. NRS–13. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 38 p.

Smith, N.; Deal, R.; Kline, J. [et al.]. 2011. Ecosystem services as a framework for forest stewardship: Deschutes National Forest overview. Gen. Tech. Rep. PNW-GTR-852. Portland OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 46 p.

Stephens, S.L.; Boerner, R.E.; Moghaddas, J.J. [et al.]. 2012. Fuel treatment impacts on estimated wildfire carbon loss from forests in Montana, Oregon, California and Arizona. Ecosphere. 3: 38.

Sturm, M.; Goldstein, M.A; Parr, C. 2017. Water and life from snow: a trillion dollar science question. Water Resources Research. 53: 3534–3544.

Turner, N.J.; Deur, D.; Mellot, C.R. 2011. "Up on the mountain": ethnobotanical importance of montane sites in Pacific coastal North America. Journal of Ethnobiology. 31: 4–43.

U.S. Department of Agriculture. 2018. Press release. National Agricultural Statistics Service. https://quickstats.nass.usda.gov. (14 January 2019).

U.S. Department of Agriculture, Forest Service; U.S. Department of the Interior, Bureau of Land Management [USDA and USDI]. 1994. Final supplemental environmental impact statement on management of habitat for late-successional and old-growth forest related species within the range of the northern spotted owl. Portland, OR: U.S. Department of Agriculture, Forest Service; U.S. Department of the Interior, Bureau of Land Management [Irregular pagination]. Vol. 1.

U.S. Department of Agriculture, Forest Service [USDA FS]. 2015. Baseline estimates of carbon stocks in forests and harvested wood products for the National Forest System units, Pacific Northwest Region. http://www.fs.fed.us/climatechange/documents/PacificNorthwestRegionCarbonAssessment.pdf. (16 January 2018).

U.S. Department of Agriculture, Forest Service [USDA FS]. 2019a. At a glance—benefits to people. https://www.fs.fed.us/emc/economics/at-a-glance/benefits-to-people.shtml. (31 July 2019).

U.S. Department of Agriculture, Forest Service [USDA FS]. 2019b. At a glance—jobs and income. https://www.fs.fed.us/emc/economics/at-a-glance/jobs-income.shtml. (5 August 2019).

U.S. Department of Agriculture, Natural Resources Conservation Service [USDA NRCS]. 2008. Plants for pollinators in Oregon. Tech. Notes. Plant materials No. 13. 26 p. https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_041919.pdf. (17 April 2020). 44 p.

U.S. Department of Agriculture, Natural Resources Conservation Service [USDA NRCS]. 2020. What are ecological site descriptions? Ecological site descriptions. https://www.nrcs.usda.gov/wps/portal/nrcs/detail/national/entsc/?cid=stelprdb1049096. (9 January 2018).

U.S. Department of the Interior, Bureau of Land Management [USDI BLM]. 2016. Proposed resource management plan/final environmental impact statement: western Oregon. Portland, OR: Oregon/Washington State Office. 554 p. Volume 1.

Vanbergen, A.J.; the Insect Pollinators Initiative. 2013. Threats to an ecosystem service: pressures on pollinators. Frontiers in Ecology and the Environment. 11.5: 251–259.

Warziniack, T.W.; Elmer, M.J.; Miller, C.J. [et al.]. 2018. Effects of climate change on ecosystem services. In: Halofsky, J.E.; Peterson, D.L.; Ho, J.J.; Little, N.J.; Joyce, L.A., eds. 2018. Climate change vulnerability and adaptation in the Intermountain Region. Gen. Tech. Rep. RMRS-GTR-375. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 376–403.

Westerling, A.L.; Hidalgo, H.G.; Cayan, D.R.; Swetnam, T.W. 2006. Warming and earlier spring increase western U.S. forest wildfire activity. Science. 313: 940–943.

Williams, D.R. 2008. Pluralities of place: a user's guide to place concepts, theories, and philosophies in natural resource management. In: Kruger, L.E.; Hall, T.E.; Stiefel, M.C., eds. Understanding concepts of place in recreation research and management. Gen. Tech. Rep. PNW-GTR-744. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 7–30.

Wratten, S.; Gillespie, M.; Decourtye, A. [et al.]. 2012. Pollinator habitat enhancement: benefits to other ecosystem services. Agriculture Ecosystems and Environment. 159: 112–122.

Young, A. 2016. The effect of climate change on pollinators and the implications for global agriculture: a case study in the H.J. Andrews Experimental Forest, Oregon. New Haven, CT: Yale College. 64 p. Senior thesis.

Chapter 9: Adapting to the Effects of Climate Change

Benjamin S. Soderquist and Jessica E. Halofsky[1]

Introduction

Climate change is currently affecting ecosystems and natural resources in central Oregon and the broader Pacific Northwest (chapter 2). To help prepare for shifts in temperature and precipitation, resource managers working for the U.S. Department of Agriculture (USDA), Forest Service are mandated to integrate climate change information into decision making during land management planning and project development (Obama 2013, USDA FS 2012). Implementing effective climate change management actions across large landscapes will require increased coordination between federal and state agencies, nongovernmental organizations, industry partners, and private landowners.

Climate change adaptation, or actions taken to reduce risks from changing climatic conditions and prepare for the effects of future changes (Lempert et al. 2018), will be necessary to maintain resilient ecosystems and sustainable natural resources. The process of climate change adaptation generally consists of four steps (Peterson et al. 2011): (1) synthesize and review current climate change science and integrate this information with local management and social conditions and contextual factors (review), (2) evaluate climate change sensitivities for key ecosystems and natural resources (evaluate), (3) develop and implement adaptation options (resolve), and (4) monitor the effectiveness of adaptation actions (observe) and adjust as needed. Elements from each of these steps should be integrated into locally relevant climate change vulnerability assessments.

Adaptation options developed from climate change vulnerability assessments describe specific actions that can be taken in response to climate change stressors to ensure sustainable natural resources, ecosystems, and natural processes (Peterson et al. 2011). **Adaptation strategies** have a broad focus conceptually and geographically and are first identified in response to a climate change sensitivity for a specific resource. **Adaptation tactics** are targeted and prescriptive actions that managers can implement to improve resilience to climate change at a particular location. Climate change adaptation tactics developed around broader strategies can range from small adjustments in historical management practices (e.g., upsizing a new culvert) to extensive, long-term projects (e.g., assisted migration of vulnerable tree species).

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[1] **Benjamin S. Soderquist** is a natural resource specialist, Intermountain Region, 324 25th Street, Ogden, UT 84401; **Jessica E. Halofsky** is the director, Western Wildland Environmental Threat Assessment Center and Northwest Climate Hub, Pacific Northwest Research Station, 3625 93rd Avenue SW, Olympia, WA 98512.

A climate change vulnerability assessment for the Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest Adaptation Partnership (hereafter referred to as CMWAP) was developed collaboratively to synthesize regionally focused climate change science, assess resource-specific climate change vulnerabilities, and develop locally relevant climate change adaptation options. Adaptation strategies and tactics were developed during a 2-day workshop held in Salem, Oregon, where climate change sensitivities and stressors were reviewed for six key resource areas: hydrology and infrastructure (chapter 3), fish and aquatic habitat (chapter 4), vegetation and disturbance (focusing on two vegetation types; chapter 5), wildlife (chapter 6), recreation (chapter 7), and ecosystem services (chapter 8). Breakout groups for each resource area identified a series of climate sensitivities and supporting adaptation strategies and tactics through facilitated discussion and worksheet exercises adapted from Swanston and Janowiak (2012). At the end of the workshop, adaptation strategies and tactics for each resource area were presented to the rest of the workshop group, and steps toward implementing them in future planning efforts and project designs were discussed.

This chapter describes the adaptation strategies and tactics that were developed to support sustainable management for each of the six resource areas mentioned above. We provide background on key climate sensitivities and discuss adaptation strategies and tactics identified during the workshop. Although the strategies and tactics presented here are not an exhaustive list of adaptation options, they do represent high-priority climate sensitivities and actions that are relevant to the CMWAP assessment area and, in many cases, the greater Pacific Northwest.

Adapting Management of Water Resources and Infrastructure to Climate Change

Climate Change Effects on Hydrology

Climate change can have direct effects on the hydrologic processes that control the timing and availability of water resources (chapters 2 and 3). In the CMWAP assessment area, precipitation occurs primarily in winter, with a large proportion falling as snow at high elevations. As temperatures increase, shifts from snow- to rain-dominated precipitation regimes can have numerous effects on the hydrologic function of ecosystems (Elsner et al. 2010).

Altered timing and amount of streamflow are a direct, well-documented effect of climate change (Stewart et al. 2005). Earlier peak flows in spring followed by prolonged low flows in summer may strain the availability of water resources to downstream ecosystems, agricultural resources, and communities. Higher variability in streamflow timing also increases the vulnerability of riparian and wetland ecosystems, fish populations, and built infrastructure such as roads, bridges, and facilities (Strauch et al. 2014). Extreme flood events, driven by earlier spring runoff and more frequent rain-on-snow events, can increase erosion, scour fish spawning beds, increase sedimentation from roads and trails, and elevate the risk of landslides and debris flows (Luce et al. 2012).

Climate change effects on hydrologic regimes will vary spatially and temporally across the CMWAP assessment area, where complex terrain and steep environmental and climatic gradients characterize the landscape. In addition to regional shifts in temperature and precipitation, local environmental characteristics such as geology, subsurface water storage capacity, topography, disturbance regimes, and downstream demand for water resources also influence overall sensitivity to hydrological shifts.

Adaptation Options for Maintaining Hydrologic Function in Riparian, Wetland, and Groundwater-Dependent Ecosystems

Functional riparian, wetland, and groundwater-dependent ecosystems are critical for the provision of water resources in the CMWAP assessment area. Degradation or loss of these systems with reductions in snowpack, decreased groundwater recharge, and prolonged droughts can have adverse effects on water storage, quantity, and quality, as well as the fish and wildlife populations that depend on these habitats. Restoring wetland and riparian ecosystems to increase resiliency to a warmer, more variable climate will help increase hydrologic function, habitat connectivity, and water quality (Beechie et al. 2013, Pollock et al. 2014). Resource managers can restore degraded habitats and protect existing hydrologic and ecological refugia by managing grazing in riparian corridors, improving soil stability, maintaining areas that provide groundwater storage, and minimizing access to degraded areas (table 9.1 and app. table 9A.1).

Adaptation Options for Responding to Water Shortages

Water shortages are anticipated with higher temperatures, reduced summer streamflow, and increased demand for water resources with growing human populations. Adapting to these pressures will require up-to-date inventories of water users and their water rights, as well as assessments on current restrictions on water withdrawals (e.g., maintaining adequate environmental flows). Water protection plans can also be developed or revised to protect headwater catchments and other primary water sources to maintain streamflows and improve water quality. As water supplies become increasingly limited, managers will likely need to expand their efforts and work across boundaries with other agencies, irrigators, stakeholders, and industry partners to align water-use practices to increase water conservation (table 9.1 and app. table 9A.1).

Table 9.1—Water resources and infrastructure adaptation options for the Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest Adaptation Partnership assessment area

Sensitivity to climate change	Adaptation strategy	Adaptation tactic
High peak flows and flooding will lead to increased road damage at stream crossings, causing increased sediment delivery to streams and damage to infrastructure.	Increase resiliency of infrastructure (e.g., roads, trails, and recreation sites) to higher peak flows and floods.	• Inform travel management updates and right-size existing transportation infrastructure. • Develop and maintain an inventory of at-risk infrastructure. • Upgrade, relocate, or close vulnerable infrastructure.
Water quantity and quality needed to support municipal supplies/domestic users, hatcheries, irrigation, and environmental flows will be reduced with climate change and increased demand.	Adapt water usage to conserve available supply and maintain water quality.	• Improve water rights and uses inventories. • Implement source water protection and water quality restoration plans. • Work with irrigators and hatcheries to increase water conservation measures and water use from alternate sources.
Climate change will increase vulnerability of groundwater-dependent ecosystems (GDEs), wetlands, and riparian areas.	Increase resilience of GDEs and riparian areas to climate change.	• Diversify and restore riparian areas to buffer against future streamflow changes; maintain water storage capacity. • Protect and restore GDEs from grazing and other operations. • Increase upland water storage and improve soil quality and stability by maintaining springs and wetlands. • Work across jurisdictions at larger scales by aligning budgets and priorities to reduce effects of increasing disturbance events.

Adaptation Options for Roads and Infrastructure

National forests frequently have a large backlog of culverts and road segments in need of repair, replacement, or upgrade. However, capacity and funding limitations often hinder these efforts. The extensive, heavily used transportation and road networks across the CMWAP assessment area may be increasingly vulnerable to shifts in streamflow, increased flooding, and increased access and use by recreationists during spring and fall as snowpacks decline (chapters 3 and 7). The following adaptation strategies can help address these stressors: (1) increase resilience of road system infrastructure to flood events, focusing on stream crossings and roads near stream channels; (2) increase resilience to landslides by protecting roads and structures from higher landslide frequency, and reduce management activities that increase landslide potential; (3) increase resilience of stream conditions to low flows; and (4) increase resilience of recreation facilities, stream crossings, historic and cultural sites, and points of diversion to peak flows, and improve public safety. Potential tactics that support these strategies include upsizing flood-prone culverts (strategy 1 above), decommissioning roads where there is high landslide risk (strategy 2), restoring riparian vegetation to increase coldwater refugia (strategy 3), and minimizing damage to high-traffic areas by controlling visitor numbers (strategy 4).

Managers may need to plan for more road decommissioning and rerouting. In some locations, adapting road management to climate change may require further reductions in the road system because actions to increase resilience will not be possible on all road segments with current funding. For example, priority for decommissioning may be given to roads that are in basins with the highest risk of increased peak flows and flooding, in areas of high landslide risk, in floodplains of large rivers, or on adjacent low terraces.

To address these vulnerabilities, updated inventories will be needed for existing roads, bridges, and culverts, and updated transportation management plans will be needed to support infrastructure construction, repair, and maintenance (table 9.1). For example, information on locations in the transportation system that currently experience frequent flood damage can be combined with spatially explicit data on projected changes in flood and landslide risk and current infrastructure condition, to identify where damage is most likely.

With higher temperatures, there may be more demand for public access to national forests during times when floods, landslides, and wildfires are occurring (chapter 7), potentially increasing risks to public safety. Recreation facilities and management of historic and cultural resources may need to be modified to address increased risk of these disturbances. Improving travel and access updates near high-use recreation sites and facilities will help minimize human risk and infrastructure damage during storms or with shifts in access patterns. When upgrading or maintaining infrastructure, work can be prioritized in high-use, flood-prone, and unstable areas (table 9.1). The high cost of relocating buildings and protecting resources from flooding and erosion hazards will be a significant barrier as flood risk continues to increase. Infrastructure may ultimately need to be relocated or decommissioned to protect natural resources and human safety in places where hydrologic changes create major hazards.

Conclusions

Altered hydrologic processes and water resources can affect many different resources in the CMWAP assessment area. Fortunately, adaptation options often have multiple benefits for both natural and built systems. For example, increasing the capacity of riparian areas, wetlands, and groundwater-dependent ecosystems to store and slowly release water can help minimize the negative effects of flooding on roads, trails, and bridges, while also mitigating prolonged low streamflows and potential water shortages that occur later in summer (Pollock et al. 2014). Increasing efforts to inventory and monitor vulnerable infrastructure (e.g., trails, roads, or stream crossings) and watershed function will improve organizational capacity to coordinate restoration and maintenance work under increasingly uncertain conditions.

Adapting Management of Fisheries and Aquatic Ecosystems to Climate Change

Climate Change Effects on Aquatic Ecosystems

The effects of climate change on hydrologic processes are expected to have significant effects on aquatic ecosystems. Higher temperatures will result in continued reductions in the proportion of precipitation falling as snow (Klos et al. 2014, Lute and Luce 2017, Mote et al. 2018). Shifts in precipitation type can directly influence streamflow, with winter flows potentially becoming flashier, and peak flows occurring earlier in spring (Regonda et al. 2005, Stewart et al. 2005). Increasingly variable winter flows and earlier spring flows can also lead to prolonged low flows during summer. Reduced summer flows can reduce the amount of coldwater habitat available and reduce channel and floodplain connectivity below the levels needed by many coldwater fish species (Isaak et al. 2016).

Water quality can also be influenced by shifts in climatic and hydrologic regimes. Water temperatures in many streams will rise with warming air temperatures, potentially crossing thermal thresholds that can lead to mortality of fish and other aquatic species (Isaak et al. 2012). However, in addition to altered water quality, the vulnerability of aquatic and riparian habitats in the CMWAP assessment area to climatic and hydrologic shifts can also be influenced by nonclimatic factors including local geology, groundwater storage, topography, elevation, historical land use practices, and invasive species. These factors interact with climate change stressors, so future effects on aquatic ecosystems will differ across the landscape (chapter 4).

Climate change poses significant challenges for fisheries management in the Pacific Northwest. In the assessment area, fisheries managers must account for the habitat requirements and life-cycle characteristics of both freshwater and anadromous fish species (Mantua and Raymond 2014). Unlike resident fish species, anadromous species will face additional climate change sensitivities across the coastal and ocean habitats where their migrations to freshwater streams originate (Beechie et al. 2013, Eliason et al. 2011). Migrating salmon (*Oncorhynchus* spp.) and steelhead (*O. mykiss* Walbaum), which are present in the assessment area, are increasingly vulnerable to changing marine and migration corridor conditions outside the assessment area. Adapting fisheries management to maintain habitat connectivity and quality across large headwater-to-coastal gradients will require coordinated efforts across management agencies and collaborative partnerships that implement restoration and conservation projects.

Adaptation Options for Conserving Coldwater Refugia and Habitat Connectivity

Conserving existing habitat and restoring degraded habitat to allow for fish passage and to provide refuge from warm water will be essential for maintaining resilient populations of coldwater and anadromous fish species (Luce et al. 2012, Rieman and Isaak 2010). Increasing habitat connectivity across management boundaries and between riparian and aquatic ecosystems will maximize access to coldwater refugia, increase biological and genetic diversity, and help restore natural ecosystem processes and function to historically degraded habitats (Rieman et al. 2015). Managers can improve the resilience of coldwater fish populations by maintaining or improving critical habitat and connectivity, reestablishing natural processes (e.g., fire, sedimentation, streamflow), reducing negative impacts of invasive species, and leveraging partnerships to increase and expand efforts across management boundaries (table 9.2 and app. table 9A.2). Potential tactics that can support these strategies include implementing watershed-scale restoration projects with neighboring partners, coordinating monitoring efforts between state and federal agencies, and increasing education and outreach to stakeholders and water users.

Reduced aquatic habitat connectivity and coldwater refugia driven by lower streamflows and increasing stream temperatures are high-priority climate change sensitivities in the CMWAP assessment area (chapter 4). A strategy for adapting aquatic systems to these stressors is to restore habitat connectivity across scales—from smaller lateral gradients extending from the streambed to the outer edge of riparian corridors, to broader longitudinal gradients spanning headwater basins to estuarine and coastal ecosystems. Adaptation tactics that support this strategy, such as replacing culverts with bridges to increase fish passage, emphasize reestablishing natural processes that have been degraded in recent decades, such as disturbance and sediment deposition (table 9.2).

Increasing aquatic habitat connectivity and coldwater refugia will also be an effective strategy for increasing the resilience of native fish populations to reduced summer flows and rising stream temperatures (table 9.2 and app. table 9A.2). Connectivity and coldwater refugia can be managed in several ways including restoration of riparian vegetation, stream channel restoration, reconnecting channels and floodplains, and streamflow regulation below dams. However, improving habitat connectivity can also benefit nonnative fish species (Isaak et al. 2012).

To mitigate negative impacts of competition with native fishes, managers can increase monitoring of invasive fish populations and implement programs to remove unwanted fish from vulnerable streams (app. table 9A.2).

Conclusions

Many adaptation strategies and tactics identified for fish and aquatic ecosystems are already widely used in current riparian and stream restoration programs. However, responding to the effects of climate change means that future management actions will need to be designed around projections of changing conditions and implemented at broader scales and at increasing rates to keep pace with climatic shifts. Fortunately, there are many opportunities on publicly managed headwater streams, wetlands, and riparian areas to restore habitat connectivity to support a sufficient network of coldwater refugia (Isaak et al. 2012) (table 9.2 and app. table 9A.2). In addition, taking proactive steps to use climate change information to identify and coordinate restoration efforts in the most vulnerable or degraded watersheds can have numerous downstream benefits for water storage, water quality, and recreational opportunities.

Adapting Forest Vegetation to Disturbance and Climate Change

Climate Change Effects on Vegetation

Climate change can affect forest vegetation directly and indirectly. Increasing temperatures can directly alter plant phenology and the length and timing of growing seasons at elevations where growth during spring and fall has been historically energy limited (Goulden and Bales 2014). Shifts in precipitation regimes from snow dominated to rain dominated can alter the timing and amount of soil moisture availability (Harpold and Molotch 2015). Warming temperatures and increasing evaporative demand will lead to hotter and drier summers, potentially reducing vegetation growth during periods of drought (Ficklin and Novick 2017). These climatic shifts may be rapid in some areas, driving more frequent and extreme drought and disturbance events than some forest ecosystems experienced in the past.

Trees and other vegetation are often resilient to occasional extreme weather conditions. However, this resilience has limitations, and some drought-intolerant species may exceed climate-related mortality thresholds in response to warming temperatures and more frequent and severe drought (Allen et al. 2010, Anderegg et al. 2015). Younger trees, particularly seedlings, may also be vulnerable to extreme drought conditions (Stevens-Rumann and Morgan 2019). As a result, water-limited ecosystems comprising vegetation with differing drought tolerances and seral stages

Table 9.2—Fish and aquatic habitat adaptation options for the Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest assessment area

Sensitivity to climate change	Adaptation strategy	Adaptation tactic
Climate change and shifting streamflows may reduce lateral and longitudinal aquatic habitat connectivity.	Increase and maintain lateral and longitudinal habitat connectivity and heterogeneity across riparian and aquatic ecosystems.	• Restore aquatic ecosystems at the reach scale by removing artificial constrictions, dams, roads, and diversions, and by reducing water withdrawals. • Restore natural regimes and functions at the watershed scale. • Maintain, monitor, and protect properly functioning watershed processes.
Decreased snowpack and earlier peak flows lead to reduced summer streamflow.	Increase the quantity and access to summer rearing habitat.	• Increase connectivity. • Increase instream flow.
Increasing summer temperatures will lead to warming stream temperatures.	Increase habitat resilience to climate change.	• Restore structure and function of streams. • Enhance and protect hyporheic zones. • Restore and maintain riparian vegetation.
Warmer stream temperatures may favor nonnative species.	Increase resilience of native fish species through management of nonnative species.	• Monitor nonnative population distributions/abundance. • Suppress, eliminate, or control invasive species populations. • Develop outreach and education for target audiences at sensitive sites.

may be sensitive to increasing drought-induced mortality or indirect disturbance, such as insect outbreaks and wildfire.

Adaptation strategies developed during the assessment workshop focused on (1) mixed Oregon white oak (*Quercus garryana* Douglas ex Hook.) and ponderosa pine (*Pinus ponderosa* Douglas ex P. Lawson & C. Lawson) forests, and (2) western hemlock (*Tsuga heterophylla* [Raf.] Sarg.) forests. Increasing frequency and severity of fire and biotic attacks were the primary concern for both forest ecosystems. Maintaining or increasing the resilience of these vegetation types will help mitigate the negative effects of increasing disturbance and drought severity (Hessburg et al. 2016).

Adaptation Options in Mixed Oak and Pine Forests

Mixed Oregon white oak and ponderosa pine forests occur at lower elevations in the CMWAP assessment area (chapter 5) (figs. 5.2 through 5.4). Although oak/pine forests are relatively rare compared to other forest types, they provide wildlife habitat and support biodiversity within the matrix of more common vegetation. Warming temperatures may lead to earlier spring growth and an overall increase in growing season length at higher elevations and more mesic locations. Vegetation growth is typically water limited in oak/pine forests, and increased drought and reduced soil moisture availability may reduce summer and fall productivity. Increasing temperatures and shifts in drought frequency and intensity are projected across the range of mixed oak/pine stands, potentially leading to more frequent beetle outbreaks, fires, and establishment of invasive species (Hessburg et al. 2015, 2016).

Adapting these forest types to changing climate and disturbance regimes includes a range of options that increase or maintain resilient forests across the landscape (table 9.3). Mapping current and potential mixed oak/pine refugia as well as the current distribution of invasive plants across the assessment area will help managers prioritize locations for treatment and protection. For example, high-priority locations could include sites with legacy trees and undisturbed native plant communities. Managers can reduce stand densities via prescribed burning and mechanical treatments and suppress fires where wildfire would cause adverse outcomes (e.g., the wildland-urban interface [WUI] or critical wildlife habitat; table 9.3 and app. table 9A.3).

Adaptation Options in Western Hemlock Forests

Western hemlock forests occur at middle to higher elevations where biophysical conditions tend to be cool and moist (figs. 5.2 through 5.4). As growing seasons lengthen with warmer temperatures, western hemlock stands may become increasingly vulnerable to more frequent drought, beetle outbreaks, and invasive species (table 9.4 and app. table 9A.4). Adaptation tactics identified to support increased western hemlock resilience include (1) reducing stand density to reduce drought stress, and (2) increasing genetic diversity by planting seedlings propagated from a variety of seed zones (table 9.4). These tactics can be prioritized at locations along lower elevation transition zones where vulnerability to drought, disturbance, and shifts in vegetation type is typically the greatest (Hessburg et al. 2015) or where patches of climate change refugia are most likely to occur (Morelli et al. 2016).

Conclusions

Climate change can affect vegetation directly and indirectly, resulting in complex ecosystem responses. To increase the effectiveness of large-scale treatments, managers can leverage existing partnerships to develop new collaborative projects that expand restoration and conservation efforts across management boundaries. However, climate stressors interact with other landscape characteristics in complex

Table 9.3—Adaptation options for mixed oak and pine forests in the Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest Adaptation Partnership assessment area

Sensitivity to climate change	Adaptation strategy	Adaptation tactic
Dry oak/pine woodlands will experience earlier and prolonged fire seasons with warmer temperatures.	Maintain and increase resilience of oak/pine forests to fire.	• Identify current and potential refugia along with areas that may transition to other forest or vegetation types with warming temperatures. • Reduce stand densities and fuels to shift composition toward species that are more drought tolerant. • Map, reduce, and mitigate the spread of invasive plants that increase fire risk. • Protect legacy trees and enhance native plant communities through site preparation, planting, or seeding.
Increasing drought stress may lead to more frequent and severe bark beetle outbreaks and forest mortality events.	Decrease stand susceptibility to bark beetle outbreaks.	• Use thinning, prescribed fire, and wildfire, managed for resource benefits to reduce stand density, with density and structural goals based on projected future conditions. • Promote age class and structural diversity across the landscape through regeneration harvest, thinning, prescribed fire, and wildfire managed for resource benefits. • Reforest sites with consideration of appropriate genetics and species composition to reduce susceptibility to future outbreaks. • Manage slash piles to prevent *Ips* beetle outbreaks.
Climate change may lead to increased establishment and spread of invasive species.	Maintain integrity of native plant populations and prevent invasive species establishment.	• Use early detection/rapid response when implementing herbicide treatments and other direct eradication methods to prevent invasive plant introductions during projects. • Promote weed-free seed and seed native plant species in areas with invasive species. • Ensure weed-free policies are included in planning documents and coordinate weed-free seed standards and regulations among agencies. • Reduce grazing practices that encourage spread of invasive species.

ways, making projections of vegetation response and management effectiveness difficult (Millar et al. 2007). Despite this uncertainty, managers can integrate their knowledge and expertise with locally relevant scientific information to design and implement climate adaptation projects. In general, adaptation tactics that provide “win-win” opportunities to benefit multiple resource areas (e.g., wildlife habitat and fuels reduction) will be the most efficient to implement at the large spatial scales required for effective vegetation management.

Table 9.4—Adaptation options for western hemlock forests in the Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest Adaptation Partnership assessment area

Sensitivity to climate change	Adaptation strategy	Adaptation tactic
Climate change will lead to increased drought stress, more frequent disturbances, and decreased habitat suitability in western hemlock forests.	Maintain and increase resilient western hemlock forests.	• Reduce stand density, change planting strategies, and increase species diversity to reduce drought stress. • Incorporate more locally adapted species in managed stands. • Increase genetic diversity via mixed seed sources that are locally adapted to have genetic variation that is suited to contend with pathogen, insect, and climate pressures. • Prioritize ecosystem edges and transition zones when introducing genotypes and species outside their current range.
Higher temperatures may increase drought stress in high-elevation western hemlock forests.	Identify, protect, and monitor potential and existing refugia.	• Work across management boundaries when planning and investing in restoration projects. • Map current and future western hemlock refugia. • Facilitate establishment of dispersal-limited species in potential refugia (e.g., assisted migration).
Climate change will lead to increased opportunity for invasive species establishment in western hemlock forests.	Implement early detection/rapid response and prevention approaches when managing invasive species.	• Reseed with native species or treat invasive species before establishment can occur. • Monitor the spread and establishment of invasive species through aerial and on-the-ground surveys. • Increase prevention efforts.

Adapting Wildlife Habitat to Climate Change

Climate Change Effects on Wildlife Habitat

Wildlife and the habitat they depend on are sensitive to numerous and interacting climatic and environmental stressors. These stressors can affect a variety of habitat types. For example, open large-tree ponderosa pine forests at lower elevations are critical habitat for ungulates and bird species, including the flammulated owl (*Psiloscops flammeolus* Kaup) and white-headed woodpecker (*Leuconotopicus albolarvatus* Cassin). These forests may be vulnerable to increased fire frequency and extent caused by increasing drought frequency, high levels of fuel loading relative to historical conditions, and proximity to residential developments where human-caused ignitions are more likely. Other climate sensitivities of wildlife habitat in the CMWAP assessment area include altered distribution and abundance of plant species resulting from altered disturbance regimes, decreased habitat connectivity caused by shifts in vegetation type or repeated disturbances, and loss of water-dependent habitat refugia, such as riparian areas, wetlands, and meadows

(McLaughlin et al. 2017) (chapter 6). Adaptation strategies and tactics focus on maintaining late-successional, riparian, and wetland habitats and increasing habitat connectivity across large landscapes.

Adaptation Options for Late-Successional Habitat

In the CMWAP assessment area and the greater Pacific Northwest, late-successional forests provide critical wildlife habitat and continue to be a conservation priority for forest and wildlife managers (Stine et al. 2014). Over the past century, land use conversion, timber harvest, and fire exclusion have diminished the amount and quality of late-successional habitat (LSH) as well as connectivity between habitat patches (Mershel et al. 2014). Climate change may further diminish the amount of remaining LSH through changes in drought, fire, and biotic disturbance regimes (Mawdsley et al. 2009). With disturbance events potentially increasing in frequency and extent, lower elevation LSH may be increasingly vulnerable to conversion to drier forest types that do not provide the habitat characteristics or structure required by LSH-obligate species (chapters 5 and 6).

To adapt LSH to these changes, old trees can be protected from disturbances by (1) thinning surrounding fuels to reduce fire risk, (2) developing or revising silvicultural programs to increase landscape heterogeneity (e.g., increased diversity in stand age or species composition), and (3) reintroducing fire on the landscape and managing wildfire in ways that mimic historical fire regimes (Lehmkuhl et al. 2015) (table 9.5). Managers can also consider managing human activities in areas where increasing access and recreational opportunities can have negative impacts on vulnerable LSH and wildlife species (chapter 7). Adaptation tactics aimed at managing visitor use or reducing the construction of trails and roads in vulnerable locations can accelerate the restoration process, improve habitat conditions, and increase wildlife resilience (app. table 9A.5).

Adaptation Options for Riparian and Wetland Habitats

Riparian areas and wetlands are hotspots for biodiversity, providing habitat for birds, amphibians, reptiles, and many other water-dependent species (Dwire and Mellmann-Brown 2017, chapter 6). Shifts in hydrologic regimes can directly affect aquatic habitats and wetlands (chapter 3). For example, the hydrologic function of many wetlands, fens, and riparian areas is often related to the amount and timing of snowpack accumulation and melt. At elevations where shifts from snow to rain may occur, warming temperatures can lead to significant reductions in snowpack that may have cascading impacts on wildlife that depend on habitats with snow.

Managers can help protect and retain rare and critical habitats by reducing grazing, preventing the spread of invasive species, and minimizing the effects of wildfire by reducing fuels where appropriate (table 9.5). Managers can also consider maintaining forest stands at specific densities to increase rates of snow deposition and retention. Restoring the hydrologic function of streams and wetlands can further increase or improve habitat resilience. For example, reconnecting channels and restoring stream structure can increase habitat connectivity, coldwater refugia, and establishment of riparian vegetation (Luce et al. 2012).

Table 9.5—Wildlife adaptation options for the Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest Adaptation Partnership assessment area

Sensitivity to climate change	Adaptation strategy	Adaptation tactic
Climate change and increasing disturbance may lead to a loss of habitat structure and spatial heterogeneity.	Increase resilience of late-successional habitat (LSH) and vegetation structure.	• Protect, maintain and recruit legacy structures (e.g., large trees, snags, downed wood). • Identify areas on the landscape where LSH is most at risk of shifting to a drier forest type. • Maintain a landscape that is likely to support mixed-severity fire.
Climate change may reduce resilience of high-priority riparian and wetland habitats including springs, bogs, fens, seeps, snowmelt-dependent meadows, lentic systems, and lotic systems.	Identify, retain, and restore riparian and wetland habitat for wildlife.	• Maintain and restore snow-dominated aquatic systems for habitat. • Maintain and restore streamside and riparian habitats. • Maintain and restore riparian and wet habitats including lotic and lentic systems that support rare or at-risk species.
Climate change may reduce habitat connectivity.	Provide opportunities for wildlife to move to new habitats in response to climate change.	• Identify and map areas where connectivity may be reduced with climate change. • Identify populations of native species that are likely to colonize adjacent areas. • Consider habitat connectivity during project planning.

Adaptation Options for Increasing Habitat Connectivity

Connectivity between habitat patches is critical for the movement of wildlife populations. Climate change may reduce habitat connectivity and opportunities for wildlife passage by accelerating habitat fragmentation through increased fire frequency and extent, increased drought intensity, and increased establishment of nonnative and invasive species (Hellmann et al. 2015). These effects can lead to expansion of dry forest and other drought-tolerant species into previously mesic areas or could potentially alter the dominant vegetation growth form (e.g., forest to grassland) (Halofsky et al. 2014, Hessburg et al. 2016).

Developing management plans to increase habitat connectivity can be difficult given the diverse ownerships, land use priorities, disturbance regimes, and landscapes that wildlife inhabit across the assessment area. However, projects that are coordinated across large spatial scales can improve habitat conditions for wildlife movement. Managers can consider adaptation tactics that increase habitat connectivity including (1) mapping and surveying areas where habitat connectivity is threatened by repeated disturbances, drought, future shifts in vegetation type, and human-related stressors; (2) mapping and surveying the spatial distribution of populations that can potentially colonize or repopulate habitats affected by disturbance and climate change; and (3) integrating habitat connectivity concepts into project plans, transportation plans, and land management planning (table 9.5 and app. table 9A.5).

Conclusions

Maintaining and restoring wildlife habitat and habitat connectivity across the landscape will continue to be a management priority in the assessment area. Fortunately, many of the treatments currently used to increase connectivity and improve habitat structure are also useful approaches for adapting to climate change. However, it can be challenging to work across management boundaries, and projections of how climate may facilitate novel conditions are uncertain. Expanding inventory programs, mapping, and monitoring of key habitats will help managers categorize vulnerable areas and prioritize project locations. Establishing or growing existing collaborative partnerships with watershed, fish, and wildlife conservation groups can facilitate more efficient project planning and implementation. Monitoring treatment effectiveness following project implementation will be critical to ensure long-term habitat sustainability.

Adapting Recreation to Climate Change

Climate Change Effects on Recreational Resources

Public lands in the CMWAP assessment area provide recreational opportunities across all seasons, and annual recreational demand is increasing with growing populations (chapter 7). Spatial and temporal patterns of access and recreation are linked with seasonal weather conditions. As a result, the interacting effects of increasing demand for recreation and climate change are creating multiple stressors on ecosystems and natural resources.

Shifting climatic regimes will alter the length of winter and summer recreation seasons in areas that are sensitive to changes in precipitation type. Climate change will directly affect winter recreation as warming temperatures lead to reduced snowpack and snow residence time, resulting in fewer opportunities for snow-based recreation (e.g., skiing and snowmobiling) at lower elevations. Although snow-based recreation opportunities may decline in some areas or occur over shorter seasons, they will likely be replaced by alternative forms of recreation (e.g., hiking and mountain biking) as access to previously snow-dominated elevations increases and warm-weather recreation seasons lengthen.

Rising temperatures may also lead to increased demand for water-based recreation. Shifts in precipitation regimes from snow dominated to rain dominated can lead to shifts in the timing and magnitude of streamflows during spring and summer (chapter 3). As a result, opportunities for floating, swimming, or fishing may occur earlier in the year or extend across longer seasons, depending on the type of recreation and water body. However, with earlier peak flows in spring, access to more water-limited sites may be reduced with lower summer streamflows and prolonged water shortages. Increasing streamflow variability, flooding frequency, and access to rivers and high-elevation sites earlier in the year will also lead to increased risk for recreationists. Climate change is expected to affect recreation patterns throughout the assessment area. Workshop attendees developed adaptation options for shifts in the timing of seasonal recreation, increased risk to disturbance and natural hazards (e.g., hazard trees), and increased demand for water-based recreation.

Adaptation Options for Shifting Seasonal Recreation

Shifts in the timing and spatial patterns of recreational use and opportunities are expected with warming temperatures. However, recreationists are typically highly adaptable and will likely shift their choice of recreation type or location under warmer or more variable conditions (chapter 7). Managers can prepare for year-round recreation use in areas where recreation was historically seasonal. Facilities and road networks near popular recreation sites may need to be improved to safely accommodate increased use, or decommissioned if safety risks are too high. For specific recreation types, such as skiing, managers can identify ways to increase access and recreational opportunities into higher elevations (tables 9.6 and app. table 9A.6). In addition, warmer summers may result in higher demand for water-based activities at low-elevation sites.

With continued warming, both high- and low-elevation recreation sites can become increasingly congested and vulnerable to human-related stressors. Mitigating the undesired effects of both increased use and climate change may require increased maintenance of facilities and infrastructure, additional staffing, and special permitting, all of which are challenges for managers who have limited financial resources and personnel.

Table 9.6—Recreation adaptation options for the Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest Adaptation Partnership assessment area

Sensitivity to climate change	Adaptation strategy	Adaptation tactic
Changing temperatures and seasonality will reduce access to snow-dependent recreation; winter recreation use will become concentrated in a smaller number of high-elevation sites over shorter seasons and increasingly replaced by summer recreation use over longer seasons.	Plan for year-round use, and for more concentrated use at higher elevations.	• Shift snow-dependent recreational facilities and access from low-elevation areas to high-elevation areas. • Invest in lower footprint temporary/mobile structures (portable entrance stations, yurts) in transitional areas, or permanent structures where there will be opportunities for year-round use. • Build sustainable roads and trails that can handle year-round use, and close or decommission unsustainable roads and trails. • Adjust staffing to handle shifting seasonal use, or collaborate with other groups to increase capacity for managing recreation.
Tree mortality from fire and other disturbances will lead to threats to infrastructure and public safety from hazard trees.	Plan for increased presence of dead and hazard trees on the landscape.	• Build temporary, disposable, or inexpensive infrastructure that is more resilient to impacts from falling trees. • Consider long-term recreation use and integrate hazard risk into recreation and restoration planning. • Identify locations where hazard trees or fallen trees will not be treated, and communicate risks to the public; develop a risk evaluation process for trails and dispersed recreation areas. • Invest in training and equipment to address presence of more dead trees on the landscape.
Warmer temperatures will lead to increased demand for water-based recreation, while hydrologic shifts simultaneously reduce quality and quantity of water at recreation sites.	Plan for shifts in the timing and demand for water-based recreation.	• Construct more developed sites to access water (boating/swimming), and redesign or restrict access to vulnerable sites. • Extend existing boat ramps to handle lower water levels, and create temporary infrastructure to handle changing and more extreme conditions. • Conduct additional research on effects of algal blooms on recreational use, and develop appropriate responses.

Adaptation Options to Reduce Risk to Disturbance and From Hazard Trees

Hazard trees represent a significant risk to recreationists. Increasing tree mortality following disturbance events, such as wildfires and insect outbreaks, will elevate the risk created from dead trees that can fall on campsites or across travel corridors. Managers will be challenged to raise public awareness, and in extreme circumstances, manage risk by controlling public access to areas where hazard trees are prevalent. To adapt developed sites to increasing damage risk, managers can consider installing structures that are temporary, easily replaced, or more structurally resistant to damage from falling trees (table 9.6).

Snags and hazard trees can remain on the landscape for decades. Implementing adaptation tactics that integrate hazard-tree risks in recreation management and restoration planning can reduce exposure and damage over longer periods of time. Managers can prioritize mapping efforts to better understand current and future high-risk areas and integrate this information into recreation management plans and evacuation procedures.

As disturbance events grow in frequency and extent, hazard trees may become a risk that cannot be completely avoided. To mitigate exposure, managers can invest in public and internal workforce education, hazard-tree removal programs, and coordination efforts that maximize hazard reduction while minimizing exposure to agency employees and the public (table 9.6 and app. table 9A.6).

Responding to Increasing Demand for Water-Based Recreation

Increased demand for water-based recreation will likely lead to higher concentrations of users in riparian corridors, lakes, and other aquatic ecosystems. Providing sustainable recreation while maintaining water quality and ecosystem function will be a growing management challenge as climatic and human-caused stressors increase. Managers can consider increasing maintenance efforts or constructing more resilient infrastructure (e.g., trails, boat ramps, and parking areas) to prepare for increased and prolonged seasonal use in popular locations (table 9.6). For example, in lakes and reservoirs that experience significant summer withdrawals or fluctuations, boat ramps and launches may need to be extended to allow continued access by watercraft during periods of drought. If infrastructure cannot be adapted to account for increased use and climate change stressors, public access may need to be managed through temporary closures or permitting programs.

Human health and safety may also be a growing concern on some water bodies. Earlier and higher spring peak flows may increase the risk of drowning, particularly as the number of floaters increases during the late spring. Some lakes and reservoirs may be vulnerable to toxic algal blooms as warming water temperatures create conditions that are suitable for rapid and prolonged algae growth (tables 9.6 and app. 9A.6). To mitigate these risks, managers can consider increasing hazard and safety communication programs, consulting with local search-and-rescue groups to revise rescue and evacuation plans, and working with stakeholders to identify vulnerable sites and develop coordinated rapid-response plans (e.g., closure of a beach in response to algal blooms). Implementing tactics that increase flexibility in the ways recreational access and seasonal staffing resources are managed will facilitate recreation opportunities under changing and more variable conditions.

Conclusions

In the CMWAP assessment area, warming temperatures will drive shifts in seasonal opportunities and patterns of use. To adapt to changing seasonality, increasing recreational demands, and safety concerns, managers can consider a wide range of adaptation options that increase their flexibility to reduce the negative effects of recreational use in sensitive areas while providing sustainable recreation opportunities. Managers can further expand their work capacity by leveraging existing partnerships with local recreation and conservation groups to help identify vulnerable locations, maintain recreation sites and infrastructure, and increase communication and outreach to the public.

Adapting Ecosystem Services to Climate Change

Adaptation Options for Forage Production and Grazing

Many ecosystem services in the CMWAP assessment area are tied to plant phenology and seasonal fluctuations in vegetation productivity. Warming temperatures, shifts in precipitation, and increasing carbon dioxide levels can have interacting but significant effects on growing season length and other conditions (chapter 5). Shifts in the timing and amount of vegetation growth can affect numerous ecosystem services, particularly public land grazing and the production of forage for livestock.

Grazing on public lands must be carefully managed to ensure sustainable forage production while minimizing negative effects on ecosystem function. With shifting growing seasons, climate-smart grazing practices can increase the flexibility of managers and ranchers to vary the timing and intensity of grazing to better align with seasonal forage growth and reproductive cycles, while minimizing the spread of invasive plants and damage to root systems, soils, and water resources. These management strategies are most effective when they are collaborative and applied across multiple management boundaries (table 9.7 and app. table 9A.7).

Adaptation Options in the Wildland-Urban Interface

Much of the assessment area is in the wildland-urban interface (WUI). Warming temperatures, along with continued population and growth and development in the WUI, will increase fire risk to many ecosystem services, communities, and infrastructure across longer fire seasons. Assessing fire risk at the community level will be essential for maintaining safe conditions and planning climate-smart development. To improve risk assessments, managers can expand the use of fire risk frameworks to better identify high-risk locations, communicate risks to local communities, and develop solutions that minimize fire danger (table 9.7 and app. 9A.7). These fire-safe concepts can also be incorporated in zoning laws and regulations that guide the development of communities in the WUI. Implementing adaptation tactics that safeguard ecosystem services while ensuring safe communities will depend on successful partnerships, active education and outreach, and local commitment to long-term projects.

Adaptation Options for Carbon Sequestration and Landscape Aesthetics

Highly productive forest ecosystems in the assessment area play an important role in carbon storage and sequestration (Rogers et al. 2011) (chapter 8). However, forest successional trajectories and the interacting effects of more frequent drought and disturbance events can influence the rate of carbon sequestration and the capacity of ecosystems to act as a net carbon source or sink. To increase the scale of management strategies that increase carbon sequestration, managers can increase awareness about the importance of managing resilient forests for carbon benefits. Recently disturbed sites and vegetation transition zones can be opportunities to enhance carbon sequestration through restoration projects and educating the public on the carbon cycle and carbon management (table 9.7 and app. table 9A.7). Partnerships with state and local agencies as well as private landowners can also help expand the implementation of carbon sequestration projects across management boundaries.

Raising awareness about climate change effects linked to forest ecology, carbon sequestration, and disturbance regimes can also be a tactic to help manage public expectations for general landscape aesthetics. Shifting climate and disturbance regimes will likely alter landscapes across the assessment area in ways that cannot be easily predicted or avoided, even with the best available science or significant management actions. Increasing education and outreach to communicate how ecosystem services, such as scenic values, water resources, and recreational opportunities, may change will help residents prepare for and adapt to changes in their local environment.

Table 9.7—Ecosystem services adaptation options for the Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest Adaptation Partnership assessment area

Ecosystem service	Sensitivity to climate change	Adaptation strategy	Adaptation tactic
Grazing	Shifting climatic variability and warming temperatures will affect grazing resources and policy.	Develop an all-lands, holistic approach to grazing management.	• Modify flexibility in timing, duration, and intensity of authorized grazing. • Use grazing as a tool to achieve desired conditions (e.g., targeted grazing of noxious weeds). • Minimize livestock impacts by designing more resilient livestock water sources or restricting access to vulnerable locations. • Consider adding pollinator habitat as a component of grazing/pasture unit management.
Communities in the wildland-urban interface (WUI)	Increasing fire frequency and extent will increase fire risk to communities located in the WUI.	Prioritize and expand fuels management projects in vulnerable WUI locations.	• Use fire-risk models to prioritize and map high-risk areas, and identify solutions to increase resilience of WUI communities. • Encourage markets for biomass generated from fuel treatments where cost recovery is a challenge and prescribed burning may not be an option. • Integrate wildfire risk into community planning efforts.
First foods	Climate change and vegetation shifts may shift seasonality and availability of first foods.	Identify opportunities to support the expansion of first-food sources through vegetation management.	• Use restoration projects to increase resilience of first-foods sources (e.g., Oregon white oak ecosystems).
Carbon sequestration	Climate change may increase or decrease the capacity of ecosystems to sequester carbon.	Increase internal and external educational opportunities to manage carbon resources and sequestration.	• Improve understanding (internally and externally) that short-term loss of carbon storage may be necessary to provide for long-term carbon sequestration and other objectives. • Identify opportunities for enhancing carbon sequestration following disturbance (e.g., following fire, plant native perennial grasses and forbs that promote carbon sequestration in the soil).
Landscape aesthetics	Climate change and increasing disturbance events may reduce visual aesthetics of high-value landscapes and ecosystems.	Enhance public understanding of the role of disturbance in changing landscape aesthetics.	• Identify scenic values and vulnerable sites; develop plans to maintain visual values. • Manage public expectations of landscape change and disturbance (e.g., fire, smoke, and forest mortality). • Use postdisturbance restoration to increase scenic values and landscape resilience.

Literature Cited

Allen, C.D.; Macalady, A.K.; Chenchouni, H. [et al.]. 2010. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. Forest Ecology and Management. 259: 660–684.

Anderegg, W.R.; Hicke, J.A.; Fisher, R.A. [et al.]. 2015. Tree mortality from drought, insects, and their interactions in a changing climate. New Phytologist. 208: 674–683.

Beechie, T.; Imaki, H.; Greene, J. [et al.]. 2013. Restoring salmon habitat for a changing climate. River Research and Applications. 29: 939–960.

Dwire, K.A.; Mellmann-Brown, S. 2017. Climate change and special habitats in the Blue Mountains: riparian areas, wetlands, and groundwater-dependent ecosystems. In: Halofsky, J.E.; Peterson, D.L., eds. Climate change vulnerability and adaptation in the Blue Mountains. Gen. Tech. Rep. PNW-GTR-939. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 251–323.

Eliason, E.J.; Clark, T.D.; Hague, M.J. [et al.]. 2011. Differences in thermal tolerance among sockeye salmon populations. Science. 332: 109–112.

Elsner, M.M.; Cuo, L.; Voisin, N. [et al.]. 2010. Implications of 21st century climate change for the hydrology of Washington State. Climatic Change. 102: 225–260.

Ficklin, D.L.; Novick, K.A. 2017. Historic and projected changes in vapor pressure deficit suggest a continental-scale drying of the United States atmosphere. Journal of Geophysical Research: Atmospheres. 122: 2061–2079.

Goulden, M.L.; Bales, R.C. 2014. Mountain runoff vulnerability to increased evapotranspiration with vegetation expansion. Proceedings of the National Academy of Sciences, USA. 111: 14071–14075.

Halofsky, J.S.; Halofsky, J.E.; Burcsu, T.; Hemstrom, M.A. 2014. Dry forest resilience varies under simulated climate-management scenarios in a central Oregon, USA landscape. Ecological Applications. 24: 1908–1925.

Harpold, A.A.; Molotch, N.P. 2015. Sensitivity of soil water availability to changing snowmelt timing in the Western U.S. Geophysical Research Letters. 42: 8011–8020.

Hellmann, J.J.; Byers, J.E.; Bierwagen, B.G.; Dukes, J.S. 2008. Five potential consequences of climate change for invasive species. Conservation Biology. 22: 534–543.

Hessburg, P.F.; Churchill, D.J.; Larson, A.J. [et al.]. 2015. Restoring fire-prone inland Pacific landscapes: seven core principles. Landscape Ecology. 30: 1805–1835.

Hessburg, P.F.; Spies, T.A.; Perry, D.A. [et al.]. 2016. Tamm review: management of mixed-severity fire regime forests in Oregon, Washington, and northern California. Forest Ecology and Management. 366: 221–250.

Isaak, D.J.; Wollrab, S.; Horan, D.; Chandler, G. 2012. Climate change effects on stream and river temperatures across the northwest U.S. from 1980–2009 and implications for salmonid fishes. Climatic Change. 113: 499–524.

Isaak, D.J.; Young, M.K.; Luce, C.H. [et al.]. 2016. Slow climate velocities of mountain streams portend their role as refugia for cold-water biodiversity. Proceedings of the National Academy of Sciences. 113: 4374–4379.

Klos, P.Z.; Link, T.E.; Abatzoglou, J.T. 2014. Extent of the rain-snow transition zone in the western U.S. under historic and projected climate. Geophysical Research Letters. 41: 4560–4568.

Lehmkuhl, J.F.; Gaines, W.L.; Peterson, D.W. [et al.]. 2015. Silviculture and monitoring guidelines for integrating restoration of dry mixed-conifer forest and spotted owl habitat management in the eastern Cascade Range. Gen. Tech. Rep. PNW-GTR-915. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 158 p.

Lempert, R.; Arnold, J.; Pulwarty, R. [et al.]. 2018. Reducing risks through adaptation actions. In: Reidmiller, D.R.; Avery, C.W.; Easterling, D.R. [et al.], eds. Impacts, risks, and adaptation in the United States: fourth national climate assessment. Volume II. Washington, DC: U.S. Global Change Research Program: 1309–1345.

Luce, C.H.; Morgan, P.; Dwire, K.A. [et al.]. 2012. Climate change, forests, fire, water, and fish: building resilient landscapes, streams and managers. Gen. Tech. Rep. RMRS-GTR-290. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 207 p.

Lute, A.C.; Luce, C.H. 2017. Are model transferability and complexity antithetical? Insights from validation of a variable-complexity empirical snow model in space and time. Water Resources Research. 53: 8825–8850.

Mantua, N.J.; Raymond, C.L. 2014. Climate change, fish, and aquatic habitat in the North Cascade Range. In: Raymond, C.L.; Peterson, D.L.; Rochefort, R.M., eds. Climate change vulnerability and adaptation in the North Cascades region, Washington. Gen. Tech. Rep. PNW-GTR-892. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 235–270.

Mawdsley, J.R.; O'Malley, R.; Ojima, D.S. 2009. A review of climate-change adaptation strategies for wildlife management and biodiversity conservation. Conservation Biology. 23: 1080–1089.

McLaughlin, B.C.; Ackerly, D.D.; Klos, P.Z. [et al.]. 2017. Hydrologic refugia, plants, and climate change. Global Change Biology. 23: 2941–2961.

Mershel, A.G.; Spies, T.A.; Heyerdahl, E.K. 2014. Mixed-conifer forests of central Oregon: effects of logging and fire exclusion vary with environment. Ecological Applications. 24: 1670–1688.

Millar, C.I.; Stephenson, N.L.; Stephens, S.L. 2007. Climate change and forests of the future: managing in the face of uncertainty. Ecological Applications. 17: 2145–2151.

Morelli, T.L.; Daly, C.; Dobrowski, S.Z. [et al.]. 2016. Managing climate change refugia for climate adaptation. PLoS ONE. 11: e0159909.

Mote, P.W.; Li, S.; Lettenmaier, D. [et al]. 2018. Dramatic declines in snowpack in the Western U.S. Npj Climate and Atmospheric Science. 1: 2.

Obama, B. 2013. Executive Order 13653—preparing the United States for the impacts of climate change. Washington, DC: The White House, Office of the Press Secretary. https://obamawhitehouse.archives.gov/the-press-office/2013/11/01/executive-order-preparing-united-states-impacts-climate-change. (21 January 2021).

Peterson, D.L.; Millar, C.I.; Joyce, L.A. [et al.]. 2011. Responding to climate change on national forests: a guidebook for developing adaptation options. Gen. Tech. Rep. PNW-GTR-855. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 109 p.

Pollock, M.M.; Beechie, T.J.; Wheaton, J.M. [et al.]. 2014. Using beaver dams to restore incised stream ecosystems. Bioscience. 64: 279–290.

Regonda, S.K.; Rajagopalan, B.; Clark, M.; Pitlick, J. 2005. Seasonal cycle shifts in hydroclimatology over the Western United States. Journal of Climate. 18: 372–384.

Rieman, B.E.; Isaak, D.J. 2010. Climate change, aquatic ecosystems, and fishes in the Rocky Mountain West: implications and alternatives for management. Gen. Tech. Rep. RMRS-GTR-250. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 46 p.

Rieman, B.E.; Smith, C.L.; Naiman, R.J. [et al.] 2015. A comprehensive approach for habitat restoration in the Columbia Basin. Fisheries. 40: 124–135.

Rogers, B.M.; Neilson, R.P.; Drapek, R. [et al.]. 2011. Impacts of climate change on fire regimes and carbon stocks of the U.S. Pacific Northwest. Journal of Geophysical Research Biogeosciences. 116: G03037.

Stevens-Rumann, C.S.; Morgan, P. 2019. Tree regeneration following wildfires in the western U.S.: a review. Fire Ecology. 15: 15.

Stewart, I.T.; Cayan, D.R.; Dettinger, M.D. 2005. Changes toward earlier streamflow timing across western North America. Journal of Climate. 18: 1136–1155.

Stine, P.; Hessburg, P.; Spies, T. [et al.]. 2014. The ecology and management of moist mixed-conifer forests in eastern Oregon and Washington: a synthesis of the relevant biophysical science and implications for future land management. Gen. Tech. Rep. PNW-GTR-897. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 254 p.

Strauch, R.L.; Raymond, C.L.; Hamlet, A.F. 2014. Climate change, hydrology, and access in the North Cascade Range. In: Raymond, C.L.; Peterson, D.L.; Rochefort, R.M., eds. Climate change vulnerability and adaptation in the North Cascades region. Gen. Tech. Rep. PNW-GTR-892. Portland OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 45–112. Chapter 4.

Swanston, C.; Janowiak, M., eds. 2012. Forest adaptation resources: climate change tools and approaches for land managers. Gen. Tech. Rep. NRS-87. Newtown Square, PA: U.S. Department of Agriculture, Forest Service, Northern Research Station. 121 p.

U.S. Department of Agriculture, Forest Service [USDA FS]. 2012. 2012 planning rule. Washington, DC: U.S. Department of Agriculture, Forest Service. Federal Register. 77(68). 115 p. http://www.fs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb5362536.pdf. (21 January 2021)

Chapter 9 Appendix: Adaptation Options Tables

Table 9A.1—Adaptation options for water resources and infrastructure

Sensitivity to climatic variability and change: High peak flows and flooding will lead to increased road damage at stream crossings causing increased sediment delivery to streams and damage to infrastructure.

Adaptation strategy/approach: Increase resiliency of infrastructure (e.g., roads, trail, and recreation sites) to higher peak flows and floods.

	Specific tactic A	Specific tactic B	Specific tactic C
Tactics	Inform travel management updates and right-size existing transportation infrastructure.	Develop and maintain an inventory of at-risk infrastructure.	Upgrade, relocate, or close vulnerable infrastructure.
When/where can tactics be applied?	During project planning and implementation for at-risk sites identified with climate change information.	At-risk infrastructure sites (e.g., floodplains, debris flow prone channels, outburst flood zones, unstable slopes), new construction projects.	At-risk infrastructure sites (e.g., floodplains, debris-flow prone channels, outburst flood zones, unstable slopes).
Opportunities for implementation	During watershed restoration, road management, and postdisturbance recovery projects.	Work with existing partners to leverage stewardship and Good Neighbor Authority agreements. Incorporate remotely sensed datasets (e.g., LiDAR).	During watershed restoration, road management, and postdisturbance recovery projects.

Sensitivity to climatic variability and change: Water quantity and quality needed to support municipal supplies/domestic users, hatcheries, irrigation, and environmental flows will be reduced with climate change and increased demand.

Adaptation strategy/approach: Adapt water usage to conserve available supply and maintain water quality.

	Specific tactic A	Specific tactic B	Specific tactic C	Specific tactic D
Tactics	Improve water rights and uses inventories (including environmental flows).	Implement source water protection plans and Water Quality Restoration Plans and apply best management practices during operations.	Work with irrigators and hatcheries to increase water conservation measures and water use from alternate sources.	Identify vulnerable water sources and work with municipalities, irrigators, and U.S. Forest Service (USFS) facilities to build resilience.
When/where can tactics be applied?	Domestic and irrigation diversions, coldwater refugia, high-priority subwatersheds, wild and scenic rivers, areas where water supply and demand are mismatched.	Drinking water source areas, 303(d) water quality limited streams, and other potentially affected waters.	Domestic and irrigation diversions, coldwater refugia, high-priority subwatersheds, wild and scenic rivers, areas where water supply and demand are mismatched.	Springs, headwaters, and subwatersheds most at risk.
Opportunities for implementation	Work with watershed groups, U.S. Environmental Protection Agency (EPA), irrigation districts, utility providers, river and fish conservation partners; application of the watershed conservation framework.	Work in priority watersheds collaborating with municipalities, Oregon Department of Environmental Quality, Oregon Water Resources Department, soil and water conservation districts, and other organizations.	Work with watershed groups, EPA, irrigation districts, utility providers, river and fish conservation partners; application of the watershed conservation framework.	Work with municipalities, nongovernmental organizations (NGOs), Oregon Water Resources Department, soil and water conservation districts.

Table 9A.1—Adaptation options for water resources and infrastructure (continued)

Sensitivity to climatic variability and change: Climate change will increase vulnerability of groundwater-dependent ecosystems (GDEs) and riparian areas.

Adaptation strategy/approach: Increase resilience of GDEs and riparian areas to climate change.

	Specific tactic A	Specific tactic B	Specific tactic C	Specific tactic D
Tactics	Diversify and restore riparian areas to buffer against future streamflow changes and maintain water storage capacity (e.g., water table retention).	Protect and restore GDEs from grazing and other operations.	Increase upland water storage and improve soil quality and stability by maintaining springs and wetlands.	Work across jurisdictions at larger scales by aligning budgets and priorities to reduce effects of increasing disturbance events.
When/where can tactics be applied?	Along streams, lakes, and wetlands with emphasis on coldwater refugia, priority subwatersheds, wild and scenic rivers.	Recreation sites, wetlands, water sources, riparian areas, spring developments.	High-elevation watersheds, vulnerable water sources, degraded and vulnerable sites.	Along streams, lakes, and wetlands with emphasis on coldwater refugia, priority subwatersheds.
Opportunities for implementation	Stage Zero, instream restoration, vegetation treatment in riparian reserves, legacy road work.	Timber management, grazing, recreation, fire suppression.	Watershed stewardship groups, soil and water conservation districts, fish and wildlife conservation organizations, instream restoration.	Watershed stewardship groups, soil and water conservation districts, fish and wildlife conservation organizations, Good Neighbor Authority partnerships.

Sensitivity to climatic variability and change: Climate change will result in higher peak flows and lower low flows that increase vulnerability of built infrastructure and aquatic habitat.

Adaptation strategy/approach: Manage for high-functioning ecosystems that can absorb and slowly release water across the landscape.

	Specific tactic A	Specific tactic B	Specific tactic C	Specific tactic D
Tactics	Restore natural channels, reconnect floodplains, and allow stream channels to migrate.	Reduce drainage efficiency by adding wood and logs to stream channels, or by reintroducing beavers or beaver mimicry.	Conduct vegetation management to develop appropriate vegetation density and composition for optimal water balance and healthy watersheds.	Manage for resilient soils by maintaining cover that builds soil carbon, helps to prevent erosion, and increases water storage capacity.
When/where can tactics be applied?	Locations where hydrologic function has been degraded.	Where beaver populations can be supported and where land-use has degraded riparian habitat.	High-density stands with high fuel loads, meadows and riparian areas.	All areas, with emphasis on locations with degraded soil.
Opportunities for implementation	Watershed stewardship groups, soil and water conservation districts, fish and wildlife conservation organizations, Good Neighbor Authority partnerships.	Watershed stewardship groups, soil and water conservation districts, fish and wildlife conservation organizations.	Watershed stewardship groups, soil and water conservation districts, fish and wildlife conservation organizations, Good Neighbor Authority partnerships.	Watershed stewardship groups, soil and water conservation districts, fish and wildlife conservation organizations, Good Neighbor Authority partnerships.

Table 9A.2—Adaptation options for fish and aquatic habitats

Sensitivity to climatic variability and change: Climate change and shifting streamflows may reduce lateral and longitudinal aquatic habitat connectivity.

Adaptation strategy/approach: Increase and maintain lateral and longitudinal habitat connectivity and heterogeneity across riparian and aquatic ecosystems.

	Specific tactic A	**Specific tactic B**	**Specific tactic C**
Tactics	Restore aquatic ecosystems at the reach scale by removing artificial constrictions, dams, roads, and diversions and reducing water withdrawals.	Restore natural regimes and functions at the watershed scale (e.g., disturbance, temperature and flow, sediment transport, and storage of organic matter).	Maintain, monitor, and protect properly functioning watershed processes.
When/where can tactics be applied?	Prioritize areas of unconfined valley bottoms and hillslope source areas, especially in areas where there are few management limitations.	Riparian areas outside range of natural conditions.	Locations and refugia that are properly functioning and resilient in their current condition.
Opportunities for implementation	Existing partnerships that work across management boundaries.	Existing partnerships that work across management boundaries.	Funding for monitoring installations and maintenance, citizen science groups, partnerships with conservation groups and NOGs.

Sensitivity to climatic variability and change: Reduced summer streamflow.

Adaptation strategy/approach: Increase the quantity of and access to summer rearing habitat

	Specific tactic A	**Specific tactic B**	**Specific tactic C**
Tactics	Increase connectivity.	Increase instream flow.	Increase water retention.
When/where can tactics be applied?	Low- and moderate-elevation spawning tributaries.	Low- and mid-elevation spawning tributaries in areas of critical habitat for Endangered Species Act-listed species (coho).	Anadromous subwatersheds.
Opportunities for implementation	Partnerships across all land ownership.	Partnerships across all land ownership. Improve water infrastructure.	Partnerships across all land ownership, with focus on higher elevations public lands

Sensitivity to climatic variability and change: Warming stream temperatures

Adaptation strategy/approach: Increase habitat resilience

	Specific tactic A	**Specific tactic B**	**Specific tactic C**
Tactics	Restore structure and function of streams.	Enhance and protect hyporeic zones.	Restore and maintain riparian vegetation.
When/where can tactics be applied?	Lower gradient occupied fish habitat.	Stream channels and floodplains.	Along stream channels and throughout floodplains.
Opportunities for implementation	Partnerships across all land ownership.	Partnerships across all land ownership.	Partnerships across all land ownership.

Table 9A.2—Aquatic organisms adaptation options (continued)

Sensitivity to climatic variability and change: Warmer stream temperatures may favor nonnative species

Adaptation strategy/approach: Increase resilience of native fish species through management of nonnative species

	Specific tactic A	**Specific tactic B**	**Specific tactic C**
Tactics	Monitor nonnative populations distribution/abundance.	Suppress, eliminate, or control invasive species populations.	Develop outreach and education for target audience at sensitive sites.
When/where can tactics be applied?	Established areas, new distribution areas resulting from warming, and adjacent connected habitats. Include areas occupied by native fish species.	Established areas, new distribution areas resulting from warming, and adjacent connected habitats. Include areas occupied by native fish species.	Throughout SWOAP area. Engage public schools and students. Educate anglers at boat ramps and angler access points.
Opportunities for implementation	Partnerships across all land ownership. Collaborate with Oregon Department of Fish and Wildlife (ODFW) and citizen scientists (i.e., DNA sampling).	Partnerships across all land ownership. Collaborate with ODFW. Use nonnative species as food sources. Enforce mandatory “catch and keep” regulations in addition to other developing tactics.	Produce brochures, flyers, signage, and use of social media. Collaborate with ODFW.

Sensitivity to climatic variability and change: Climate change will result in native species distribution shifts and community realignments

Adaptation strategy/approach: Conduct biodiversity surveys to describe current baseline conditions and manage distribution shifts

	Specific tactic A	**Specific tactic B**	**Specific tactic C**
Tactics	Protect refugia habitat and restore degraded habitat	Implement monitoring and population surveys.	Conduct climate niche modeling for future distribution scenarios.
When/where can tactics be applied?	Current or known refugia habitats, areas of critical habitat, and locations with intrinsic potential to become refugia habitats.	Throughout CMWAP area. In known distributions and previously unsurveyed areas.	Throughout CMWAP area, where data are available.
Opportunities for implementation	Partnerships across all land ownership.	Partnerships across all land ownership. Use eDNA methods. Increase data sharing among land managers.	Partner with researchers (OSU, ODFW, USFS, Cow Creek Tribe, USGS). Maintain long-term datasets on temperature, discharge, etc.

OSU = Oregon State University; ODFW = Oregon Department of Fish and Wildlife; USGS = U.S. Geological Survey.

Table 9A.3—Vegetation and disturbance adaptation options in dry mixed oak and pine forests

Sensitivity to climatic variability and change: Dry oak/pine woodlands will experience earlier and prolonged fire seasons with warmer temperatures.

Adaptation strategy/approach: Maintain and increase resilient oak/pine forests.

	Specific tactic A	**Specific tactic B**	**Specific tactic C**	**Specific tactic D**
Tactics	Identify current and potential refugia along with areas that may transition to other forest or vegetation types with warming temperatures.	Reduce stand densities and fuel loads to shift composition towards species that are more drought tolerant.	Map, reduce, and mitigate the spread of invasive plants (e.g., annual grasses) that increase fire risk	Protect legacy trees and enhance native plant communities through site preparation, planting, or seeding.
When/where can tactics be applied?	All current and potential mixed oak/pine locations.	High-priority stands assessed across current distribution of mixed oak/pine forests.	High-priority stands and sites where invasive plants have established.	High-priority stands and sites where invasive plants have established.
Opportunities for implementation	Partnerships with federal agencies, NGOs, and state agencies to map current vegetation distribution and identify areas where vegetation shifts are likely.	State agencies, private landowners, and other collaborative partnerships. Stewardship agreements and the Good Neighbor Authority.	Proactive treatments and post-treatment and post-fire management. Cooperative weed management programs. Collaborative projects and stewardship agreements with adjacent partners.	Proactive treatments and postfire management. Cooperative weed management programs. Collaborative projects and stewardship agreements with adjacent partners.

Sensitivity to climatic variability and change: Increasing drought stress may lead to more frequent and severe bark beetle outbreaks and forest mortality events.

Adaptation strategy/approach: Decrease stand susceptibility to bark beetle outbreaks.

	Specific tactic A	**Specific tactic B**	**Specific tactic C**	**Specific tactic D**
Tactics	Reduce stand density by thinning, prescribed fire, and wildfire use, with density and structural goals based on predicted future conditions.	Promote age class and structural diversity across the landscape through regeneration harvest, thinning, prescribed fire, and wildfire use.	Reforest sites considering appropriate genetics and species composition to reduce susceptibility to future outbreaks.	Manage slash piles to prevent *Ips* beetle outbreaks.
When/where can tactics be applied?	Dry mixed conifer stands at risk depending on species, size class, age class, and stand density.	Dry mixed conifer stands at risk of converting to oak/pine based on species, size class, age class, and stand density.	Recently disturbed areas.	Pine treatment areas.
Opportunities for implementation	Fuels treatments, timber harvests, Forest Health Protection (FHP) prevention and suppression project funding, Good Neighbor Authority agreements.	Fuels treatments, timber harvests, FHP prevention and suppression project funding, Good Neighbor Authority agreements.	Projects using the Seedlot Selection Tool. Reforestation trust fund, Knudton-Vandenberg funds.	Fuels treatments, timber harvests, FHP prevention and suppression project funding, Good Neighbor Authority agreements.

Table 9A.3—Vegetation and disturbance adaptation options in dry mixed oak and pine forests (continued)

Sensitivity to climatic variability and change: Climate change may lead to increased establishment and spread of invasive species.

Adaptation strategy/approach: Maintain integrity of native plant populations and prevent nonnative species invasions.

	Specific tactic A	Specific tactic B	Specific tactic C	Specific tactic D
Tactics	Use early detection/rapid response when implementing herbicide treatments and other direct eradication methods to prevent nonnative plant introductions during projects.	Promote weed-free seed and seed native plant species in areas with nonnative species.	Ensure weed-free policies are included in planning documents, and coordinate weed-free seed standards and regulations among agencies.	Reduce grazing practices that encourage spread of nonnative species.
When/where can tactics be applied?	Riparian areas, transportation and utility corridors, disturbed areas, postfire recovery, and other areas vulnerable to invasion.	Restoration projects, postdisturbance recovery, road and infrastructure construction and maintenance.	Restoration projects, post-disturbance recovery, road and infrastructure construction and maintenance.	Grazing allotments, riparian areas, and other sites that are vulnerable to invasion.
Opportunities for implementation	Collaborate with counties, Oregon Department of Transportation, and other agencies and partners; cost-share programs.	Collaborate with The Nature Conservancy, Oregon Department of Transportation, native plant societies, and other partners; cost-share programs.	Collaborative projects with neighboring agencies and partners. Learn from private landowners in adjacent areas.	Collaborate with neighboring Bureau of Land Management units, counties, landowners, ranching associations, state of Oregon, and other partners.

Sensitivity to climatic variability and change: Climate change will lead to increased drought stress, more frequent disturbances, and decreased habitat suitability in western hemlock forests.

Adaptation strategy/approach: Maintain and increase resilient western hemlock forests.

	Specific tactic A	Specific tactic B	Specific tactic C
Tactics	Reduce stand density, change planting strategies, and increase species diversity to reduce drought stress; incorporate more locally adapted species in managed stands.	Increase genetic diversity via mixed seed sources that are locally adapted to have genetic variation that is suited to contend with pathogen, insect, and climate pressures (i.e., more dry-adapted populations).	Prioritize ecosystem edges and transition zones when introducing climate-smart genotypes and species.
When/where can tactics be applied?	Plantations, postfire rehabilitation efforts.	Across the range of western hemlock forests, but prioritize locations at the leading edge of current distribution.	High-priority stands and sites where invasive plants have established.
Opportunities for implementation	Development or revision of program of work. Collaboration with state agencies, private landowners, and other partnerships; stewardship agreements and the Good Neighbor Authority.	State agencies, private landowners, timber companies; monitoring and research projects with USFS research and development and local universities.	Proactive treatments and postfire management, cooperative weed management areas, collaborative projects and stewardship agreements with adjacent partners.
Comments			Introducing early-seral species is a priority in higher elevation forests across the eastern portion of the CMWAP.

Table 9A.4—Vegetation and disturbance adaptation options in western hemlock forests

Sensitivity to climatic variability and change: Higher temperatures may increase drought stress in high-elevation western hemlock forests.

Adaptation strategy/approach: Identify, protect, and monitor potential and existing refugia.

	Specific tactic A	**Specific tactic B**	**Specific tactic C**
Tactics	Prioritize restoration efforts in multiple-use areas and work across management boundaries when planning and investing in restoration projects.	Map current and future western hemlock refugia.	Facilitate establishment of dispersal-limited species into potential refugia (e.g., assisted migration).
When/where can tactics be applied?	Postdisturbance restoration efforts, fuels treatments.	Aerial surveys, on the ground forest monitoring.	High elevations near the leading edge of western hemlock forests.
Opportunities for implementation	Development or revision of program of work. Collaboration with state agencies, private landowners, and other partnerships. Stewardship agreements and the Good Neighbor Authority.	Collaboration with USFS and university researchers.	Collaboration with USFS and university researchers, postdisturbance reforestation.

Sensitivity to climatic variability and change: Climate change will lead to increased opportunity for invasive species establishment in western hemlock forests.

Adaptation strategy/approach: Implement early detection, rapid response, and prevention approaches when managing invasive species.

	Specific tactic A	**Specific tactic B**	**Specific tactic C**
Tactics	Reseed and/or treat invasive species before establishment can occur.	Monitor the spread and establishment of invasive species through aerial and on the ground surveys.	Increase prevention efforts.
When/where can tactics be applied?	Restoration projects, postfire rehabilitation, road construction and maintenance.	All western hemlock forests, particularly at uninvaded sites and around edges of currently known invasions.	Education programs, interpretive signs, and cleaning stations in high-use areas.
Opportunities for implementation	Postfire restoration, construction and infrastructure maintenance, Forest Health Protection, Program of Work, Knutson-Vandenberg receipts, stewardship agreements, county weed and pest programs.	Forest Health Protection, Program of Work, Knutson-Vandenberg receipts, stewardship agreements, county weed and pest programs.	Partnerships with NGOs, state of Oregon, stewardship collaboratives, county weed and pest programs.

Table 9A.5—Wildlife adaptation options

Sensitivity to climatic variability and change: Climate change and increasing disturbance may lead to a loss of habitat structure and spatial heterogeneity.

Adaptation strategy/approach: Increase resilience of late-successional habitat (LSH) and vegetation structure.

	Specific tactic A	**Specific tactic B**	**Specific tactic C**
Tactics	Protect, maintain, and recruit legacy structures (e.g., large trees, snags, downed wood): • Develop burn and silvicultural prescriptions with the intent of protecting legacy trees. • Engage with fire managers and consider pre-fire season mapping of LSH.	Identify areas on the landscape where LSH is most at risk of shifting to a drier forest type: • Reevaluate management plans for LSH that include climate assessment information. • Consider fuel modifications to decrease fire severity. • Consider thinning to promote resiliency. • Treat and maintain dry forests that are more fire resilient or have rare vegetation (i.e., manzanita and oak).	Maintain a landscape that is likely to support mixed-severity fire: • Consider use of prescribed fire that mimics mixed-severity fire. • Use mechanical treatments to break up contiguous fuels prior to prescribed fire. • Use wildland fire for resource benefit. • Consider fire restrictions and ignition sources in LSH during critical times of the year. • Consider where and how recreation development will occur in LSH.
When/where can tactics be applied?	Postdisturbance environments.	High-priority locations with fire refugia based on topography and aspect.	Areas with a variety of topographic settings (aspect, topographic position). Mechanical treatments may be necessary to protect legacy structures, spotted owl habitat areas, and landscapes with low topographic diversity
Opportunities for implementation	Thinning projects, fuel treatments, salvage and timber sales, wildlife-urban interface projects, reforestation and planting projects, revised fire suppression and management strategies.	Research opportunities assessing recruitment of downed wood as climate changes. Use partnerships to work across management boundaries to ensure consistent data collection and monitoring.	Engage research communities (including social scientists) to learn more about climate-smart management of LSH. Public education communicating fire science. Use collaborative partnerships to expand education and outreach efforts.
Comments	Need constant training on how to protect legacy structures.		Need to work on smoke management guidelines that are currently a barrier to use of prescribed fire.

Table 9A.5—Wildlife adaptation options (continued)

Sensitivity to climatic variability and change: Climate change may reduce resiliency of high-priority riparian and wet habitats including: springs, bogs and fens, seeps, snowmelt-dependent meadows, and lentic and lotic systems.

Adaptation strategy/approach: Identify, retain, and restore riparian and wetland habitat for wildlife.

	Specific tactic A	**Specific tactic B**	**Specific tactic C**
Tactics	Maintain and restore snow-dominated aquatic systems for habitat: • Inventory and map vulnerable locations • Maintain meadow vegetation characteristics through prescribed fire and conifer encroachment treatments. • Manage recreation and other anthropogenic stressors in sensitive areas to maintain wildlife habitat.	Maintain and restore streamside and riparian habitats: • Manage recreation and other anthropogenic stressors in sensitive areas to maintain wildlife habitat • Maintain riparian vegetation to provide wildlife habitat and stream shading • Restore or improve beaver habitat • Restore floodplain function • Control invasive species including introduced nonnative fish, amphibians, and reptiles	Maintain and restore riparian and wet habitats including lotic and lentic systems that support rare or at-risk species: • Remove conifer encroachment • Inventory and map • Remove invasive species • Maintain native vegetation composition and structure • Maintain nesting and breeding habitat • Manage recreation and other anthropogenic stressors in sensitive areas to maintain wildlife habitat
When/where can tactics be applied?	Where hydrologic function may be the most at risk because of changes in snowmelt timing and frequency; habitats outside of wilderness.	Across all riparian habitats, but prioritize locations where hydrologic function may be the most at risk and where implementation will increase connectivity across watersheds.	Native turtle and amphibian habitat; bogs, fens, springs, and seeps that support native invertebrates and vertebrates; spiraea around lakeshores; areas where habitat connectivity can be improved.
Opportunities for implementation	Watershed stewardship groups, soil and water conservation districts, fish and wildlife conservation organizations, instream restoration projects.	Watershed stewardship groups, soil and water conservation districts, fish and wildlife conservation organizations, instream restoration projects.	Watershed stewardship groups, soil and water conservation districts, fish and wildlife conservation organizations.
Comments	Monitor treatment effectiveness.	Monitor treatment effectiveness.	Monitor treatment effectiveness.

Table 9A.5—Wildlife adaptation options (continued)

Sensitivity to climatic variability and change: Climate change may reduce habitat connectivity.

Adaptation strategy/approach: Provide opportunities for wildlife to move across elevational and latitudinal gradients in response to climate change.

	Specific tactic A	**Specific tactic B**	**Specific tactic C**
Tactics	Identify and map areas where connectivity may be problematic owing to climate change: • Prioritize riparian areas being fragmented by drought or fire. • Consider where land use allocations are located in high-priority areas.	Locate nearby populations of native species that are likely to colonize new niches created by climate change.	Consider "climate-smart connectivity" during project planning along temperature and moisture gradients. • Build resilience by incorporating redundancy (i.e., multiple opportunities in watersheds). • Consider connectivity before, during, and after planned and nonplanned fire or other disturbance events.
When/where can tactics be applied?	High-elevation habitats that are becoming fragmented; south-facing lower elevation habitats that are expanding. Areas with recreation or transportation infrastructure. While infrastructure is being built, consider opportunities to facilitate passage.	Across all forested landscapes, but efforts should include all stages of forest succession. During the early stages of land management planning or revision.	Areas where refugia will be limited or most affected by disturbance and or climate. Where landscape topography can help maintain connectivity between habitat patches. Regional-, forest-, and project-level planning efforts or revisions.
Opportunities for implementation	Work with local NGOs and other partners on educational programs and outreach support.	Work with local NGOs and other partners on educational programs and outreach support.	Integrate climate-smart connectivity when conducting project-scale minimum roads analyses. • Partnerships with Western Federal Highways and other connectivity partners • Land acquisitions that increase ability for movement or conservation easements that limit further development; engage with Land and Water Conservation Fund and other public-land acquisition collaboratives. NGOs like Western Rivers, Trust for Public Lands, The Nature Conservancy, etc.

Table 9A.6—Recreation adaptation options

Sensitivity to climatic variability and change: Changing temperatures and seasonality will reduce access to snow-dependent recreation, with winter-recreation use becoming concentrated in a smaller number of high-elevation sites over shorter seasons and increasingly replaced by summer-recreation use over longer seasons.

Adaptation strategy/approach: Plan for year-round use, and for more concentrated use at higher elevations.

	Specific tactic A	**Specific tactic B**	**Specific tactic C**	**Specific tactic D**
Tactics	Shift snow-dependent recreational resources from low-elevation areas to high-elevation areas.	Invest in lower-footprint temporary/mobile structures (portable entrance stations; yurts) in transitional areas, or permanent structures where there will be opportunities for year-round use.	Build sustainable roads and trails that can handle year-round use, and close or decommission unsustainable roads and trails.	Adjust staffing to handle shifting seasonal use, or reach out to other groups to support staffing needs.
When/where can tactics be applied?	Low-elevation winter recreation sites, mountain passes (e.g., some Sno-Parks along major highways: shift resources to higher elevation Sno-Parks along this corridor).	High-elevation sites that may see increased use, and low-elevation sites that offer year-round recreation opportunities.	Old poorly designed trails prone to heavy erosion damage; areas experiencing increased use with declining snowpack.	Areas with increased shoulder season use.
Opportunities for implementation	Collaboration with permittees and winter recreation clubs (Nordic skiing/snowmobiling, etc.).	Collaboration with permittees and summer recreational clubs (off-highway vehicle [OHV], mountain biking, etc.).	Interdisciplinary planning efforts to improve sustainability of roads/trails across management boundaries.	Collaboration with recreational clubs (OHV, mountain biking, etc.).
Comments				Increased staffing may be cost-prohibitive; consider involving volunteer groups as well.

Table 9A.6—Recreation adaptation options (continued)

Sensitivity to climatic variability and change: Tree mortality from fire and other disturbances will lead to threats to infrastructure and public safety from hazard trees.

Adaptation strategy/approach: Plan for increased presence of dead and hazardous trees on the landscape.

	Specific tactic A	**Specific tactic B**	**Specific tactic C**	**Specific tactic D**
Tactics	Build temporary, disposable, or inexpensive infrastructure that is more resilient to impacts from falling trees.	Consider long-term recreation use and integrate hazard-tree risk into recreation and restoration planning.	Identify locations where hazard trees or downed trees will not be treated, and communicate risks to the public; develop a risk evaluation process for trails and dispersed areas.	Invest in training and equipment to address presence of more dead trees on the landscape.
When/where can tactics be applied?	Bridges and developed sites along with some dispersed sites in areas at higher risk to damage from tree mortality.	Campgrounds and trails where restoration efforts are planned.	Along transportation corridors, facilities, trails, and dispersed sites.	Wilderness areas, campgrounds, trails.
Opportunities for implementation	Collaboration with USFS engineering, USFS technology center; incorporation of successful models from other agencies; reallocate funds from more expensive structures.	Increased collaboration across resource management groups (recreation, aquatics, wildlife, fuels, etc.) during the early stages of land management or project planning.	Collaboration with Office of General Council, communication specialists, safety officers.	Collaborate with saw program leads and partners.

Table 9A.6—Recreation adaptation options (continued)

Sensitivity to climatic variability and change: Warmer temperatures will lead to increased demand for water recreation, while hydrological shifts simultaneously reduce quality and quantity of water at recreation sites.

Adaptation strategy/approach: Plan for shifts in the timing of and demand for water-based recreation.

	Specific tactic A	**Specific tactic B**	**Specific tactic C**
Tactics	Construct more developed sites to access water (boating/swimming), and redesign or restrict access to vulnerable sites.	Extend existing boat ramps to handle lower water levels, and create temporary infrastructure to handle changing and more extreme conditions.	Conduct additional research into impacts of algal blooms on recreational use, and plan responses accordingly.
When/where can tactics be applied?	Rivers, lakes, and streams with reliable water supplies near urban areas; campgrounds in riparian zones that are negatively affecting water quality or at risk of flooding.	Areas without boat ramps capable of handling lower flows; areas where portable boardwalks could improve access.	High-use areas that are likely to be prone to negative impacts from algal blooms.
Opportunities for implementation	Collaborate with partners to develop or improve sites on other lands and consider relicensing procedures as an opportunity to improve preparedness.	Access points along rivers and reservoirs, Implementing regular relicensing to improve preparedness.	Collaborate with water specialists and other scientific groups.

Table 9A.7— Ecosystem services adaptation options (grazing)

Sensitivity to climatic variability and change: Shifting climatic variability and warming temperatures will affect grazing resources and policy.

Adaptation strategy/approach: Develop an all-lands, holistic approach to grazing management.

	Specific tactic A	**Specific tactic B**	**Specific tactic C**	**Specific tactic D**
Tactics	Modify flexibility in timing, duration, and intensity of authorized grazing.	Use grazing as a tool to achieve desired conditions (e.g., targeted grazing of noxious weeds).	Minimize livestock impacts by designing more resilient livestock water sources or restricting access to vulnerable locations.	Consider adding pollinator habitat as a component of grazing/ pasture unit management.
When/where can tactics be applied?	Across USFS lands and BLM districts.	Across USFS lands, and BLM districts and other areas where invasive plants can be treated effectively through grazing.	Across USFS lands and BLM districts, riparian areas and wetlands, and recently disturbed areas.	Locations where there are partnerships with permittees, adjacent landowners, and NGOs.
Opportunities for implementation	Work with state, federal, and county partners across management boundaries; engagement with local ranchers.	Work with state, federal, and county partners across management boundaries.	Watershed improvement projects, Good Neighbor Authority, partnerships with fish and wildlife conservation organizations and NGOs, engagement with local ranchers.	Watershed improvement projects, Good Neighbor Authority, partnerships with fish and wildlife conservation organizations and NGOs; engagement with local ranchers.
Comments				Small allotments and meadows in the Columbia River Gorge may have this opportunity.

Table 9A.7—Ecosystem services adaptation options (wildland-urban interface) (continued)

Sensitivity to climatic variability and change: Increasing fire frequency and severity will increase fire risk to communities located in the wildland-urban interface (WUI).

Adaptation strategy/approach: Prioritize and expand fuels management projects in vulnerable WUI locations.

	Specific tactic A	**Specific tactic B**	**Specific tactic C**
Tactics	Use fire risk models to prioritize and map high-risk areas and identify solutions to increase resiliency of WUI communities.	Encourage markets for biomass generated from fuels treatments where cost recovery is a challenge and prescribed burning may not be an option.	Encourage “firewise” behaviors within rural communities by integrating of wildfire risk into community planning efforts.
When/where can tactics be applied?	In WUI and across adjacent landscapes (large-scale treatments many be needed to protect communities).	Fuels projects in and around WUI.	Rural communities and other population centers; planning meetings and proposal development.
Opportunities for implementation	Partnerships with state, private commercial timber, tribes, Natural Resources Conservation Service, and local conservation districts.	U.S. Department of Agriculture grants to encourage development of alternative products, stewardship and Good Neighbor Authority agreements.	Fire awareness in schools and communities, fire protection plan partnerships.

Table 9A.7—Ecosystem services adaptation options (first foods) (continued)

Sensitivity to climatic variability and change: Climate change and altered vegetation distribution may shift seasonality and availability of first foods.

Adaptation strategy/approach: Identify opportunities to support the expansion of first-food sources through restoration or ecosystem enhancement.

	Specific tactic A	**Specific tactic B**	**Specific tactic C**
Tactics	Implement restoration projects to increase resiliency of first foods sources (e.g., white oak ecosystems) where the plant community is likely to persist.		
When/where can tactics be applied?	Wherever first foods are distributed.		
Opportunities for implementation	Reference potential vegetation areas maps; partnerships with tribes and NGOs (e.g., Cascade Oaks Partnerships).		

Table 9A.7—Ecosystem services adaptation options (carbon sequestration) (continued)

Sensitivity to climatic variability and change: Climate change may increase or decrease the capacity of ecosystems to sequester carbon.

Adaptation strategy/approach: Increase internal and external educational opportunities to manage carbon resources and sequestration.

	Specific tactic A	Specific tactic B	Specific tactic C
Tactics	Improve understanding—internally and externally—that short-term loss of carbon storage may be necessary to provide for long-term carbon sequestration.	Identify opportunities for enhancing carbon sequestration following disturbance events. For example, following fire, plant native perennial grasses and forbs that promote carbon sequestration underground.	
When/where can tactics be applied?	Fire-prone and insect/disease-affected landscapes.	Vegetation transition zones from a forest to non-forest condition following disturbances.	
Opportunities for implementation	Demonstration sites, case studies, public outreach (e.g., fire science communication pamphlets and public presentations).	Partnerships with tribes for first foods and the state or Oregon for game management.	

Table 9A.7— Ecosystem services adaptation options (landscape aesthetics) (continued)

Sensitivity to climatic variability and change: Climate change and increasing disturbance events may reduce visual aesthetics of high-value landscapes and ecosystems.

Adaptation strategy/approach: Enhance public understanding about the role of disturbance in changing landscapes and the limited capacity of managers to control landscape aesthetics.

	Specific tactic A	Specific tactic B	Specific tactic C
Tactics	Identify important scenic values and vulnerable sites and develop plans to maintain visual values into the future.	Manage public expectations of landscape change and disturbance (e.g., fire, smoke, and forest mortality).	Use postdisturbance restoration to increase scenic value and landscape resiliency.
When/where can tactics be applied?	Wherever there are high-value scenic resources.	Local communities, chambers of commerce, visitor centers, recreation sites, and other outreach venues.	In recently disturbed and highly valued scenic areas.
Opportunities for implementation	Use scenery management systems (SMS) to help identify scenic values.	Use SMS as a communication tool to provide updates and inform users.	Community partnerships, social media, story maps, and other emerging technologies.

Chapter 10: Conclusions

David L. Peterson[1]

Introduction

The Columbia River Gorge National Scenic Area, Mount Hood National Forest, and Willamette National Forest Adaptation Partnership (CMWAP) contributed to our understanding of climate change vulnerabilities and responses to potential climate change effects in north-central Oregon and southern Washington. This effort synthesized the best available scientific information to assess climate change vulnerability for key resources of concern, develop recommendations for adaptation options, and catalyze a collaboration of land management agencies and stakeholders seeking to address climate change issues. Furthermore, the vulnerability assessment and corresponding adaptation options provided information to support national forests in implementing agency climate change objectives described in the National Roadmap for Responding to Climate Change (USDA FS 2010a) (see chapter 1).

Relevance to U.S. Department of Agriculture, Forest Service Climate Change Response Strategies

The CMWAP process is directly relevant to the climate change strategy of the U.S. Department of Agriculture, Forest Service (Forest Service). Information presented in this report is also relevant for other land management entities and stakeholders in the CMWAP assessment area. This process can be replicated and implemented by any organization, and the adaptation options are applicable beyond Forest Service lands. As with previous assessment and adaptation efforts (e.g., Halofsky and Peterson 2017; Halofsky et al. 2011, 2018a, 2018b, 2019, 2022; Hudec et al. 2019; Raymond et al. 2014), a science-management partnership was critical to the success of the CMWAP. Those interested in using this approach are encouraged to pursue a partnership as the foundation for increasing climate change awareness, assessing vulnerability, and developing adaptation plans.

Communication, Education, and Organizational Capacity

Building organizational capacity to address climate change requires information exchange and training for employees in management units. Information sharing and education were built into the CMWAP process through a 2-day workshop. On the first day of the workshop, resource managers and scientists presented results of the vulnerability assessment, including the effects of climate change on water resources and infrastructure, fish and aquatic habitat, vegetation, wildlife, recreation, and

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[1] **David L. Peterson** is a research biological scientist (emeritus), U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, 400 N 34th Street, Suite 201, Seattle, WA 98103.

ecosystem services. On the second day of the workshop, resource managers and stakeholders developed adaptation options in response to climate sensitivities identified in the assessment. This hands-on approach allowed resource managers to both participate in the process and contribute directly to information and outcomes, thus increasing organizational capacity to address climate change in the future.

Partnerships and Engagement

Relationships developed through the CMWAP process were as important as the products that were developed, because these relationships build the partnerships that are a cornerstone for successful agency responses to climate change. We built a partnership across the Forest Service, stakeholders, and the University of Washington. This partnership will remain relevant for future forest planning efforts and restoration conducted by the Forest Service in collaboration with other partners and stakeholders. Working with partners enhances the capability to respond effectively to climate change.

Climate change response is a relatively new and evolving aspect of land management, and the CMWAP provided an opportunity for participants to effectively communicate their professional experiences with respect to climate change and resource management in a collaborative and supportive environment. The workshop was especially valuable because it covered a broad range of topics, and multidisciplinary group discussions resulted in conceptual breakthroughs across disciplines.

Assessing Vulnerability and Adaptation

Forest Service management units are required to identify resources vulnerable to climate change, assess the expected effects of climate change on those resources, and identify management strategies to improve the adaptive capacity of national forest lands. The CMWAP vulnerability assessment describes the climate change sensitivity of multiple resources, and adaptation options developed for each resource area can be incorporated into resource-specific management plans.

Dialogue among groups of resource managers and scientists identified management practices that are useful for increasing resilience and reducing stressors to various ecosystem components. Although implementing all adaptation options developed in the CMWAP process may not be feasible, resource managers can draw from the list of options as needed. Some adaptation options can be implemented now, whereas others may require changes in management plans or policies or become more appropriate as climate change effects become more apparent.

Science and Monitoring

Where applicable, chapters in this publication have identified information gaps and uncertainties important to understanding climate change vulnerabilities and management influences on vulnerabilities. These information gaps can help determine where monitoring and research would reduce uncertainties inherent in management decisions. In addition, current monitoring programs that provide information for detecting climate change effects and additional monitoring needs were identified for some resources in the vulnerability assessment. Working across multiple jurisdictions and boundaries will allow CMWAP participants to potentially increase collaborative monitoring on climate change effects and effectiveness of adaptation actions. Scientific documentation in the assessment can also be incorporated into large landscape assessments, such as national forest land management plans, environmental analysis for National Environmental Policy Act (NEPA) projects, and specific project design criteria and mitigations.

Implementation

Although challenging, implementation of adaptation options is expected to occur gradually with time, often motivated by extreme weather and large disturbance events, and facilitated by changes in policies, programs, and land management plan revisions. It will be especially important for ongoing restoration programs to incorporate considerations for climate change adaptation to ensure effectiveness. A focus on thoroughly vetted strategies may increase ecosystem function and resilience while minimizing implementation risk. Land management agencies, American Indian tribes, and private landowners working together can facilitate effective implementation, particularly across boundaries.

Toward a Landscape Approach

In many cases, similar adaptation options were identified for more than one resource sector, suggesting a need to integrate adaptation planning across multiple disciplines. Adaptation options that yield benefits to more than one resource are likely to have the greatest benefit (Halofsky and Peterson 2017; Halofsky et al. 2011, 2018a, 2018b, 2019, 2022; Hudec et al. 2019; Peterson et al. 2011; Raymond et al. 2014). However, some adaptation options involve tradeoffs and uncertainties that need further exploration. Assembling an interdisciplinary team to tackle this issue will be critical for assessing risks and developing risk management options. Scenario planning may be a useful next step.

Information in this assessment can be incorporated into everyday work through climate-informed thinking, assist in planning, and influence management priorities such as public safety. Flooding, wildfires, and insect outbreaks may all be exacerbated by climate change, thus increasing the frequency and extent of hazards faced by federal employees and the public. Resource management can help minimize these hazards by restoring hydrologic function, reducing fuels, and modifying forest structure. These management activities are commonplace, demonstrating that, in many cases, current resource management is already preparing for a warmer climate.

Integration Across Resources

Within this report, climate sensitivities are discussed in separate chapters for each resource. In practice, these resources interact with one another in terms of biophysical function and management applications. For example, water is a resource used by vegetation, terrestrial and aquatic wildlife, and people. Vegetation provides habitat for wildlife as well as a scenic landscape for recreationists. Forests provide shade that cools streams for fish habitat. Figure 10.1 illustrates some of the interactions that exist among different resources within a forest. Forests also provide benefits beyond the borders of the forests themselves. Figure 10.2 illustrates the benefits (ecosystem services) that can be transported from public lands or are simply valued outside of those lands.

Looking across adaptation options for each chapter in this report, many of the resource areas share common climate change sensitivities. For example, water, infrastructure, and recreation are sensitive to winter soil saturation that can lead to erosion and landslides. Higher temperatures and earlier snowmelt affect most resources. Lower summer streamflow, increased disturbances, and change in timing of events are also prominent effects. The compound influences of multiple stressors leading to larger and more frequent disturbances affect many resources. Identifying common concerns across resource areas may provide opportunities to coordinate adaptation efforts, thus improving effectiveness and efficiency.

Although many resource areas are sensitive to similar climate change effects, adaptation options in each chapter are generally designed to protect individual resources. Reorganizing adaptation strategies and tactics by sensitivity may provide insight on opportunities for coordination. Recognizing shared goals can enhance organizational capacity to respond to climate change.

Operations

Implementation of adaptation actions may be limited by insufficient human resources, insufficient funding, and conflicting priorities. However, climate-influenced effects are already apparent for some resource areas, such as reduced

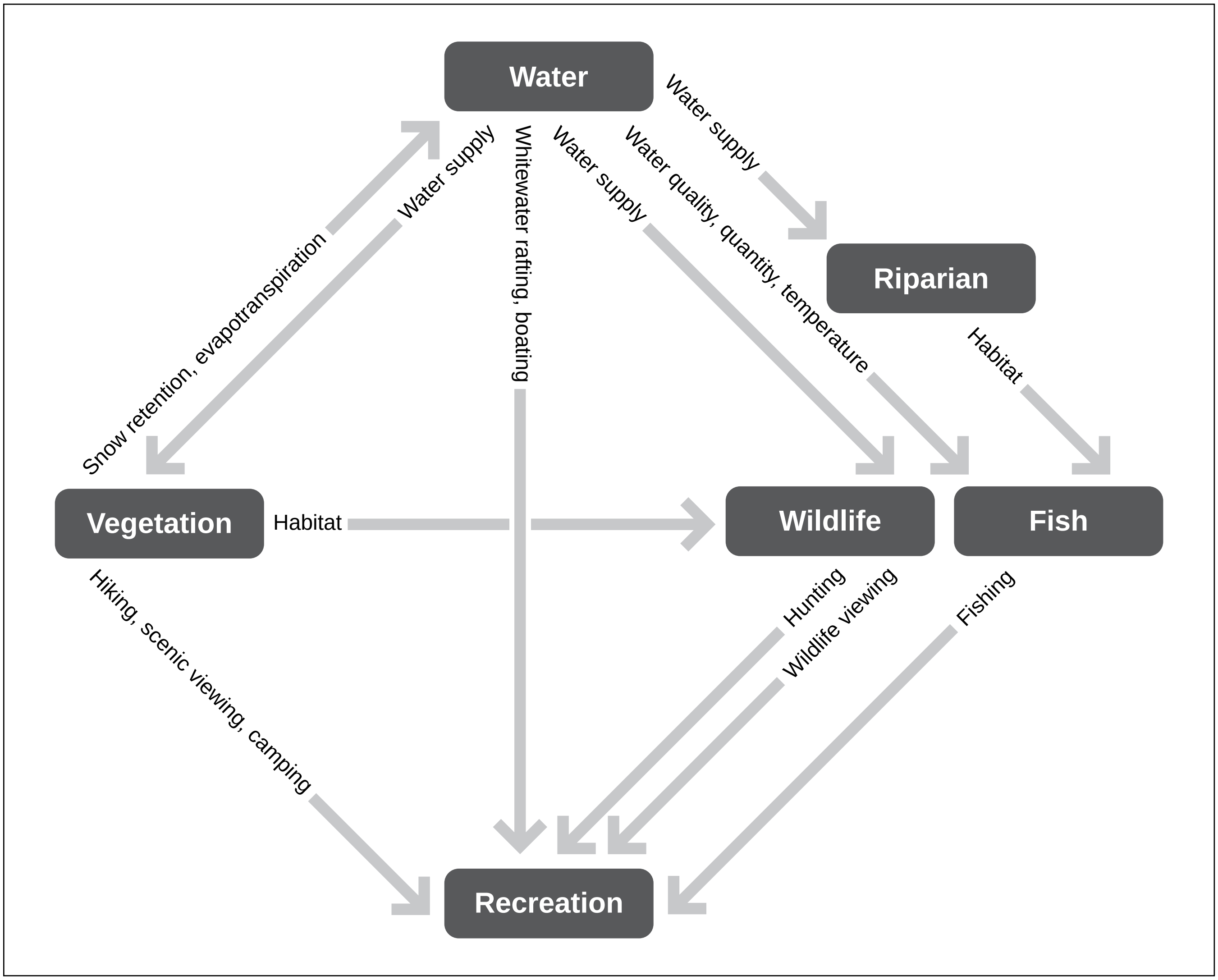

Figure 10.1—Conceptual depiction of interactions among resources.

snowpack and altered hydrologic regimes. Some adaptation options may be precluded, and resources may be compromised, if actions are not implemented soon. This creates an imperative for timely inclusion of climate change considerations as a component of resource management and agency operations.

The climate change vulnerability assessment and adaptation approach developed by the CMWAP can be used by the Forest Service and other organizations in many ways. From the perspective of federal land management, this information can contribute to the following aspects of agency operations:

- **Landscape and resource assessments**—The vulnerability assessment provides information on departure from desired conditions and best available science on climate change effects to resources. The adaptation options describe desired conditions and management objectives for inclusion in planning documents.

- **Resource management strategies**—The vulnerability assessment and adaptation options can be used in forest resilience and restoration plans, conservation strategies, fire management plans, infrastructure planning, and state wildlife action plans.
- **Project NEPA analysis**—The vulnerability assessment provides best available science for documentation of resource conditions, climate change effects analysis, and development of alternatives. Adaptation options provide mitigations and project design recommendations for specific locations.
- **Monitoring plans**—The vulnerability assessment can help identify knowledge gaps that can be addressed by monitoring.
- **National forest land management plan revision process**—The vulnerability assessment provides a foundation for understanding key resource vulnerabilities caused by climate change for the assessment phase of forest plan revision. Information from vulnerability assessments can be applied in assessments required under the Forest Service 2012 Planning Rule, describe potential climatic conditions and effects on key resources, and identify and prioritize resource vulnerabilities to climate change in the future. Climate change vulnerabilities and adaptation strategies can inform forest plan components, such as desired conditions, objectives, standards, and guidelines.
- **Project design/implementation**—The vulnerability assessment and adaptation options provide recommendations for mitigation and project design at specific locations.

We are optimistic that climate change awareness, climate-informed management and planning, and implementation of climate change adaptation options in the CMWAP assessment area will continue to evolve. We anticipate that the following will be accomplished within a few years:

- Climate change will become an integral component of federal agency operations.
- The effects of climate change on natural and human systems will be continually assessed.
- Monitoring activities will include indicators to detect the effects of climate change on species and ecosystems.
- Agency planning processes will provide more opportunities to manage across boundaries.
- Restoration activities will be implemented in the context of the influence of a changing climate.
- Management of carbon will be included in adaptation planning.
- Organizational capacity to manage for climate change will increase within federal agencies and with local stakeholders.

- Resource managers will implement climate-informed practices in long-term planning and management.

This assessment provides a foundation for understanding potential climate change effects and implementing adaptation options that help reduce the negative impacts of climate change and transition resources to a warmer climate. We hope that by building on existing partnerships, the assessment will foster collaboration in climate change adaptation and resource management planning throughout the CMWAP assessment area.

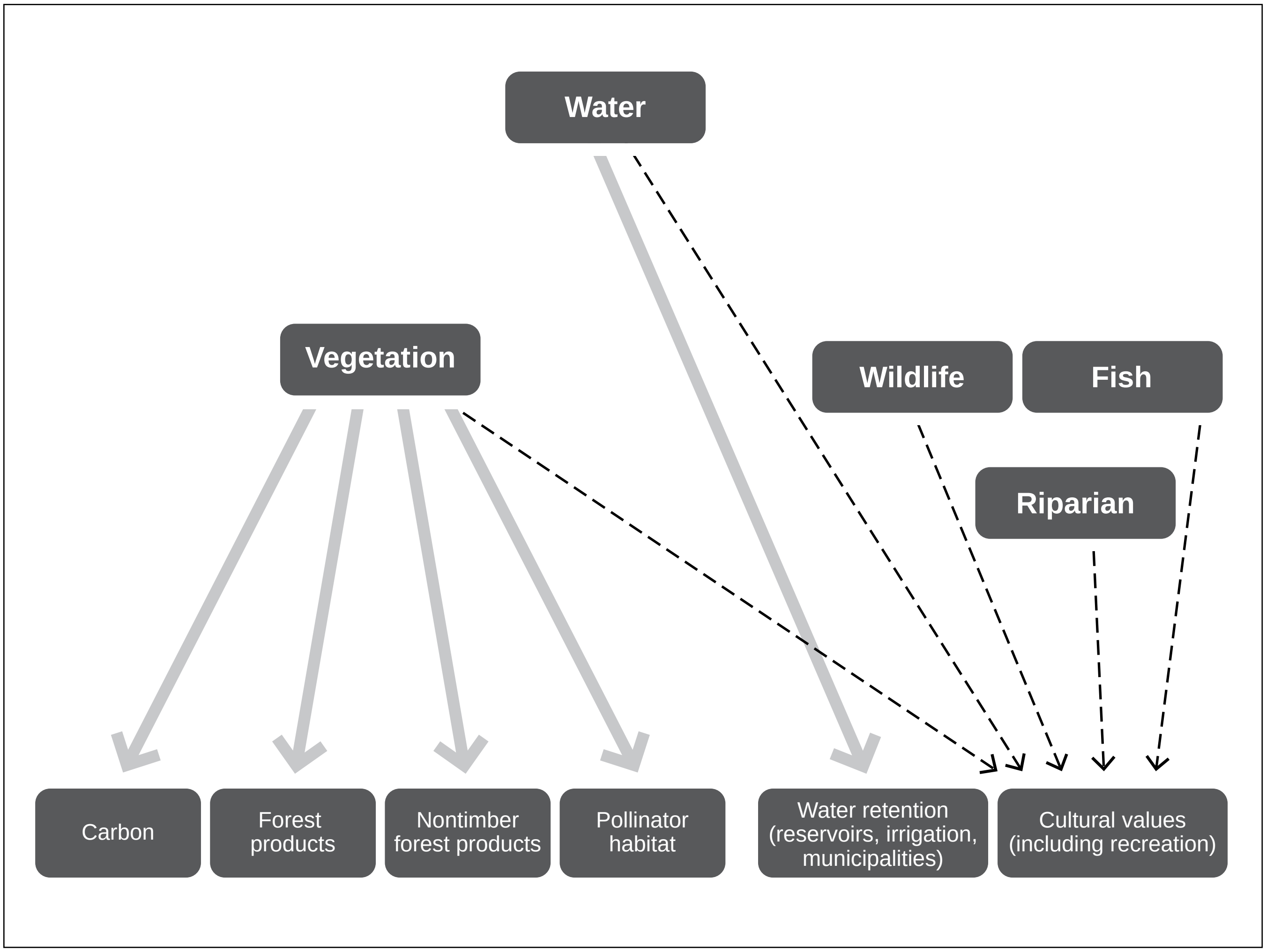

Figure 10.2—Conceptual depiction of ecosystem service benefits beyond the boundaries of a forest. Ecosystem services are listed along the bottom; recreation is considered a subset of cultural activities. Solid arrows represent quantifiable benefits, and dashed arrows represent social values that are not quantifiable.

Literature Cited

Halofsky, J.E.; Peterson, D.L., eds. 2017. Climate change vulnerability and adaptation in the Blue Mountains. Gen. Tech. Rep. PNW-GTR-939. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 331 p.

Halofsky, J.E.; Peterson, D.L.; Dante-Wood, S.K. [et al.]. 2018a. Climate change vulnerability and adaptation in the Northern Rocky Mountains. Gen. Tech. Rep. RMRS-GTR-374. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. Parts I and II. 475 p.

Halofsky, J.E.; Peterson, D.L.; Ho, J.J. [et al.], eds. 2018b. Climate change vulnerability and adaptation in the Intermountain Region. Gen. Tech. Rep. RMRS-GTR-375. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 246 p.

Halofsky, J.E.; Peterson, D.L.; Ho, J.J., eds. 2019. Climate change vulnerability and adaptation in south-central Oregon. Gen. Tech. Rep.PNW-GTR-974. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 473 p.

Halofsky, J.E.; Peterson, D.L.; Ho, J.J., eds. 2022. Vulnerability and adaptation to climate change in southwest Oregon. Gen. Tech. Rep. PNW-GTR-995. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 445 p.

Halofsky, J.E.; Peterson, D.L.; O'Halloran, K.A.; Hoffman, C.H. 2011. Adapting to climate change at Olympic National Forest and Olympic National Park. Gen. Tech. Rep. PNW-GTR-844. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 130 p.

Hudec, J.L.; Halofsky, J.E.; Peterson, D.L., eds. 2019. Vulnerability and adaptation to climate change in southwest Washington. Gen. Tech. Rep. PNW-GTR-977. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 249 p.

Peterson, D.L.; Millar, C.I.; Joyce, L.A. [et al.]. 2011. Responding to climate change in national forests: a guidebook for developing adaptation options. Gen. Tech. Rep. PNW-GTR-855. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 109 p.

Raymond, C.L.; Peterson, D.L.; Rochefort, R.M., eds. 2014. Climate change vulnerability and adaptation in the North Cascades region. Gen. Tech. Rep. PNW-GTR-892. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 279 p.

U.S. Department of Agriculture, Forest Service [USDA FS]. 2010a. National roadmap for responding to climate change. http://www.fs.fed.us/climatechange/pdf/roadmap.pdf. (9 February 2017).

U.S. Department of Agriculture, Forest Service [USDA FS]. 2010b. A performance scorecard for implementing the Forest Service climate change strategy. http://www.fs.fed.us/climatechange/pdf/performance_scorecard_final.pdf. (9 February 2017).

U.S. Equivalents

When you know:	Multiply by:	To get:
Millimeters (mm)	0.0394	Inches
Centimeters (cm)	0.394	Inches
Meters (m)	3.28	Feet
Kilometers (km)	0.621	Miles
Square kilometers (km^2)	0.386	Square miles
Cubic meters per second ($m^3 s^{-1}$)	35.3	Cubic feet per second
Hectares (ha)	2.47	Acres
Tonnes per hectare (t/ha)	0.893	Pounds per acre
Teragrams (Tg)	1,102,311.3	Tons
Degrees Celsius (°C)	1.8 °C + 32	Degrees Fahrenheit

Metric Equivalents

When you know:	Multiply by:	To get:
Gallons (gal)	3.78	Liters
Pounds (lb)	0.454	Kilograms

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