CHAPTER 3

Managing Effects of Drought and Other Water Resource Challenges in Alaska and the Pacific Northwest

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CLIMATE, BIOGEOGRAPHIC, AND SOCIAL CONTEXT

The physical, ecological, and social environments of Alaska and the Pacific Northwest (PNW) regions of the United States are extremely diverse. Alaska ranges from the Arctic Ocean and the very cold, dry environments of the North Slope to the cool and very rainy coastal North Pacific region of southeast Alaska. Most precipitation falls as snow at higher elevations. In Arctic Alaska, average annual temperature is 14.6 °F, and average annual precipitation is 11 inches (Alaska Climate Division 1, 1980–2009). By contrast, in southeast Alaska, average annual temperature is 35.8 °F, and annual average precipitation is 143 inches (Alaska Climate Divisions 9–12, 1980–2009).

The PNW, defined here as Idaho, Oregon, and Washington, ranges from the Pacific Coast (annual precipitation of 200 inches) to interior semi-arid regions (annual precipitation of 8 inches). Precipitation patterns in the PNW are strongly governed by orographic phenomena, with high, persistent snowpack in the higher mountains (e.g., record annual snowfall of 1,130 inches at Mount Baker, WA, in 1999–2000).

Examples of Alaskan ecosystems include mixed tundra in the northern portions of the State and above treeline in mountains; boreal forests dominated by black spruce (*Picea mariana*), white spruce (*P. glauca*), paper birch (*Betula papyrifera*), and quaking aspen (*Populus tremuloides*) in interior and southcentral Alaska; and perhumid temperate coniferous forests in southeast Alaska. Ecosystems in the PNW include productive temperate coniferous forests near the Pacific coast and along the (wet) west slope of the Cascade Range, less productive mixed-conifer forest along the (dry) east slope of the Cascades and in interior mountain ranges, and sagebrush-steppe and shrublands at lower elevations in much of the interior and mountain valleys. Large rivers and thousands of smaller tributaries form an extensive network of riparian, wetland, and estuarine systems that provide critical hydrological function and biological diversity at broad and fine spatial scales.

Alaska and the Pacific Northwest have many natural resource issues in common. Water is important for wildlife and people. Water provides critical habitat for salmon, which are culturally and economically valuable species. Timber production has declined in recent decades. Recreation has emerged as a major revenue source. The following sections describe the social and regulatory context, historical climate, and projected future climate for each region.

Alaska

Social and regulatory context—Water in Alaska is used for fish habitat and passage, transportation, small-scale energy production, local water supplies, water-based recreation, and small-scale agriculture. Some communities, especially in southeast Alaska, derive power and municipal water from small-scale hydroelectric operations. River networks provide access to subsistence and recreational fishing and hunting opportunities in roadless parts of the State. Alaska's abundant anadromous salmon and resident freshwater fisheries depend on intact freshwater systems and associated streamflow (Chilcote et al. 2017). During 1998–2007, national forests in Alaska provided habitat for an average annual commercial harvest of 62.4 million fish, with an average dockside value of $84.9 million (adjusted to 2007 dollars) (Alexander 2011).

Many Alaska Natives depend on subsistence foods for their livelihoods, including fish, terrestrial mammals, and wild plants (Ballew et al. 2006), which may also generate a substantial portion of their cash income. A study covering subsistence communities in five regions in Alaska showed that subsistence foods accounted for approximately 20 percent of total energy intake and 40 percent or more of the protein consumed in all regions (Ballew et al. 2006). Subsistence foods are also integral to the culture and identities of Alaska Natives.

Timber production in southeast Alaska (primarily on Federal land) has declined greatly since the late-20th century (Alexander 2011). The Tongass National Forest land management plan includes an old-growth habitat conservation strategy to provide the necessary ecological characteristics and conditions for biological communities and target species. A reserve system, consisting of large, medium, and small tracts of old-growth forest and associated riparian, beach, and estuary habitats, is central to species conservation and delivery of ecosystem services. Populations of fish and wildlife are managed for continued subsistence, sport, and commercial use. Amendment of the land management plan in 2016 was accomplished in part to "transition away from old-growth timber harvesting and towards a forest products industry that uses predominantly second-growth—or young-growth—forests" (USDA FS 2016a: 1–9). Thus, the 2016 amendment maintained the integrity of the old-growth habitat conservation strategy and associated old-growth reserves initiated in the original 1979 Forest Plan, and it more explicitly outlined management of young-growth forest (USDA FS 2016b). Riparian and stream restoration, along with stream buffer requirements and improvements for fish passage (especially for culverts), are being implemented across the forest, providing protection for intermittent, headwater, and anadromous fish streams.

A small proportion of the 5.4 million acres in Chugach National Forest in southcentral Alaska is suitable for timber production. Less than 20 percent of the national forest is classified as forest, and over 98 percent of this forested vegetation is within inventoried roadless areas where timber production is prohibited. The roaded corridor of Chugach National Forest includes lands within one-quarter mile of roads, and an estimated 11,170 acres within this area are available for wood products management with ground-based equipment.

Historical climate—Over the past 50 years, Alaska has warmed more than twice as fast as the increase in mean global temperature (Overland et al. 2014, Taylor et al. 2017). Statewide, mean annual air temperature for 1986–2016 was 1.7 °F warmer than temperatures for 1925–1960 (Vose et al. 2017). Over the last century, higher temperatures have increased the duration of the growing season in interior Alaska by 45 percent, from 85 to 123 days (Wendler and Shulski 2009). Warming temperatures have also reduced the duration of snow and ice and have contributed to both elevated wildfire risk and northward extensions in the distribution of some insect species (Chapin et al. 2014, Hollingsworth et al. 2017).

In most regions of Alaska, the distribution of seasonal precipitation is more like that of the Southwestern United States than the PNW, with a drier spring and early summer and more annual precipitation falling in late summer and autumn. Drought varies in response to snowpack volume and failure of late summer precipitation, occurring when the time between availability of snowmelt water and late summer onset of precipitation is longer than normal. There are few useful long-term precipitation records for analyzing historical trends, but those that do exist show either a long-term increase or decrease in precipitation, depending on subregion, and that the changes in precipitation have been less pronounced than changes in temperature (Bieniek et al. 2014).

Intact watersheds in Alaska have accommodated extensive and sometimes rapid historical change. For example, the retreat of glaciers since their maximum extent has led to strong directional (rather than cyclic) changes in stream geomorphology, hydrology, and ecology (Gough and Wilson 2001, Hayward et al. 2017) (fig. 3.1). At the last glacial maximum (20,000 years BP), most of southcentral and southeast Alaska was under ice, and enormous glaciers occurred in the Brooks Range. The current topography and vegetation of these regions represent the outcome of climate warming and resulting glacial retreat followed by species recolonization over the last 14,000 years (Ager 2007).

The area of Arctic sea ice varied greatly over a 1,300-year period before the 1900s. Intervals of sustained low cover of sea ice occurred between about 800 and 1300 AD (Medieval Warm Period), with the pre-industrial maximum occurring in the mid-600s AD. High levels of sea ice cover occurred in the 1400s and 1800s AD. However, compared to variability over the previous 1,450 years, the pronounced decline in sea ice cover that began around 1990 AD is unprecedented in magnitude and duration (Halfar et al. 2013, Kinnard et al. 2011). Since the early 1980s, annual average Arctic sea ice has decreased in extent around 4 percent per decade, become thinner by 4.3–7.5 feet, and melted for at least 15 more days each year (Taylor et al. 2017).

Increasing temperatures and reduced snow cover have accelerated permafrost thaw in Alaska since at least the 1980s (AMAP 2011). Thawing leads to altered drainage patterns and drying of soils. Currently, 80 percent of Alaska is underlain by permafrost, with 70 percent of the permafrost landscape vulnerable to subsidence upon thawing (Jorgenson et al. 2008). Over the next 20 years, uneven sinking of the ground in response to permafrost thaw is expected to add $3.6–6.1 billion (an additional 10–20 percent) to current costs of maintaining public infrastructure (buildings, pipelines, roads, airports) (Larsen et al. 2008).

Loss of permafrost damages infrastructure associated with potable water, sanitation, and food storage for rural communities. Ice cellars critical to family food storage are lost, and systems for potable water and sewage deteriorate as permafrost melts (Brubaker et al. 2011). Consequences extend directly into rural community structure if families are forced to move from villages to culturally unfamiliar cities. Lakes formerly defined by permafrost have decreased in area in the last 50 years (Riordan et al. 2006), reducing waterfowl habitat, which

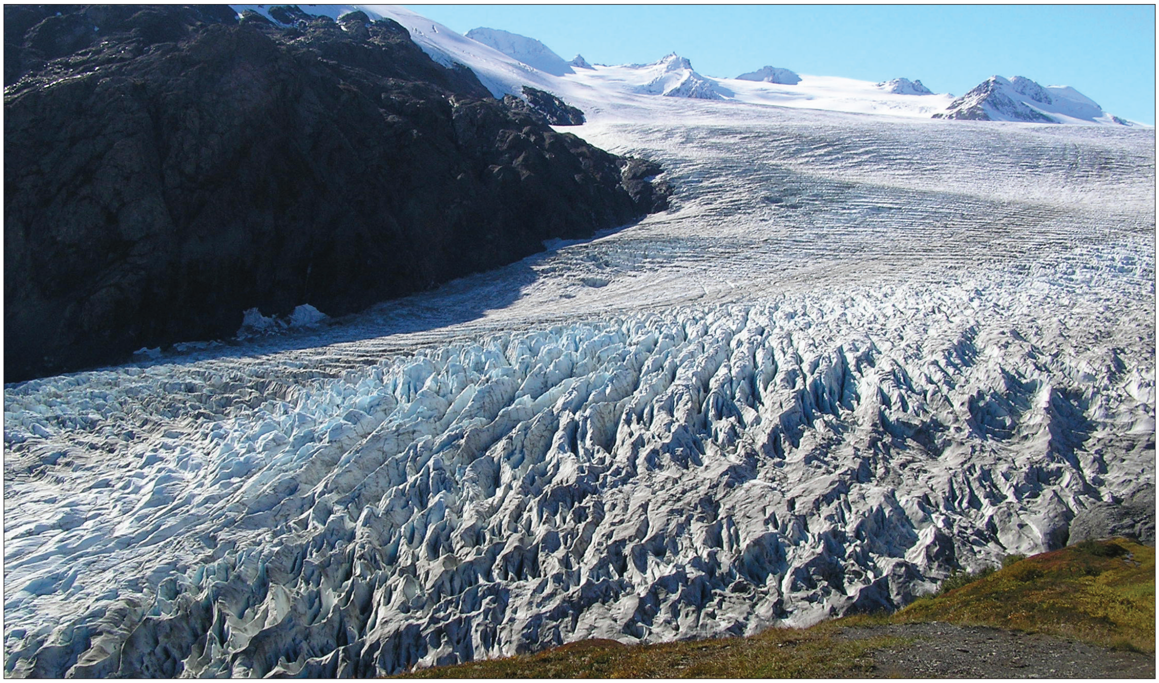

Figure 3.1—Exit Glacier (Kenai Fjords National Park) is an iconic example of the ongoing retreat of glacial ice in southern Alaska. Note recently exposed rock and soil in the foreground that has become vegetated. (Photo from https://commons.wikimedia.org/wiki/File:1055_-_exit_glacier.jpg)

in turn reduces the number of birds for subsistence hunters and the size of migratory populations for the lower 48 States. Permafrost degradation and further transitions from continuous to discontinuous permafrost are projected to continue for the remainder of the 21st century (Grosse et al. 2016).

Distribution of shrubs and trees is expanding into tundra biomes in northern Alaska, altering the distribution of animals such as moose (*Alces alces*) and willow ptarmigan (*Lagopus lagopus*) (Tape et al. 2006, 2016). Changes in water dynamics, duration of growing season, precipitation, and woody vegetation expansion are causing more area to be burned by wildfire; tundra that rarely burned in the past 5,000 years has burned in recent years (Chapin et al. 2014, Hu et al. 2010). Fire has the potential to shift forests of interior Alaska from dominance by spruce to broad-leaved trees for the first time in 4,000 years (Barrett et al. 2011).

Projected future climate—Future climate in Alaska was modeled using an ensemble of global climate models (GCMs) from the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Taylor et al. 2012). Relative to 1970–1999, mean annual temperatures are projected to increase 3.3–8.6 °F by 2030–2059 and 4–14 °F by the end of the 21st century, depending on location and greenhouse gas emissions (Walsh et al. 2018). By the late-21st century, precipitation across Alaska may increase at least 10–20 percent and up to 60 percent in northern Alaska. This projected increase is based on Alaska's proximity to the Pacific Ocean, diminishing ice cover in the Bering Sea and Arctic Ocean, and patterns of storm tracks (Walsh et al. 2018). Despite the projected increases in precipitation, future water availability is expected to be reduced in much of the State because of increased evaporation associated with higher air temperatures and longer growing seasons. For example, for boreal forests, a 15-percent increase in precipitation is needed to offset evaporative loss from a 1.8 °F increase in temperature (Flannigan et al. 2016).

Climate model projections for Alaska from CMIP5 suggest that the length of "warm-spell" periods (defined as at least 6 consecutive days when the maximum temperature on each day is above the 90th percentile threshold for that calendar day) will probably increase by at least 40 days in the central and eastern interior and as much as 200+ days in the Aleutians (2046–2065 relative to 1981–2000) (Sun et al. 2015). Similarly, the duration of cold spells, defined as a period of at least 6 consecutive days when the minimum temperature on each day is below the 10th percentile threshold for that calendar day, is projected to decrease by 4 to 7 days, with the largest changes in southern coastal Alaska. Models project no change in either the expected dry-spell duration or the annual longest duration of consecutive days with <1 mm of precipitation, relative to historical climate (Sun et al. 2015). Therefore, drought exposure and its consequences will be driven not just by precipitation, but also by temperature increases and their effects on snowpack, permafrost, and water demand.

By the mid-21st century, warming trends are expected to cause snow droughts for some low-elevation landscapes. Snow droughts are periods of abnormally low snowpack at a given time of year caused by either below-normal cold-season precipitation (dry snow drought) or a lack of snow accumulation despite near-normal precipitation (warm snow drought) (AMS 2018, Harpold et al. 2017). Snow droughts are likely to affect hydrology and vegetation dynamics at lower elevations (fig. 3.2). For example, at elevations below 1,500 feet in Chugach National Forest, snow-day fraction (the proportion of days when precipitation falls as snow) is projected to decrease by 23 percent between October and March, resulting in 26-percent less water in snowpack at the end of winter (relative to 1970–1999) (Littell et al. 2017). The future warm season (when freezes are rare) at low elevations will increase from 200 to 230 days (SNAP n.d., Walsh et al. 2018). Future snowpack at high elevations, where temperatures

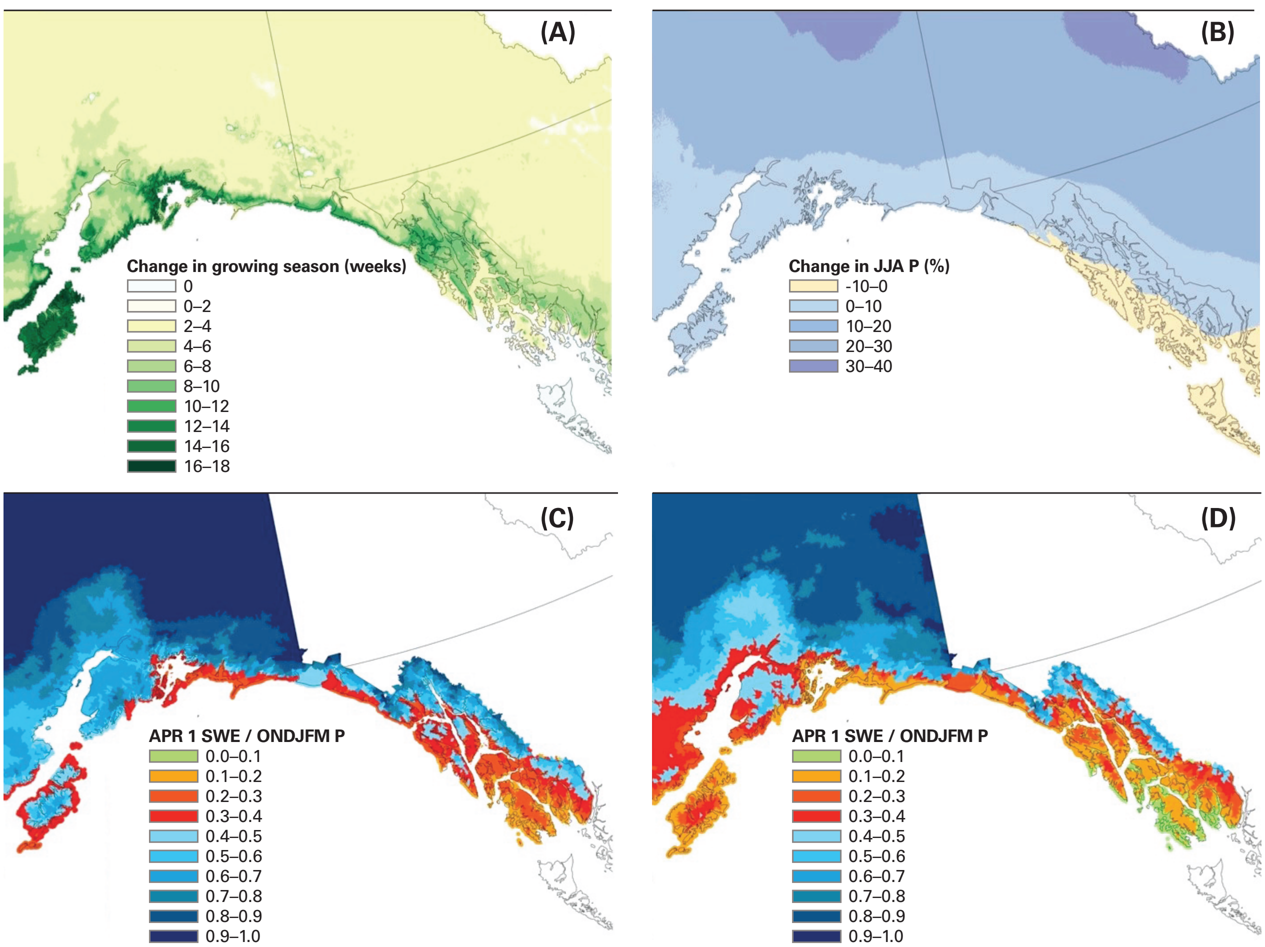

Figure 3.2—Projected changes in ecologically relevant climate variables for southcentral and southeast Alaska, comparing 2040–2069 climatology to 1970–1999. Changes are based on a five-GCM average (NCAR CCSM4, NOAA GFDL-CM3, NASA GISS-E2-R, IPSL-CM5ALR, MRI-CGCM3) for the Representative Concentration Pathway (RCP) 8.5 emissions scenario. (A) Change in growing season length. (B) Change in June/July/August precipitation. (C) Historical ratio of April 1 snow-water equivalent to October–March snow index (P). (D) Future ratio of April 1 snow-water equivalent to October–March snow index given future temperature and precipitation. Data for (A) and (B): Scenarios Network for Alaska and Arctic Planning (SNAP n.d.). Data for (C) and (D): after Littell et al. (2017).

remain below freezing much of the year, is projected to increase by as much as 10 percent because of the overall increase in precipitation, as described earlier (Littell et al. 2017).

Altered snowpack will affect most elements of the ecological and human environment, including streamflow, avalanche frequency, vegetation dynamics, glacier dynamics, and road and trail conditions. The proximity of Alaskan national forests to the marine environment on the Gulf of Alaska often results in winter temperatures near freezing and substantial precipitation. Therefore, a small change in temperature affects both snowfall and snow accumulation. Warming temperature in the future will result in less frequent snow and reduced seasonal snowpack at low elevations.

Pacific Northwest

Social and regulatory context—Although the PNW can be generally characterized as "wet" in areas west of the Cascade Range and "dry" east of the Cascades (except at high elevations, which have more precipitation), water has great importance throughout the region. In the western part of the PNW, water is valued for municipal water supplies for major metropolitan areas such as Seattle and Portland, hydropower, habitat for salmon and other aquatic species (including where threatened and endangered species occur), and recreation. In the eastern part of the region, water is used for irrigation of a wide range of crops, both perennial (e.g., apples and other fruit) and annual (e.g., potatoes, hay), municipal water supplies, fish habitat, and recreation (fig. 3.3). Water supply in the eastern part of the PNW is a concern in years when precipitation is average, and the need becomes more acute during drought years.

Several salmon stocks are listed as threatened or endangered, and nearly all populations are much lower than they were before 1900, largely as a consequence of human impacts on the environment, including dams, urbanization, agriculture, and fishing (National Research Council 1996). High temperatures and drought reduce habitat quality for salmonid species across all spatial and temporal scales, facilitating expansion of nonnative fish species that tolerate higher water temperature (Isaak et al. 2010). Salmon and other traditional food sources have high economic and cultural value for Native American communities throughout the region (Lynn et al. 2013). Streams and riparian areas are often hot spots of terrestrial and aquatic biodiversity (Naiman et al. 1993), especially in drier areas of the PNW.

Although timber production is still an important component of local economies, it is lower than it was prior to 1990, and most timber harvest now occurs on private lands (Simmons et al. 2016). The Northwest Forest Plan (USDA and USDI 1994), implemented for western Cascade Range and coastal Federal lands, focuses on retention and development of late-successional forest habitat for specific vegetation structure, aquatic ecosystems, and wildlife habitat for threatened and endangered animal species. Northern spotted owl (*Strix occidentalis caurina*), marbled murrelet (*Brachyramphus marmoratus*), and red tree vole (*Arborimus longicaudus*) are a few of the many species included in current conservation plans in Oregon and Washington.

Grazing by domestic livestock on public and private lands is an important enterprise in rangelands on the east side of the Cascade Range, which also provide habitat for elk (*Cervus elaphus*), mule deer (*Odocoileus hemionus*), and many other animal species. Management of greater sage-grouse (*Centrocercus urophasianus*) habitat is a major conservation issue in sagebrush-steppe systems in the PNW and throughout the intermountain West.

Recreationists in the PNW participate in a wide range of outdoor activities, including hiking, camping, sightseeing, skiing, hunting, fishing, and water-based activities. Most of these activities are affected in some way by a warmer climate and drought. For example, the record low snowfall of 2014–2015 reduced skiing but increased warm-weather recreation (Hand et al. 2019).

The issues and ecosystem services discussed above are interwoven with the economy, lifeways, and culture of Native Americans. This has always been true for salmon and other "first foods," but interest has been increasing in integrating traditional ecological knowledge in biodiversity conservation (Charnley et al. 2007). In recent years, Federal agencies have begun to include Tribes as partners when developing conservation plans and implementing projects related to public land management.

Historical climate—Between 1895 and 2011, the PNW warmed by about 1.3 °F (Mote et al. 2014). Average annual temperature in the PNW since 1990 has mostly been above the 20th-century average, with many of the

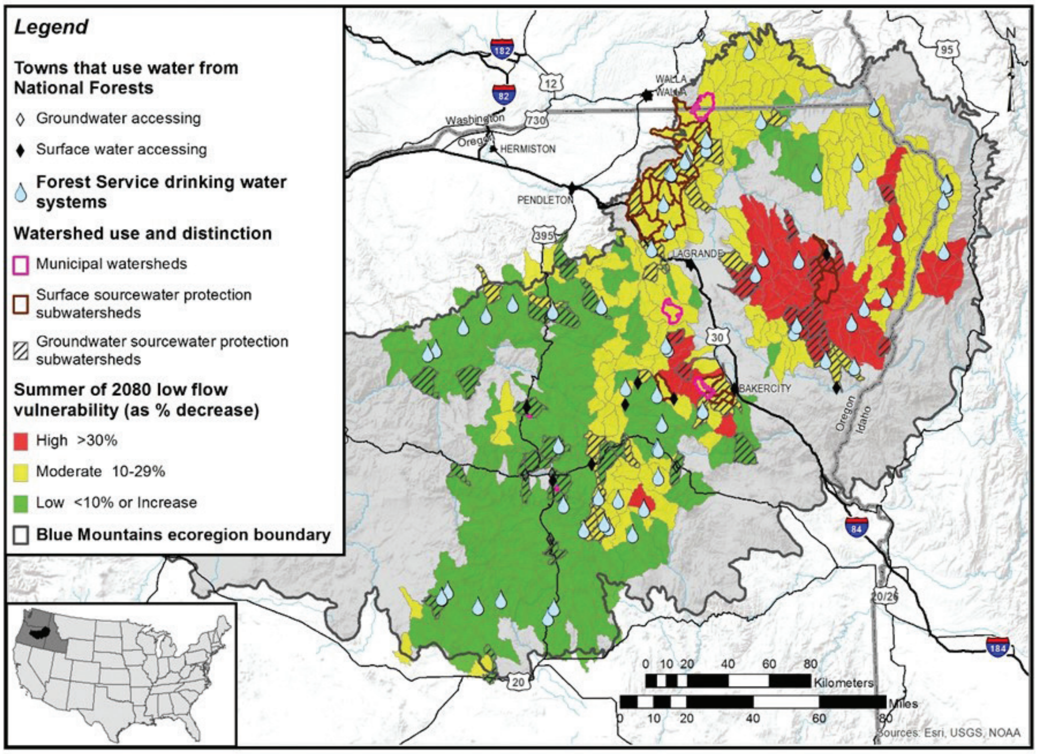

Figure 3.3—Projected risk of summer water shortage in the Blue Mountains region of Washington and Oregon, based on low streamflows for 2080. The Variable Infiltration Capacity model was used to calculate differences between historical streamflow data (1915–2006) and streamflow projections for the A1B emissions scenario (Wenger et al. 2010). From Clifton et al. (2017).

warmest years on record occurring recently. No clear trends in precipitation have been observed in the region (Mote et al. 2014).

The warming effects of anthropogenic greenhouse gas emissions in recent decades are clear (Abatzoglou et al. 2014, Knutson et al. 2013, Vose et al. 2016), but other conditions in and over the Pacific Ocean also affect climate in the PNW. The El Niño-Southern Oscillation (ENSO) is a cyclical phenomenon that involves coupled ocean-atmosphere variations in the equatorial Pacific Ocean and in the PNW. Positive ENSO (El Niño) events result in warmer, drier winters and springs, whereas negative ENSO (La Niña) events result in cooler, wetter winters and springs (Mote et al. 2014). The Pacific Decadal Oscillation (PDO) is a North Pacific phenomenon, resulting in sea surface temperature patterns that appeared to occur in 20- to 30-year phases during the 20th century (Mantua et al. 1997). Positive phases of the PDO were associated with warmer, drier conditions in the PNW.

Projected future climate—An ensemble of GCMs (from CMIP5) projected increases in mean annual temperature of 2.0–8.5 °F in the PNW for 2040–2071 (compared to 1950–1999, under the Representative Concentration Pathway 8.5 here and below) (Mote et al. 2014). Warming is expected to occur during all seasons, but most models project the largest temperature increases (3.4–9.4 °F) in summer (Mote et al. 2014).

Changes in precipitation are more uncertain; projecting future precipitation is difficult because of uncertainty in projecting changes in the large-scale circulation that affects cloud formation and precipitation (Shepherd 2014). Annual average precipitation is projected to increase by 3 percent, with projections ranging from -4.7 to +13.5 percent, depending on the GCM (Mote et al. 2014). Most models project decreased summer precipitation; for the other seasons, some models project increases and others decreases.

Warming temperatures and altered precipitation will affect hydrological processes in the PNW, specifically the amount, timing, and type of precipitation, and the timing and rate of snowmelt (Luce et al. 2012, 2013; Mote et al. 2018; Safeeq et al. 2013) (fig. 3.4). Snowmelt will affect snowpack volumes (Hamlet et al. 2005), streamflows (Hidalgo et al. 2009, Mantua et al. 2010), and stream temperatures (Isaak et al. 2012, Luce et al. 2014). In response to warming, shifts from snowmelt-dominant to mixed rain-and-snow watersheds, and from mixed rain-and-snow to rain-dominant watersheds, are projected by the 2040s (Tohver et al. 2014). This warming trend is expected to result in earlier and lower spring peak flow, higher winter flow, and lower late-summer flow (Raymondi et al. 2014) (fig. 3.5). Winter streamflows could increase in rain-dominant watersheds with precipitation increases, but the timing of streamflow will not shift significantly (Raymondi et al. 2014). With future increases in temperature and potentially in the amount of precipitation in the winter months, extreme hydrological events (e.g., those now rated as having 100-year recurrence intervals) may become more frequent (Hamlet et al. 2013).

ASSESSING THE EFFECTS OF DROUGHT AND OTHER WATER RESOURCE CHALLENGES

In general, GCMs project future increases in annual and seasonal precipitation in Alaska, and more winter precipitation but similar or less precipitation in the PNW (chapter 2). GCMs project that temperature will rise, and the magnitude of temperature changes will likely decrease summer water availability, especially if precipitation remains near historical levels. Although we have considerable confidence in long-term projections (years to decades) of decreasing water availability, the manifestation of drought can be difficult to forecast at short time scales (weeks to months).

Alaska

Water resources and aquatic ecosystems— Decreased snowpack, especially during snow drought years, will have far-reaching consequences by the mid-21st century. The source phase (snow or rain) of water in the system influences stream dynamics, including seasonal patterns of flow, silt and bedload, water chemistry, and changes in bank and bed morphology (Dery et al. 2009, Schnorbus et al. 2014). Groundwater, runoff from rain and snowmelt, and rain-on-snow events each result in different stream conditions (Battin et al. 2007, Chilcote et al. 2017, Paustian 2010). As snow becomes less common at low elevations, both the hydrology and habitat conditions of streams are expected to change.

In Chugach National Forest, water discharge over time in 61 of the 720 watersheds (8.5 percent) is likely to change because of projected reductions in snowpack (with increasing temperatures) over the next 60 years (Chilcote et al. 2017). This change in timing and volume of runoff will cause fundamental changes in fish habitat that could improve conditions for some species and degrade conditions for others (Chilcote et al. 2017). Watersheds that transition from snow-dominated to rain-dominated may periodically experience extreme low flows and high water temperatures, resulting in marginal conditions for some fish species. Islands, particularly outer islands in the southern Tongass National Forest, are expected to receive much less snow by the end of the century (EcoAdapt 2014). Freshwater systems used by salmon in the region are largely intact. This projected stability suggests that shifts in the hydrograph may favor one species over another but without resulting in broad-scale declines in the capacity of streams to support salmon in the short term; long-term changes are more uncertain (Chilcote et al. 2017, EcoAdapt 2014).

Wildlife—Snowpack provides critical habitat for many animal species. Changes in the distribution and timing of snow will alter habitat conditions, favoring some species and reducing habitat quality for others. Subnivean (under the snow) environments protect small animals and plants from extreme cold in winter (Emers et al. 1995, Pauli et al. 2013). In some environments, wolverines (*Gulo gulo*) rely on snow dens to preserve energy, provide thermal cover, and care for young during late winter (McKelvey et al. 2011). The duration of denning season by black bears (*Ursus americanus*) and grizzly bears (*U. arctos*) may be partly determined by the duration of snow cover (Goldstein et al. 2010). Snow depth, stability, and water content influence the ability of Sitka black-tailed deer (*Odocoileus hemionus sitkensis*) to forage, and of deer and gray wolves (*Canis lupus*) to travel, so changes in these variables alter predator-prey dynamics (Person et al. 1996).

Recreation, transportation, and infrastructure— Snow, river ice, and frozen soils facilitate winter travel in much of Alaska. With longer growing seasons in the future, muddy conditions will extend later in the autumn and begin earlier in the spring, a phenomenon that will be exacerbated if low-snow years increase as expected (Hayward et al. 2017). Similarly, snowpack suitable for skiing and snowmobile travel will occur for a shorter portion of the winter. Existing recreation trailheads could become "stranded" below sufficient snow for snowmobile and backcountry ski access (Hayward et al. 2017). Most recreation facilities, including cabins,

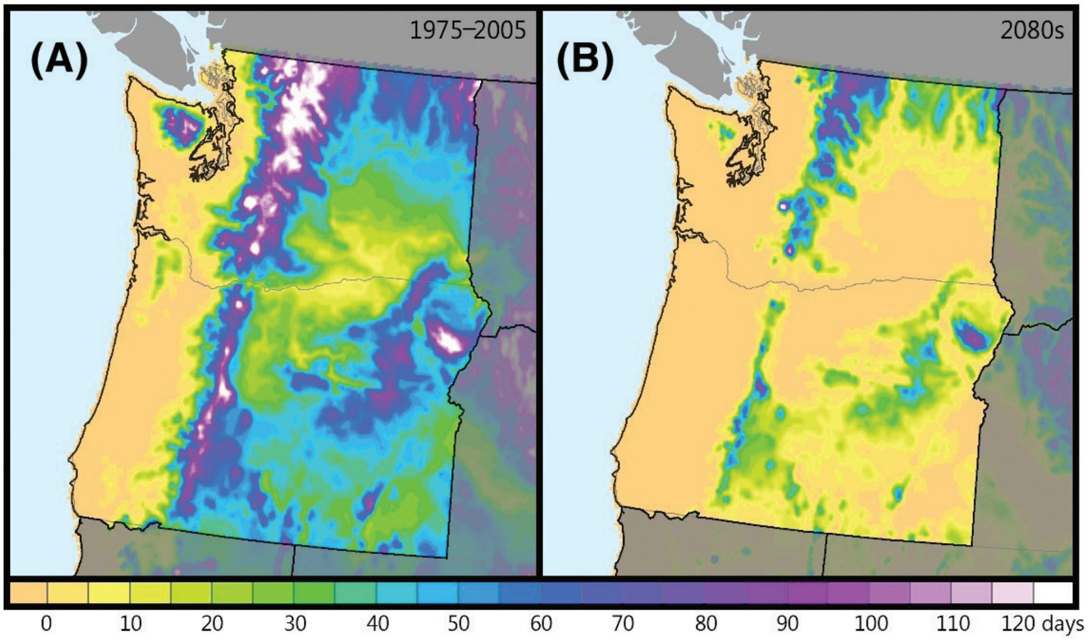

Figure 3.4—Modeled snow residence time in Washington and Oregon for (A) a historical period (1975–2005) and (B) projected for the 2080s with the Representative Concentration Pathway (RCP) 8.5 emissions scenario. Snow residence time will decrease in the Pacific Northwest in the future, particularly east of the Cascade Range. For more details, see https://usfs.maps.arcgis.com/apps/MapSeries/index.html?appid=4d6e58342f5a451dbe9e9c946bf76f85&entry=2.

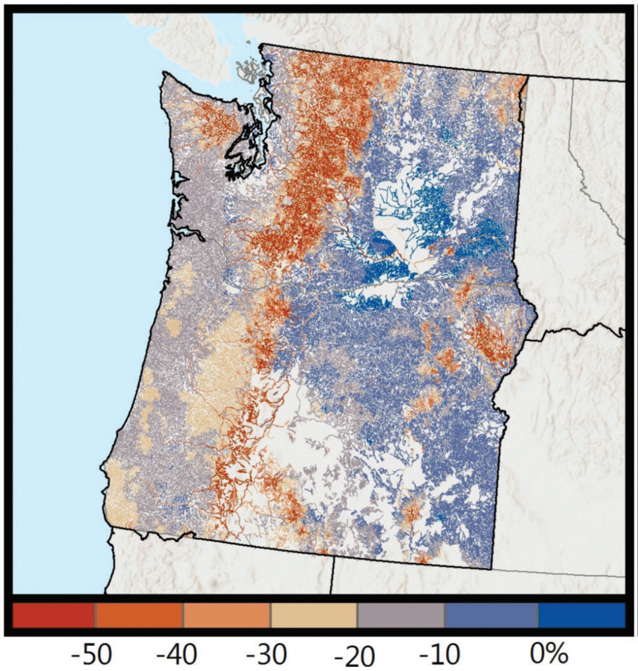

Figure 3.5—Projected change in mean summer streamflow in Washington and Oregon between historical (1977–2006) and future (2080s) time periods for the Representative Concentration Pathway (RCP) 8.5 emissions scenario. The largest reductions are shown in the mountainous areas, likely influenced by reduction in snowpack at higher elevations. From Luce et al. (2019).

day-use sites, trailheads, and campgrounds are below 1,500-foot elevation, where projected reductions in snowpack will be greatest.

The longer snow-free period at low and mid elevations is expected to shorten the duration of the winter recreation season, with significant effects by 2050. As low-elevation areas become stranded below the snowline, Alaska may see a shift from downhill skiing and other snow sports to other activities like hiking and biking (Hayward et al. 2017). With less snow and frozen soils, access to subsistence resources (e.g., hunting, trapping) could be altered at traditional low-elevation access points in Chugach National Forest. For example, less snow accumulation in some areas will allow Sitka black-tailed deer to remain dispersed throughout the winter, limiting the ability of subsistence hunters to find deer (Morton and Huettmann 2017).

Although average snowpack is likely to decline in coming decades, high variability in snowpack, combined with the potential for more severe storms, may lead to occasional deep snowpack and significant rain-on-snow events. Snowpack and melt conditions have the potential to damage human-built infrastructure. High runoff following rain-on-snow events, increased glacier melt, and high snowpack may exceed the capacity of culverts, leading to road washout and damage. Landslides, snow slides, and high snow loads threaten recreation-use cabins, campground structures, and agency administrative buildings.

Forest ecosystems, disturbance, and carbon—Water deficit has both direct and indirect effects. It directly contributes to potentially lethal stresses in forest ecosystems by intensifying negative water balances (Littell et al. 2008, Milne et al. 2002, Restaino et al. 2016, Stephenson 1998). A reduction in productivity ("browning") in boreal forests of Alaska has been observed in recent decades (Beck and Goetz 2011, Parent and Verbyla 2010), which may be caused by temperature-induced drought stress (Barber et al. 2000, Parent and Verbyla 2010). Water deficit also indirectly increases the frequency, extent, and severity of disturbances, especially wildfire and insect outbreaks (Logan and Powell 2009, McKenzie et al. 2004). These indirect disturbances alter forest ecosystem structure and function, at least temporarily, much faster than do chronic effects of water deficit (e.g., Loehman et al. 2017).

Water supply and soil moisture influence plant species distribution and abundance at broad spatial scales. Projections of future vegetation distributions are varied. In one study, modeling of tree species distribution suggested that the distribution of temperate rainforests in Alaska would not shift significantly during the 21st century (Hollingsworth et al. 2017). In contrast, another study showed that inland conifer and shrub species have been moving upward in elevation on the Kenai Peninsula by as much as 30 feet per decade since 1950 (Dial et al. 2007). Similarly, broad-scale forest monitoring suggests that Alaska cedar (*Callitropsis nootkatensis*) distribution is moving northward in Alaska and that its basal area has recently increased (Barrett and Christensen 2011). Where altitudinal treeline expands, alpine vegetation may be reduced.

Alaska cedar is valued as a commercial product and by Alaska Natives for shelter, clothing, canoe paddles, and totem poles. Prior to 1995, some coastal rainforest stands lost 70 percent or more of Alaska cedar trees, totaling 200,000 acres in southeast Alaska (Hennon et al. 2012). Although Alaska cedar stands with high rates of mortality represent a small percentage of their total distribution (Barrett and Pattison 2016), losses in some areas have reduced timber harvest. Alaska cedar mortality is linked to water dynamics associated with climate; injury to fine roots occurs when low snowpack and poorly drained soils result in springtime freezing of roots (Hennon et al. 2012).

Compared to the late-20th century, some projections suggest that area burned by wildfire in Alaska will double by mid-21st century and triple by late-21st century (Balshi et al. 2008, Pastick et al. 2017). Historically, fires typically burned in the Yukon River basin, between the Alaska Range and the Brooks Range, and this happened during episodic fire years when warm conditions in spring and early summer dried fuels and summer rains were minimal. Since the early 2000s, extreme fire weather conditions have promoted the spread of large fires in boreal forests of interior Alaska. Other regions have historically experienced much less fire, although the western Kenai Peninsula has a history of human and natural ignitions that contributed to significant wildfires, with return intervals around 100 years (Anderson et al. 2006). However, as temperatures and duration of growing season increase and spring snowpack melts earlier, dry fuels are expected to be available for longer than in the historical record, increasing the likelihood of fire ignition and spread (Young et al. 2017).

Vulnerability of human development to fire is expected to increase in the next 50 years, especially if warmer summers facilitate extreme fire weather (Hollingsworth et al. 2017). By 2065, the value of structures at risk to fire on the Kenai Peninsula, particularly in the boreal transition forests of the western Kenai Peninsula, is projected to grow by 66 percent on private lands, and the projected value of structures in landscapes with high to extreme fire risk may approach $3.8 billion (based on 2014 dollars) (Hollingsworth et al. 2017). In contrast, wildfire is rare in the temperate coastal rainforest on the eastern Kenai Peninsula, throughout Prince William Sound, and in southeast Alaska, and it is expected to remain rare in the future (Barrett and Christensen 2011, Hollingsworth et al. 2017).

In a warmer climate with more prolonged dry periods, terrestrial carbon storage in Alaskan ecosystems may be vulnerable to higher decomposition rates and more wildfire. Tongass National Forest stores an estimated 650 million tons in aboveground tree carbon, more than any other national forest, with a 4.5-percent increase in aboveground carbon storage over the past decade (Barrett 2014). Belowground carbon storage is also high throughout the region (D'Amore and Lynn 2002). As temperatures warm, the capacity for soil decomposition to increase may result in net carbon loss in the future (D'Amore et al. 2015). Aboveground, though, forest carbon storage may continue to increase, at least in forests not subjected to fire.

Cultural resources—A strong social, cultural, and economic relationship exists between salmon and human communities in Alaska. Shifts in snowpack and air temperature will result in altered hydrology, geomorphology, stream temperature, and stream chemistry, which in turn will influence salmon, positively in some cases and negatively in others. Warmer streams and changes in timing of extreme runoff may improve conditions for some salmon stocks, although a warmer climate may also make salmon runs more variable in time and space. Temperatures during late summer in some spawning streams, particularly on island systems in southeast Alaska, have exceeded values tolerated by returning salmon, resulting in mortality and reduced spawning.

Changes in the timing, species mix, or abundance of salmon influence daily life, social interactions, and cultural practices of Alaska Natives throughout the State. Traditions in obtaining, processing, and distributing wild resources define Alaska Native groups, a reality that was codified in the Alaska Native Claims Settlement Act of 1971.

Winter transportation with sled dogs, sled-dog racing, and recreational mushing are part of Alaska Native culture and contemporary social traditions in Alaska. Declines in snowpack led to the recent cancellation and course changes in major sled-dog races that draw thousands of tourists. The World Champion sprint-dog race was cancelled for 2 consecutive years, and the Iditarod route was changed three times in 5 years. These types of effects are expected to occur more frequently in the future.

Pacific Northwest

Water resources and aquatic ecosystems—Water is the most widely valued resource provided by public lands in the United States (Furniss et al. 2010). During times of drought, decisions about allocation of limited water often involve tradeoffs among fish habitat, municipal and agricultural use, hydroelectric power, recreational use, and livestock grazing. In addition to affecting the quantity of water available, drought also affects water quality by increasing water temperature and turbidity. Warmer temperature, in addition to limited water availability, increases the likelihood of algal blooms that degrade aquatic habitat and can be harmful to people, pets, and livestock (Hand and Lawson 2018, Paerl and Huisman 2008).

Across mountainous landscapes in the PNW, surficial geology and soils determine both drainage properties and the severity of drought effects. For example, in areas with highly permeable volcanic rocks and pumice soils, water rapidly infiltrates down hundreds of feet, supporting neither water storage for human uses nor water availability for vegetation during drought (Konrad 2006). Melting snow during the growing season has historically provided water for vegetation (Elsner et al. 2010), but reduced snowpack, associated with warmer winters, decreases late-season snowmelt. Warmer winters lead to earlier peak flows and lower, warmer base flows (Kormos et al. 2016, Mote et al. 2018, Stewart et al. 2013). Some areas are also likely to experience a decline in summer streamflow, as water drains into deep groundwater storage in basalt aquifers (Drost et al. 1990).

Forest ecosystems, disturbance, and carbon—Tree growth is likely to decrease in most areas in the PNW because of water limitations, especially in low- to mid-elevation coniferous forests. Douglas-fir (*Pseudotsuga* *menziesii*), which is an important species ecologically and economically, is expected to have lower growth rates on both the east and west sides of the Cascade Range (Littell et al. 2008, Restaino et al. 2016). High-elevation coniferous forests, in contrast, are likely to have faster growth rates because less snowpack will lead to a longer growing season in landscapes where water limitations will be less common (Littell et al. 2010, Mote et al. 2018).

Overall, more tree mortality is expected, especially in dense stands at the lower tree line where drought exacerbates water deficit. Trees of many species and sizes can be affected simultaneously. Dry soils and topographic positions that do not retain soil moisture are vulnerable, especially where they affect seedling establishment (i.e., seeds near the ground or with small root mass) (Joslin et al. 2000). Western hemlock (*Tsuga heterophylla*), which has shallow fine roots, can be especially sensitive to prolonged dry weather (Burns et al. 1990). As growth decreases and disturbances increase, current levels of carbon stored in vegetation and soils will be increasingly difficult to maintain.

Dense forests are particularly susceptible to bark beetle attack, and although beetles typically target weakened trees, they can also attack nearby vigorous trees (Fettig et al. 2007, Lieutier 2004). Lodgepole pine (*Pinus contorta* var. *latifolia*) in particular has experienced significant mortality from mountain pine beetles (*Dendrodoctonus ponderosae*), at least partly accelerated by drought periods, as part of a much larger pattern of beetle-caused mortality in the Western United States and British Columbia (Hicke et al. 2016).

Drought frequency and duration also affect the extent and severity of wildfires. In forests, fine fuels will dry earlier in the growing season and stay dry longer, and live fuel moisture will also decrease significantly, increasing fire hazard and likely the duration of the fire season. Early-seral forest structure may become more prevalent across the landscape, replacing older trees (Kashian et al. 2006).

Rangelands—Drought reduces growth in rangelands during the growing season, especially if large numbers of invasive annual grasses are present (Fehmi and Kong 2012, Runyon et al. 2012) (fig. 3.6). Drought conditions favor the spread of invasive grasses (Kindschy 1994, Tausch et al. 1994), which further reduce the extent and productivity of native plant species. During drought, excessive reductions in aboveground growing plant

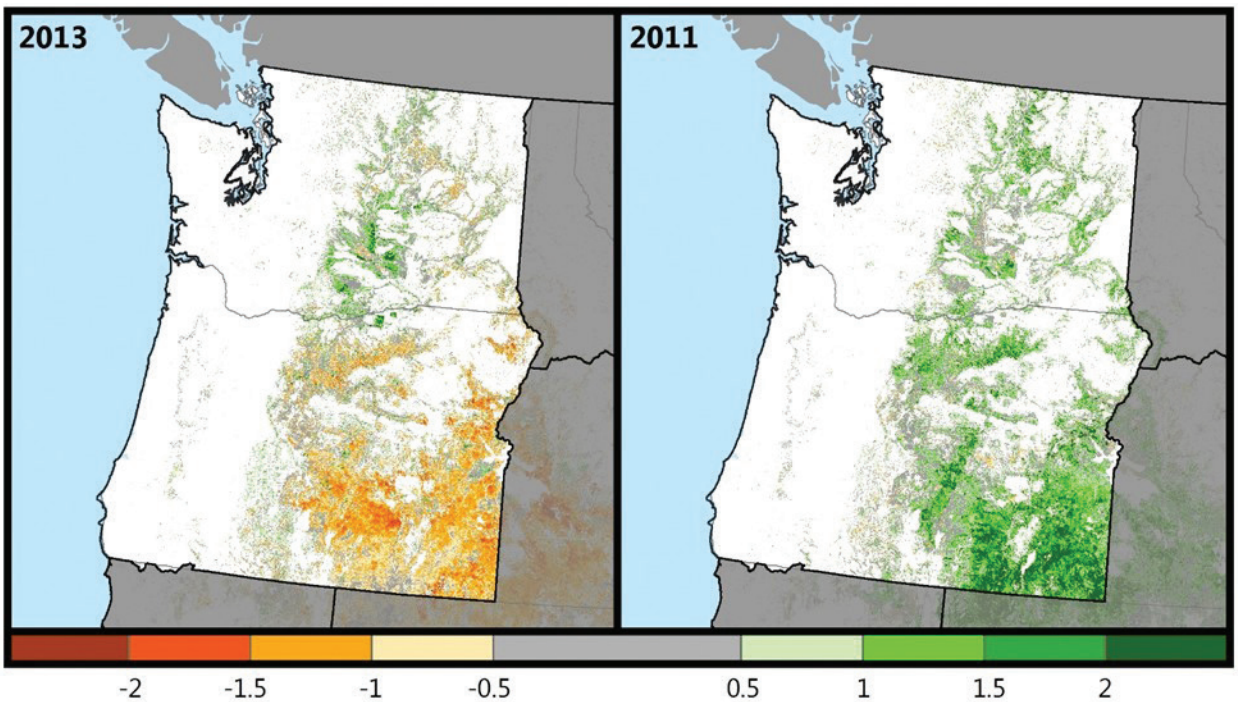

Figure 3.6—Relative rangeland productivity (z-scores) for Washington and Oregon, illustrating the standard deviation from the mean. Left (2013) represents a drought year with lower rangeland productivity. Right (2011) represents above-average moisture and productivity. For a more detailed map on rangeland productivity, see https://usfs.maps.arcgis.com/apps/MapSeries/index.html?appid=bc33cd94f0f643298c296c827ee8ed68&entry=3

material through grazing by livestock or wild horses and burros decrease belowground roots, creating growing space for invasive plant species (Biondini et al. 1998, Fuhlendorf et al. 2001). Therefore, following drought, rest from grazing is needed during the growing season to allow for plant physiological recovery. Although grazing typically occurs on perennial grasses, shrubs are also prone to browsing when grasses are unproductive or dormant. Livestock are more likely to graze riparian areas during the summer, when conditions are hottest and grasses in the adjoining uplands are dormant.

As drought intensity increases, rangeland productivity decreases, although the amount of decrease depends on the type of site (e.g., sagebrush-steppe versus mountain meadows). In semiarid sites, nonnative annual grasses, especially cheatgrass (*Bromus tectorum*), tend to increase fire frequency and spread; these nonnatives are highly flammable and have higher fine fuel biomass and greater fuel continuity than native vegetation (Balch et al. 2013). Expansion of nonnative annual grasses starts a positive feedback loop that favors further spread of invasive annual grasses and substantial reduction in cover of native shrubs, grasses, and forbs (Link 2006, Melgoza and Nowak 1991). Large rangeland fires typically occur when a high-productivity year that produces abundant fine fuels is followed by a drought that greatly reduces live fuel moisture. Overall, drought induces more intense fire behavior, increasing the difficulty of fire suppression. Although fuel quantity typically controls the energy released during a fire, drought can extend the duration of conditions under which fuels will readily burn (Brown et al. 2005). If drought occurs following fire, then an extended period of plant rest from grazing may be needed to allow recovery of productivity.

Socioeconomic effects—The most significant effect of increased frequency and magnitude of drought will be fewer available water resources because nearly all social and economic sectors have significant demands for a continuous, reliable water supply. In some cases, especially in semiarid portions of the PNW, water is already allocated near or beyond the limit of its average availability, so access to water becomes even more limited during drought years, with tradeoffs occurring among agriculture, hydroelectric power generation, and protection of fish habitat. Even on the west side of the Cascade Range, water storage for municipal and industrial uses is typically limited by reservoir capacity, which can be depleted during years when snowpack is low and water demands are high.

Recent drought years in the PNW have provided an opportunity to observe what a future with more frequent and longer droughts might look like (Marlier et al. 2017). In 2014–2015, an exceptionally warm winter and spring resulted in record low snowpack. This "snow drought," combined with high temperatures and low precipitation levels in the spring and summer, led to extremely low flows in streams and rivers, crop damage, and widespread fish mortality. In Washington State, the economic impact of the drought on agricultural crops was $336 million (Anderson et al. 2016). Most ski areas suffered financially. In the summer of 2015, wildfire burned 1 million acres in Washington. After a long period of low precipitation in summer 2017, wildfires burned more than 1 million acres in Oregon and Washington, causing economic damage in many communities, reducing access to public lands and forage for grazing, and degrading air quality for several weeks.

MANAGING FOR DROUGHT, EXTREME EVENTS, AND DISTURBANCES

The 2016 Federal Action Plan of the National Drought Resilience Partnership describes ways in which Federal departments and agencies can work with State, regional, Tribal, and local partners to respond to drought and increase long-term drought resilience. These include, for example, sharing data and information among Federal agencies and State, regional, Tribal, and local officials on drought, water use, and water availability; building local planning capacity for drought preparedness and resilience through coordinated planning and capacity-building programs; and supporting efforts to conserve and efficiently use water by carrying out relevant research, innovation, and international engagements.

There is little additional agency guidance (in the form of guidebooks or manuals) related to drought in the U.S. Department of Agriculture, Forest Service (USFS) or U.S. Department of the Interior, Bureau of Land Management (BLM), but some good examples exist. During the 2015 drought in the PNW, the Regional Forester in the Pacific Northwest Region of the USFS issued guidance to national forests. The BLM has also issued guidance on drought response in the agency through instruction memoranda. For example, in 2013, the BLM instructed its districts to monitor drought status; share drought information; seek drought information compiled by other agencies; coordinate drought responses with State, Tribal, and local governments; and adjust authorized uses as needed. No direction is specific to forest operations, other than the interagency Industrial Fire Precaution Levels used in Oregon and Washington, which prohibit industrial forest activities during times of high wildfire risk, such as drought.

Existing frameworks and tools used by the USFS and BLM either currently address drought or could be used to expand opportunities for guidance on drought management in the future (Vose et al. 2016). For example, many of the National Best Management Practices (BMPs) for Water Quality Management on National Forest System Lands (USDA FS 2012) can help mitigate drought. These BMPs address most resource program activities, including water use, aquatic ecosystems, rangeland, and recreation. Specific drought references in the BMPs include designing projects to account for water availability, addressing drought-related shoreline degradation, and responding to water availability in range permit activities. The BMPs could be reviewed and revised to more explicitly address drought response.

The USFS Watershed Condition Framework (Potyondy and Geier 2011) and regional aquatic restoration strategies guide forest watershed and aquatic restoration programs, and these restoration activities can help increase ecosystem resilience to drought. Incorporating drought in restoration planning, including in objectives and design, could further increase drought resilience. For example, planting drought-tolerant vegetation in restoration treatments and reducing forest stand density (Sohn et al. 2016) can help to decrease drought-related mortality.

Many national forests in the USFS Pacific Northwest Region have conducted climate change vulnerability assessments and adaptation efforts (e.g., Halofsky et al. 2011, Halofsky and Peterson 2017, Raymond et al. 2014). These assessments incorporate potential effects of increased temperatures and changing precipitation patterns on water resources, fish and aquatic systems, vegetation, wildlife, recreation, and ecosystem services. For example, the hydrology assessment includes projections for future summer low flows, and the vegetation assessment includes maps of soils that may be most vulnerable to drought (Halofsky and Peterson 2017). These climate change assessments and climate-informed forecasting (Preisler et al. 2017) can help to facilitate drought planning and prioritize response. Similarly, in Alaska, climate vulnerability assessments for Chugach (Hayward et al. 2017) and Tongass (EcoAdapt 2014) National Forests examine potential changes in water dynamics, providing the understanding to support adaptation plans. Building from the vulnerability assessment, the Tongass National Forest recently developed preliminary climate adaptation options for streams and riparian areas. This effort builds on a mature stream restoration program on the forest.

Disaster management tools and systems that are already in place in Federal agencies could be applied to drought response and used as a template for drought planning. Here are three examples. The Incident Command System, initially developed to coordinate response to wildfires, is a standardized, interagency approach to emergency coordination and response, and this approach could be reframed for drought. After wildfire events, the Burned Area Emergency Response process involves teams assessing values at risk, rapid assessment of fire effects, and options for treatment. A similar process could be used during and after drought events. Many national forests have a Forest Emergency Road Maintenance Plan for flood events; similar plans could be developed for drought.

Management Options for Responding to Altered Water Resources in Alaska

Infrastructure and transportation—One of the most important strategies for responding to altered water resources in Alaska will be to develop a common understanding among national forests, national forest visitors, and stakeholders about the potential effects of declining low-elevation snowpack on infrastructure, travel, and recreation (table 3.1). To develop solutions that reduce undesirable effects, this effort in public education needs an ongoing dialogue that focuses on both communicating biophysical effects and listening to stakeholders.

Maximum streamflows in the future may increase as a result of lower snowpack, earlier or faster melt, and associated rain instead of snow storm events. Under these conditions, maintenance of roads and associated infrastructure will be especially important to avoid erosion. Roads that are especially vulnerable to repeated flooding can be either removed or decommissioned and restored with vegetation to accommodate gradual flow along floodplains (fig. 3.7). Roads maintained in or near floodplains may need to be stormproofed to meet current engineering standards. Water bars can be added to disconnect streams from roads, and culverts can be added or upsized based on projected flows. All infrastructure (e.g., bridges) should be designed or modified to accommodate the peak flows that will occur

Table 3.1—Water resource vulnerabilities, adaptation strategies, and adaptation tactics for Alaskan ecosystems

VULNERABILITY	ADAPTATION STRATEGY	ADAPTATION TACTICS
Infrastructure and transportation		
High winter streamflows and flooding that damage roads, bridges, and other structures.	• Increase resilience of roads and infrastructure to increased flooding; remove vulnerable roads and infrastructure. • Develop a common understanding among national forests, visitors, and stakeholders about the effects of declining snowpack on infrastructure, travel, and recreation.	• Remove or decommission roads and restore vegetation. • Stormproof roads to current engineering standards. • Install additional culverts and increase the size of new culverts to accommodate higher flows. • Redesign trails to handle increased overland flows. • Provide public education through national forest offices, on websites, and at recreation sites.
Aquatic systems, riparian areas, and fish habitat		
High winter streamflows and flooding, longer duration of snowmelt, and later low flows in summer.	• Maintain or increase resilience in aquatic systems and riparian areas, especially in locations with high-quality fish habitat.	• Accelerate riparian restoration and stream restoration. • Add large wood to streams; encourage the growth of large conifers to provide large wood to stream channels. • Modify drainage structures, roads, and other infrastructure to reduce scouring of fish spawning gravels. • Remove fish passage barriers.
Recreation		
Less snowpack and a longer warm-weather season, altering access to recreation sites and patterns of visitor use.	• Revise spatial distribution of recreation sites. • Develop a more flexible, climate-smart network of recreation sites to provide access to visitors.	• Use modeling to identify the location of areas that will be suitable for snow-based and warm-weather recreation in the future. • Provide flexible trailhead locations to accommodate variation in snowpack. • Implement flexible snow-sport season openings. • Design administrative and recreation infrastructure to accommodate larger storm events, higher snow loads, overland flow, and higher streamflow.

Figure 3.7—Roads that wash out repeatedly, as shown here in Chugach National Forest, are good candidates for decommissioning. (Photo by USDA Forest Service)

in the future. The design and maintenance of trails could incorporate expectations for longer periods of high soil moisture and higher than normal overland runoff.

When safety issues or damage to resources are anticipated, temporary closures for some modes of travel will be necessary. For example, although fire is not expected to be as common as in interior Alaska, it will likely become more common in southcentral Alaska, and planning processes should include the potential for fires to affect transportation along the limited road network. For example, the 2016 McHugh Creek Fire closed the Seward Highway repeatedly, limiting traffic between Anchorage and the Kenai Peninsula for several days.

Increased near-surface permafrost thaw will also likely cause damage to infrastructure and transportation in Alaska (Melvin et al. 2017). Ground subsidence that occurs with permafrost thaw has consequences for buildings, roads, railroads, pipelines, and oil and gas infrastructure. Increasing temperatures can also affect the frequency of freeze-thaw cycles, which in turn can decrease the stability of foundation and underground infrastructure (Melvin et al. 2017). As this damage occurs, closures and replacement of buildings and roads will likely be necessary.

Aquatic systems, riparian areas, and fish habitat—To maintain high-quality habitat for salmonids, it is necessary to ensure that aquatic systems and riparian areas are resilient to climate-induced changes. A key element to building resilience is to accelerate riparian restoration, especially in priority areas where past land use has damaged riparian function or altered floodplain dynamics (table 3.1). For example, alder regeneration can be encouraged in riparian areas where appropriate, as well as prescriptions to encourage large trees that can deliver large wood to streams. Priorities for locating riparian restoration include conifer-dominated stands, sites where roads or past harvest activity damaged riparian areas, reaches with artificially constrained floodplains, and areas that are expected to provide high-quality salmon habitat in the future. A historically rare but possible future effect on both resident and anadromous fish habitat is the potential for fire disturbance, which would have both short-term consequences and long-term benefits for fish habitat, especially in the northern parts of southcentral Alaska.

Other improvements to fish habitat include modifying drainage structures, roads, and other infrastructures that restrict flow from a main channel to a floodplain or increase scouring of spawning gravels (e.g., by relocating roads out of the floodplain). Fish passage barriers may develop during low flows, and options for altering these barriers need to be considered. Stream restoration can replace large wood (logs) in streams and floodplains where woody structures were removed during streamside logging in the 1960s–1970s. These steps would both improve salmon habitat and restore stream function and connections to enhance resilience to hydrological stress. To achieve these goals, effective communication with local communities and stakeholders about potential changes in salmon populations, including possible fish mortality, will be increasingly important in future decades.

Recreation—Resource managers can work with regional climate science organizations to develop future scenarios of snowpack distribution and duration, using this information to prioritize relocation of current recreation infrastructure to support backcountry skiing and snow machine travel (table 3.1). These future scenarios include flexible trailhead locations, variable season openings, changes to infrastructure, and awareness of increasing fire hazards. Flexible trailhead locations will accommodate variation in snowlines and facilitate access to sufficient snow for winter sports. Variable snow-sport season openings will ensure sufficient snowpack to prevent resource damage. Administrative and recreational infrastructure (e.g., recreation cabins, trail bridges, trail drainage systems) can be designed to accommodate larger storm events, including higher snow loads, overland flow, and higher streamflow. Increased fire hazard could eventually impact recreation if fire danger limits access. The potential for fires to become more common may especially alter visitor experiences in southcentral Alaska forests.

Management Options for Responding to Drought in the Pacific Northwest

Water resources—Lower snowpack and more severe drought with changing climate will likely lead to lower stream baseflows and in some cases reduced soil moisture. Combined with increasing demand for water with future population growth, water availability will be reduced for aquatic resources, recreation, and municipal uses (Elsner et al. 2010, Prestemon et al. 2016). To ensure that water is available during times of drought, resource managers can build redundancy into water supplies and increase reliability in water systems (table

3.2). Water budgets can help to evaluate the effects of management actions, providing a framework for on-the-ground planning and accounting for water supply and demand. Conserving water and providing for increased storage capacity will help to ensure that water will be available during drought.

A key way to increase water storage, keep water temperatures low, and slow the release of water from the landscape is to manage for riparian, wetland, and groundwater-dependent ecosystem function (Peterson and Halofsky 2018). Increasing the pace and extent of riparian and wetland restoration across land ownerships and controlling sources of pollution could help maintain water quantity and quality during drought (table 3.2). Reducing the risk of high-severity fires can lower risk of post-fire erosion and sedimentation in streams (Luce et al. 2012). Managers can also implement water quality BMPs and water quality restoration plans to maximize water quality and quantity, adding and revising actions in these BMPs (e.g., manipulating forest structure in snow-dominated watersheds) to address drought.

Increasing awareness of drought and its effects can increase the capacity of agencies to respond to drought and improve effectiveness of communication with the public about drought (table 3.2). New employees can be mentored on drought and existing employees encouraged to take opportunities for professional development related to drought. Education and outreach with the public would increase drought awareness (inside and outside the agency) and acceptance of management responses. Modifications to agency processes, such as the use of National Environmental Policy Act categorical

Table 3.2—Drought vulnerabilities, adaptation strategies, and adaptation tactics for water resources in the Pacific Northwest

WATER RESOURCES		
VULNERABILITY	**ADAPTATION STRATEGY**	**ADAPTATION TACTICS**
Less water availability for national forest consumptive uses, ecological uses, and off-forest consumptive uses.	• Build redundancy in water supplies, increase reliability in water systems, and adopt a water budget perspective (e.g., consider how management actions favor one part of the water cycle at the expense of another). • Coordinate with States and Federal permittees.	• Develop water budgets and use them as a framework for evaluating management actions; plan and account for forests, range, and in-stream needs. • Increase water conservation; produce less waste; prioritize maintenance and reconstruction to ensure that infrastructure meets current standards. • Make water systems more resilient to drought (e.g., use water-smart technology); prepare for future storage needs. • Review water quality best management practices to include drought-focused strategies. • During droughts, in coordination with States and permittees, adjust water use through (1) advisories, (2) voluntary conservation, (3) mandatory conservation, and (4) rationing.
Poorer water quality during drought.	• Coordinate within and outside Federal agencies to address water quality.	• Protect and maintain water quality by implementing and adjusting water quality best management practices and water quality restoration plans. • Prioritize and target riparian and wetland restoration to provide shade over water and reduce quick flow from roads; use appropriate geospatial tools to identify priorities. • Continue to manage landscapes to reduce fire severity and promote site-adapted vegetation. • Control water pollution.
Lack of capacity to respond to severe droughts.	• Increase capacity of the workforce and awareness of leadership.	• Develop drought management plans integrated between a permittee's base property and allotment to maintain land health and productivity. • Increase drought awareness with agency leadership and the public. • Develop and expand partnerships with user groups to address water resource adaptation needs (e.g., Wyden and Good Neighbor Authorities, partnership agreements). • Conduct postdrought assessments and after-action reviews to promote learning and better responses in the future. • Mentor new employees and develop drought-focused professional development opportunities.

exclusions for projects that address drought, may facilitate timely response to drought.

Fish and aquatic systems—More drought, lower summer streamflow, and higher stream temperature in a warmer climate will create stress for fish, particularly cold-water-adapted species that are now near thresholds for fish function (Isaak et al. 2012, Mantua et al. 2010). To mitigate the consequences of drought to fish, it will be important to identify where important fish habitats and high human use overlap, then reduce human uses in those areas (table 3.3). For example, critical fish habitats can be fenced to prevent livestock use, and fishing and recreation can be prohibited in critical areas during drought. Public education about the negative effects of drought on fish may help to change human behaviors that exacerbate these effects.

The effects of drought on aquatic habitat can be exacerbated by impediments to fish movement. Impediments include culverts, fences, low-water fords, dams, and diversion structures (Matthews and Marsh-Matthews 2003). Removing physical and biological barriers to fish movement can help fish access habitat when streamflow is low (table 3.3). High temperature can also be a barrier to cold-water-adapted fish species (Mantua et al. 2010). Steps to minimize increases in stream temperature include maintaining riparian vegetation, restoring incised streams to improve infiltration of the hyporheic zone, and maximizing instream flows (Mantua et al. 2010). Lateral habitat connectivity can be improved by increasing floodplain connectivity and restoring side channels, wet meadows, and wetlands (Peterson and Halofsky 2018).

Table 3.3—Drought vulnerabilities, adaptation strategies, and adaptation tactics for fish and aquatic habitat in the Pacific Northwest

FISH AND AQUATIC HABITAT		
VULNERABILITY	**ADAPTATION STRATEGY**	**ADAPTATION TACTICS**
Limited water in times of drought, resulting in more frequent and intense disturbance because of concentrated and intensive use of water.	Identify key areas important to fish populations and human uses.	• Map areas important to fish and overlay areas of high human use (e.g., roads, campgrounds, trails). • Identify locations with the most cold-water habitat, connectivity, and presence of species of interest.
	Reduce human activities in areas important to fish populations.	• Reduce use by livestock by fencing off critical fish habitat areas and providing alternative water supplies. • Limit fishing and recreational use during drought. • Move recreation to less critical areas. • Decommission roads and trails where appropriate.
	Provide public education and outreach on needs of fish during drought.	• Educate the public, including ranching and farming communities, to encourage behaviors that protect fish. • Explain why access is limited and how it will benefit fish. • Protect key areas with personnel who can also aid with education and outreach to the public.
Lower base flows and loss of connectivity during drought.	Allow for movement of fish to reach suitable habitat by removing barriers, while maintaining barriers that limit aquatic invasive species.	• Remove physical barriers such as culverts, fences, low-water fords, dams, and diversion structures. • Remove invasive species. • Reduce temperature where it creates a thermal barrier (maintain instream flows, increase instream flows by restoring incised streams, and provide structure). • Create fish bypass areas and add screening to prevent fish from going into areas that will dry out.
	Restore or improve lateral connectivity.	• Increase floodplain connectivity. • Aggrade down-cut/incised channels. • Remove dikes and levees. • Restore side channels and alcoves (to promote lateral complexity). • Restore wet meadows and wetlands. • Increase floodplain roughness by adding more wood and restoring vegetation.

(continued)

Watersheds and stream reaches that are now in poor ecological condition are likely to be more vulnerable to drought (Matthews and Marsh-Matthews 2003). Increasing habitat complexity in watersheds and riparian areas may help reduce negative effects of drought. Habitat complexity can be increased through restoration of riparian areas, wet meadows, and wetlands, as well as streams. Reducing road density will reduce erosion and sedimentation in streams. Maintaining or restoring American beaver (*Castor canadensis*) populations can increase habitat complexity, improve water retention, trap sediment, increase infiltration of the hyporheic zone, and increase low-flow volume (Pollock et al. 2014) (fig. 3.8).

Interactions with nonnative fish species and other aquatic organisms are a significant stress for native cold-water fish species (Rahel and Olden 2008). Lower streamflows and higher temperatures favor invasive fish species, and invasions can lead to simplification of biotic communities. Reducing populations of nonnative species can help to increase viability of native fish populations. Ways to control nonnative populations include modifying fishing seasons, increasing catch limits for invasive species, and encouraging people to catch more invasive species (table 3.3), as well as traditional techniques for removal of unwanted fish such as electro-fishing and chemical treatments. Better collaboration between Federal agencies and State and Tribal fish managers would also help reduce impacts of nonnative species.

Forest ecosystems—Some current forest management practices can help to increase resilience to drought. For example, thinning treatments are generally designed

Table 3.3 (*Continued*)—Drought vulnerabilities, adaptation strategies, and adaptation tactics for fish and aquatic habitat in the Pacific Northwest

FISH AND AQUATIC HABITAT		
VULNERABILITY	**ADAPTATION STRATEGY**	**ADAPTATION TACTICS**
Drought susceptibility of marginal habitat that is less complex or watersheds in poor condition, leading to more fish exposure to warmer water, higher pollutant concentrations, less space, and less dissolved oxygen.	Increase complexity in watersheds and riparian areas to increase their resilience.	• Re-establish riparian habitat; protect, restore, and improve quality of riparian vegetation. • Reduce road density and decommission roads that damage aquatic habitat. • Remove dikes and levees to restore habitat connectivity. • Restore wet meadows and wetlands. • Manage springs to provide sufficient baseflow. • Restore incised streams. • Restore beaver habitat and colonies. • Control erosion.
	Increase in-stream flows.	• Secure in-stream water rights. • Improve water efficiencies (e.g., household use, irrigation). • Restore down-cut wet meadows. • Change point of diversion to get downstream withdrawal/redirect where water flows are occurring. • Manage surface water and groundwater concurrently. • Control invasive species that require large amounts of water.
Lower streamflows and higher temperatures that favor invasive species and simplify biotic communities.	Reduce invasive species populations.	• Modify timing of fishing season, and increase catch limits for invasive species. • Reduce nonnative fish with electro-fishing, chemical treatment, and predator species. • Use reward system to encourage people to catch invasive fish and amphibian species. • Enhance natural predators of invasive fish and amphibians. • Increase habitat complexity to protect native species and allow for native/nonnative coexistence. • Moderate stream temperature increases to favor native aquatic species. • Conduct education and outreach on how invasive species affect native fish populations. • Collaborate with State and Tribal agencies to manage fisheries to reduce impact of invasives on native fish species.

Figure 3.8—Engineering by American beavers (*Castor canadensis*) encourages the slow release of water to downstream users and retains water for migrating salmon and other aquatic species. Reintroduction of beavers can help to retain these functions in forested watersheds. (Photo by Sarah Koenigsberg, *High Country News*, http://www.hcn.org/issues/47.19/the-beaver-whisperer)

to reduce inter-tree competition for water and light and increase growth and vigor of residual trees. Thus, thinning improves both the resistance and resilience of trees to drought (Bottero et al. 2017, Clark et al. 2016, D'Amato et al. 2013, Giuggiola et al. 2013, Sohn et al. 2016, Vernon et al. 2018), where drought resistance is the ability of trees to survive and maintain growth during drought, and drought resilience is the ability of trees to survive and resume predrought growth rates after the event. Similarly, prescribed fire reduces stand densities in dry forests, so prescribed fire can increase resilience to both wildfire and drought (Johnson et al. 2007, Keeley et al. 2009, Peterson et al. 2011). These treatments are likely to be most effective in forests that historically experienced frequent, low- to mixed-severity fire and that have been affected by fire exclusion (e.g., ponderosa pine, dry mixed-conifer, and moist mixed-conifer forests). Thinning and prescribed fire treatments must be maintained or repeated to remain effective over time (Elkin et al. 2015, Sohn et al. 2016). Legislation such as the recent Good Neighbor Agreements in Washington and Oregon could help facilitate implementation of forest thinning and prescribed fire treatments on Federal lands.

Other ways to increase resilience to drought are to promote species diversity, drought-tolerant species, and large-scale diversity of structure in forest ecosystems (Temperli et al. 2012) (table 3.4). Increasing diversity is a "hedge your bets" strategy that reduces risk of major forest loss to drought (Millar et al. 2007). Areas with less species and genetic diversity will likely be more susceptible to disturbances such as drought, so promoting species and genetic diversity in plantings and in thinning treatments may increase forest resilience to drought and other stressors (Dymond et al. 2014, Halofsky et al. 2018). Fire and large-scale mortality events provide opportunities to plant diverse species and genotypes (including genotypes adapted to drought) and modify large-scale forest structure.

In preparation for drought, managers can write contingency plans to outline responses to large-scale tree mortality. There may be opportunities to use dead wood to benefit ecosystems and produce economic return. Post-fire logging can benefit agencies economically and may produce funds for forest health treatments such as thinning and prescribed fire. When mortality events do occur, the speed of response will be helped by anticipating the effects of impending tree mortality (e.g., Preisler et al. 2017) and determining in advance how to prioritize post-mortality treatments.

Other approaches to increase the capacity of Federal agencies' responses to drought include using the National Integrated Drought Information System (NIDIS) Drought Early Warning System for the PNW (table 3.4), using existing partnerships to increase capacity for mitigating and responding to drought, and creating a regional coordinating group of the National Drought Resilience Partnership. In general, embedding drought in existing agency processes would promote a timely and effective response.

Rangelands—Increasingly severe drought in PNW rangelands will exacerbate existing stressors, including invasive species, altered fire regimes, and inappropriate grazing (Finch et al. 2016). Thus, drought adaptation options for rangelands focus on increasing the resilience of rangeland ecosystems, including controlling nonnative (mostly annual grass) and limiting establishment of invasive species such as western juniper (*Juniperus occidentalis*). Methods include biological controls, targeted livestock grazing, herbicides, hand pulling, and other mechanical treatments (table 3.5). Early detection and targeted elimination of small populations of nonnatives would limit further spread. After treatment of nonnative annual grasses, resilience to future drought and warmer temperatures will be improved by using native seed sources, adapted to current and future climate conditions, for planting and restoration (table 3.5). More flexibility by land managers about delaying certain actions such as seeding (Finch et al. 2016)

Table 3.4—Drought vulnerabilities, adaptation strategies, and adaptation tactics for forest vegetation in the Pacific Northwest

FOREST VEGETATION		
VULNERABILITY	**ADAPTATION STRATEGY**	**ADAPTATION TACTICS**
Low variation in species, age, and stand structure that increases vulnerability to drought and other mortality agents.	Increase broad-scale ecological heterogeneity.	• Increase use of prescribed burning and managed wildfire in dry forests. • Reduce stand densities with variable thinning prescriptions. • In dry forests, promote species diversity and drought-tolerant species and reduce relative abundance of drought-intolerant species. • Identify and protect drought refugia; build on recent scientific findings to determine locations of drought refugia.
Increased tree mortality caused by drought and its interactions with fire, insects, and diseases.	Reduce mortality with silvicultural treatments.	• Thin stands to increase drought resilience, retaining high-vigor trees that are more likely to survive in the future. • Promote drought-resistant species and genotypes. • Use prescribed fire to decrease stand density and increase resilience to wildfire. • After mortality events, replant at lower and more variable densities, and increase diversity of planted species and genotypes.
	Identify opportunities to use dead wood.	• Produce biochar on appropriate sites and incorporate it in the soil profile where feasible. • Conduct salvage logging where appropriate to meet objectives for fuel and potential fire spread.
Low personnel capacity to manage lands during and after drought, especially multi-year droughts.	Develop capacity and guidance for drought preparedness and response.	• Use the NIDIS Drought Early Warning System. • Better prepare communities for fire by increasing fuel treatments in the wildland-urban interface and working with communities on evacuation routes. • Look for synergies with other objectives (e.g., use thinning and prescribed fire to both increase drought resilience and reduce fire hazard). • Leverage partnerships to increase capacity for mitigating and responding to drought; create a regional coordinating group of the National Drought Resilience Partnership. • Develop a risk map for drought (as for insects and disease). • Include drought in existing guidance and integrate with ongoing programs. • Support risk taking by Federal employees to encourage innovation and rapid response. • Conduct proof-of-concept interdisciplinary pilot projects related to drought resilience. • Cultivate and maintain collaborative relationships internally and externally.

NIDIS = National Integrated Drought Information System.

Table 3.5—Drought vulnerabilities, adaptation strategies, and adaptation tactics for rangelands in the Pacific Northwest

RANGELANDS		
VULNERABILITY	**ADAPTATION STRATEGY**	**ADAPTATION TACTICS**
Rangeland species with special status (e.g., greater sage-grouse, Lahontan cutthroat trout) may be particularly vulnerable to drought because of degraded habitat.	Reduce evaporative demand from soils and streams and improve habitat structure.	• Control western juniper, Russian olive, and other invasive woody plants. • Increase water retention by increasing soil organic matter and effective ground cover; improve retention/recovery of biological soil crusts.
Drought encourages the spread of invasive annual grasses and a transition to altered fire regimes.	Maintain vigorous perennial native vegetation as a preventive strategy.	• Promote grazing that is consistent with standards for rangeland integrity; evaluate and manage abundance and distribution of wild horse and burro populations. • Target areas with small exotic grass populations for spraying, and seed with desired species. • Use alternative treatment methods to manage for invasives, such as biological controls and mechanical methods. • Use prescribed burning that is appropriate for the plant community; prioritize fire response on high-value native landscapes. • Increase landscape heterogeneity by breaking up large continuous areas of shrub cover; manage large areas to promote defendable fire breaks.
Current social and economic vulnerability of communities dependent on rangelands and grazing makes them more vulnerable to drought.	Improve communication, education, and collaboration with range users and public to identify drought vulnerabilities and strategies for addressing them.	• Collaborate before, during, and after drought to improve rate of economic recovery and mitigation of losses. • Seek and use local knowledge to help design new drought programs and strategies. • Introduce/immerse employees into local ranch/range culture. • Implement experimental stewardship or similar programs to develop new knowledge and to promote partnerships. • Develop integrated drought plans for both the permittee's base property and the allotment to better maintain land health on both.
Increased susceptibility to drought results from long-term rangeland decline, related to compromised soils, reduced organic matter, limited water-holding capacity, and less vegetation biomass production.	Maintain or increase soil organic matter to improve water-holding capacity postdrought and maintain plant vigor and diversity.	• Maintain practices after drought to promote recovery and resilience for the next drought (e.g., deferred grazing to maintain/improve desired perennial plant species). • Change distribution, timing, intensity, and duration of grazing seasons to promote litter retention and root regrowth. • Vary grazing strategy on individual pastures to provide alternating periods of growth and herbivory. • Evaluate and manage abundance and distribution of wild horse and burro populations to reduce impacts during drought and promote vegetation recovery after drought. • Temporarily provide extra water for livestock, wild horses and burros, and wildlife. Site water sources to direct grazing intensity away from sensitive areas.
Drought increases social and cultural vulnerability of communities that depend on livestock production.	Ensure adequate forage to maintain grazing livestock in good condition during drought.	• Decrease timing, intensity, and duration of grazing during drought. • Maintain grazing systems with proper stocking rate, with grazing allotment designed for long-term productivity and ecological benefits. • Use range riders and place water sources to manage distribution of livestock. • Remove livestock when the utilization target is reached. • Include target utilization levels for uplands and riparian zones in allotment management plans, grazing permits, and annual operating plans.

will improve the likelihood of successfully managing rangelands during drought periods.

Grazing management will also be important to maintain and increase resilience of rangelands to drought and maintain the health of livestock. More severe drought in the future will alter the availability of forage and water, requiring evaluation of the timing, intensity, and duration of grazing; flexible grazing management plans may be necessary (Halofsky et al. 2017). For example, during and after drought, stocking rate may need to be reduced to avoid consequences to rangelands (Finch et al. 2016) (fig. 3.9). Effective grazing management can help sustain and promote soil organic matter and effective ground cover, which increases soil water-holding capacity. Target use levels for uplands and riparian zones can be developed and enforced to avoid overuse of riparian areas (table 3.5). Providing upland water sources may help to improve livestock distribution. The distribution and abundance of wild horse and burro populations may need to be controlled both to reduce impacts during drought and to promote vegetation recovery following drought. Maintaining such drought practices and restrictions after drought will contribute to recovery and increase resilience to subsequent drought events.

Effective response to drought requires careful planning before, during, and after the drought event (Finch et al. 2016). Drought management plans integrated between a permittee's base property and allotment will help maintain land health and productive capability on both, including criteria for entry into and exit out of drought, actions during drought, and criteria for sufficient recovery to assume predrought practices. Communication and collaboration among agencies, Tribes, range users, and the public is essential to facilitate timely and informed management (Prestemon et al. 2016). Drought education can be provided at range permittee meetings and neighborhood meetings, and the potential for rangeland collaboratives for restoration can be explored to facilitate action and possibly reduce conflict. Having Forest Service and BLM employees embedded in the local range culture can help them to gain local knowledge and build trust with permittees. Experimental stewardship or similar programs could help to identify effective treatments to increase drought resilience and respond to drought. Actively seeking and using local knowledge of ranchers to help design new programs and strategies, and sharing success stories, will encourage adoption of drought management strategies.

Figure 3.9—Limiting livestock grazing in riparian areas during periods of drought helps protect aquatic habitat and water quality. (Photo courtesy of USDA Forest Service, Southwestern Region)

CONCLUSIONS

The climate, biogeography, and socioeconomics of Alaska and the Pacific Northwest are diverse. However, across both regions, rising temperatures, decreasing snowpack, and less summer water availability will affect both people and ecosystems in the future. Planning for and adapting to these changes will be critical to minimize negative effects on species, ecosystems, and ecosystem services.

In general, an ecosystem's resilience to changing conditions and drought will be increased by reducing existing stressors and improving their current condition. For example, restoring riparian areas and wetlands will help to maintain water quality and quantity during drought events and maintain critical habitat for terrestrial and aquatic species. A number of steps will help fish survive when streamflow is low: limiting livestock, fishing, and recreational uses in key habitats, and removing physical and biological barriers to fish movement. In dry forests characterized by historically frequent fire, resilience to drought and fire can be increased by mitigating the effects of past fire exclusion with thinning and hazardous fuel treatments. Similarly, addressing altered fire regimes, overgrazing, and invasive species will help to maintain rangeland productivity and ecosystem resilience under changing conditions.

Limited guidance exists for land management agencies to use in response to drought. The capacity of Federal agencies to respond effectively to drought is also limited. However, several tools and frameworks could be adapted to facilitate planning for and responding to drought, including BMPs for water quality, the Watershed

Condition Framework, climate change vulnerability assessments, and disaster management frameworks. Improving coordination among partners, States, and Federal agencies, and leveraging existing programs will also help improve drought planning and response.

Successful management of the effects of drought, climate change, and other water-related issues will require Federal agencies to have the organizational capacity to assess potential changes in natural resource conditions and implement appropriate responses. These efforts will be most effective if assessments and adaptation are incorporated into ongoing planning and management processes, rather than as a separate effort. More extreme ecological events in coming decades, including drought, will be the primary mechanism through which ecosystems will respond to climate forcings, in some cases leading to abrupt changes in structure and function. Planning for anticipated future changes will not only give agencies lead time for near-term actions that may reduce adverse impacts of extreme events, but also improve their ability to quickly respond when those events occur.

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.

Ager, T. 2007. Vegetation response to climate change in Alaska: examples from the fossil record: USGS Open-File Rep. 2007-1096. Reston, VA: U.S. Geological Survey.

Alexander, S.J. 2011. Status of the Tongass National Forest 2007 Alaska National Interest Lands Conservation Act Section 706(b) report to Congress. R10-MB-747 Oct. 2011. Anchorage, AK: U.S. Department of Agriculture, Forest Service, Alaska Region.

American Meteorological Society (AMS). 2018. "Snow drought." Glossary of Meteorology. http://glossary.ametsoc.org/wiki/"snowdrought". [Date accessed: June 14, 2018].

Anderson, B.; Anderson, C.; Christensen, D. [et al.]. 2016. 2015 drought response: summary report. Olympia, WA: Washington State Department of Ecology. https://fortress.wa.gov/ecy/publications/SummaryPages/1611001.html. [Date accessed: December 9, 2017].

Anderson, R.S.; Hallet, D.J.; Berg, E. [et al.]. 2006. Holocene development of boreal forests and fire regimes on the Kenai lowlands of Alaska. The Holocene. 16: 791–803.

Arctic Monitoring and Assessment Programme (AMAP). 2011. Snow, water, ice and permafrost in the Arctic: climate change and the cryosphere. https://www.amap.no/swipa. [Date accessed: December 9, 2017].

Balch, J.K.; Bradley, B.A.; D'antonio, C.M.; Gómez-Dans, J. 2013. Introduced annual grass increases regional fire activity across the arid Western USA (1980–2009). Global Change Biology. 19: 173–183.

Ballew, C.; Ross Tzilkowski, A.; Hamrick, K.; Nobmann, E.D. 2006. The contribution of subsistence foods to the total diet of Alaska natives in 13 rural communities. Ecology of Food and Nutrition. 45: 1–26.

Balshi, M.S.; McGuire, A.D.; Duffy, P. [et al.]. 2008. Assessing the response of area burned to changing climate in western boreal North America using a multivariate adaptive regression splines (MARS) approach. Global Change Biology. 15: 578–600.

Barber, V.A.; Juday, G.P.; Finney, B.P. 2000. Reduced growth of Alaskan white spruce in the twentieth century from temperature-induced drought stress. Nature. 405: 668.

Barrett, K.; McGuire, A.D.; Hoy, E.E.; Kasischke, E.S. 2011. Potential shifts in dominant forest cover in interior Alaska driven by variations in fire severity. Ecological Applications. 21: 2380–2396.

Barrett, T.M. 2014. Storage and flux of carbon in live trees, snags, and logs in the Chugach and Tongass National Forests. Gen. Tech. Rep. PNW-889. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 889 p.

Barrett, T.M.; Christensen, G., eds. 2011. Forests of southeast and south-central Alaska, 2004–2008: five-year forest inventory and analysis report. Gen. Tech. Rep. PNW-835. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 156 p.

Barrett, T.M.; Pattison, R.R. 2016. No evidence of recent (1995–2013) decrease of yellow-cedar in Alaska. Canadian Journal of Forest Research. 47: 97–105.

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. 104: 6720–6725.

Beck, P.S.; Goetz, S.J. 2011. Satellite observations of high northern latitude vegetation productivity changes between 1982 and 2008: ecological variability and regional differences. Environmental Research Letters. 6: 045501.

Bieniek, P.A.; Walsh, J.E.; Thoman, R.L.; Bhatt, U.S. 2014. Using climate divisions to analyze variations and trends in Alaska temperature and precipitation. Journal of Climate. 27: 2800–2818.

Biondini, M.E.; Patton, B.D.; Nyren, P.E. 1998. Grazing intensity and ecosystem processes in a northern mixed-grass prairie. Ecological Applications. 8: 469–479.

Bottero, A.; D'Amato, A.W.; Palik, B.J. [et al.]. 2017. Density-dependent vulnerability of forest ecosystems to drought. Journal of Applied Ecology. 54: 1605–1614.

Brown, K.J.; Clark, J.S.; Grimm, E.C. [et al.]. 2005. Fire cycles in North American interior grasslands and their relation to prairie drought. Proceedings of the National Academy of Sciences. 102: 8865–8870.

Brubaker, M.; Berner, J.; Chavan, R.; Warren, J. 2011. Climate change and health effects in Northwest Alaska. Global Health Action. 4: 1–5.

Burns, R.M.; Honkala, B.H., tech coords. 1990. Silvics of North America: Vol. 1. Conifers. Agric. Handb. 654. Washington, DC: U.S. Department of Agriculture, Forest Service. 654 p.

Chapin, F.S., III; Trainor, S.F.; Cochran, P. [et al.]. 2014. Alaska. 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: United States Global Change Research Program: 514–536.

Charnley, S.; Fischer, A.P.; Jones, E.T. 2007. Integrating traditional and local ecological knowledge into forest biodiversity conservation in the Pacific Northwest. Forest Ecology and Management. 246: 14–28.

Chilcote, M.; Coleman, A.; Colt, S. [et al.]. 2017. Salmon. In: Hayward, G.D.; Colt, S.; McTeague, M.; Hollingsworth, T., eds. 2017. Climate change vulnerability assessment for the Chugach National Forest and the Kenai Peninsula. Gen. Tech. Rep. PNW-950. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 107–150.

Clark, J.S.; Iverson, L.; Woodall, C.W. 2016. Impacts of increasing drought on forest dynamics, structure, diversity, and management. In: Vose, J.M.; Clark, J.S.; Luce, C.H.; Patel-Weynand, 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, Washington Office: 59–96.

Clifton, C.F.; Day, K.T.; Dello, K. [et al.]. 2017. Climate change and hydrology 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-939. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 25–52.

D'Amato, A.W.; Bradford, J.B.; Fraver, S.; Palik, B.J. 2013. Effects of thinning on drought vulnerability and climate response in north temperate forest ecosystems. Ecological Applications. 23: 1735–1742.

D'Amore, D.; Edwards, R.; Herendeen, P. [et al.]. 2015. Dissolved organic carbon fluxes from hydropendologic units in Alaska coastal temperate rainforest watersheds. Soil Science Society of America Journal. 79: 378–388.

D'Amore, D.V.; Lynn, W.C. 2002. Classification of forested histosols in southeast Alaska. Soil Science Society of America Journal. 66: 554–562.

Dery, S.J.; Stahl, K.; Moore, R.D. [et al.]. 2009. Detection of runoff timing changes in pluvial, nival, and glacial rivers of western Canada. Water Resources Research. 45: W04426.

Dial, R.J.; Berg, E.E.; Timm, K. [et al.]. 2007. Changes in the alpine forest-tundra ecotone commensurate with recent warming in southcentral Alaska: evidence from orthophotos and field plots. Journal of Geophysical Research. 112: G04015.

Drost, B.W.; Whiteman, K.J.; Gonthier, J.B. 1990. Geologic framework of the Columbia Plateau aquifer system, Washington, Oregon, and Idaho. USGS Water Res. Invest. Rep. 87-4238. Portland, OR: U.S. Geological Survey.

Dymond, C.C.; Tedder, S.; Spittlehouse, D.L. [et al.]. 2014. Diversifying managed forests to increase resilience. Canadian Journal of Forest Research. 44: 1196–1205.

EcoAdapt. 2014. A climate change vulnerability assessment for aquatic resources in the Tongass National Forest. Bainbridge Island, WA: EcoAdapt. 123 p.

Elkin, C.; Giuggiola, A.; Rigling, A.; Bugmann, H. 2015. Short- and long-term efficacy of forest thinning to mitigate drought impacts in mountain forests in the European Alps. Ecological Applications. 25: 1083–1098.

Elsner, M.M.; Cuo, L.; Voisin, N. 2010. Implications of 21st century climate change for the hydrology of Washington State. Climatic Change. 102: 225–260.

Emers, M.; Jorgenson, J.C.; Raynolds, M.K. 1995. Response of arctic tundra plant communities to winter vehicle disturbance. Canadian Journal of Botany. 73: 905–917.

Fehmi, J.S.; Kong, T.M. 2012. Effects of soil type, rainfall, straw mulch, and fertilizer on semi-arid vegetation establishment, growth and diversity. Ecological Engineering. 44: 70–77.

Fettig, C.J.; Klepzig, K.D.; Billings, R.F. [et al.]. 2007. The effectiveness of vegetation management practices for prevention and control of bark beetle infestations in coniferous forests of the Western and Southern United States. Forest Ecology and Management. 238: 24–53.

Finch, D.M.; Pendleton, R.L.; Reeves, M.C. [et al.]. 2016. Rangeland drought: effects, restoration, and adaptation. In: Vose, J.M.; Clark, J.S.; Luce, C.H.; Patel-Weynand, 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, Washington Office: 155–194.

Flannigan, M.D.; Wotton B.M.; Marshall G.A. [et al.]. 2016. Fuel moisture sensitivity to temperature and precipitation: climate change implications. Climatic Change. 134: 59–71.

Fuhlendorf, S.D.; Briske, D.D.; Smeins, F.E. 2001. Herbaceous vegetation change in variable rangeland environments: The relative contribution of grazing and climatic variability. Applied Vegetation Science. 4: 177–188.

Furniss, M.J.; Staab, B.P.; Hazelhurst, S. [et al.]. 2010. Water, climate change, and forests: watershed stewardship for a changing climate. Gen. Tech. Rep. PNW-812. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 89 p.

Giuggiola, A.; Bugmann, H.; Zingg, A. [et al.]. 2013. Reduction of stand density increases drought resistance in xeric Scots pine forests. Forest Ecology and Management. 310: 827–835.

Goldstein, M.I.; Poe, A.J.; Suring, L.H. 2010. Brown bear den habitat and winter recreation in south-central Alaska. Journal Wildlife Management. 74: 35–42.

Gough, L.; Wilson, R., eds. 2001. Geologic studies in Alaska by the United States Geological Survey, 1999. Professional Paper 1633. Denver, CO: U.S. Department of the Interior, Geological Survey. 150 p.

Grosse, G.; Goetz, S.; McGuire, A.D. 2016. Changing permafrost in a warming world and feedbacks to the Earth system. Environmental Research Letters. 11: 040201.

Halfar, J.; Adey, W.H.; Kronz, A. [et al.]. 2013. Arctic sea-ice decline archived by multicentury annual-resolution record of crustose coralline algal proxy. Proceedings of the National Academy of Sciences. 110: 19737–19741.

Halofsky, J.E.; Peterson, D.L., eds. 2017. Climate change vulnerability and adaptation in the Blue Mountains. Gen. Tech. Rep. PNW-939. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 344 p.

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

Halofsky, J.E.; Peterson, D.L.; Prendeville, H.R. 2018. Assessing vulnerabilities and adapting to climate change in northwestern U.S. forests. Climatic Change. 146: 89–102.

Halofsky, J.E.; Warziniack, T.W.; Peterson, D.L.; Ho, J.J. 2017. Understanding and managing the effects of climate change on ecosystem services in the Rocky Mountains. Mountain Research and Development. 37: 340–352.

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.; Mote, P.W.; Clark, M.P.; Lettenmaier, D.P. 2005. Effects of temperature and precipitation variability on snowpack trends in the Western United States. Journal of Climate. 18: 4545–4561.

Hand, M.L.; Lawson, M. Effects of climate change on recreation in the Northern Rockies region. 2018. In: Halofsky, J.E.; Peterson, D.L.; Dante-Wood, S.K. [et al.], eds. Climate change vulnerability and adaptation in the Northern Rockies. Gen. Tech. Rep. RMRS-374. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 398–433.

Hand, M.L.; 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.

Harpold, A.; Dettinger, M.; Rajagopal, S. 2017. Defining snow drought and why it matters. EOS Earth & Space Science News. 98.

Hayward, G.D.; Colt, S.; McTeague, M.; Hollingsworth. T., eds. 2017. Climate change vulnerability assessment for the Chugach National Forest and the Kenai Peninsula. Gen. Tech. Rep. PNW-950. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 340 p.

Hennon, P.E.; D'Amore, D.V.; Schaberg, P.G. [et al.]. 2012. Shifting climate, altered niche, and a dynamic conservation strategy for yellow-cedar in the North Pacific coastal rainforest. Bioscience. 62: 147–158.

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. Forest Science. 62: 141–153.

Hidalgo, H.G.; Das, T.; Dettinger, M.D. [et al.]. 2009. Detection and attribution of streamflow timing changes to climate change in the Western United States. Journal of Climate. 22: 3838–3855.

Hollingsworth, T.; Barrett, T.; Bella, T. [et al.]. 2017. Vegetation. In: Hayward, G.D.; Colt, S.; McTeague, M.; Hollingsworth, T., eds. Climate change vulnerability assessment for the Chugach National Forest and the Kenai Peninsula. Gen. Tech. Rep. PNW-950. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 163–264.

Hu, F.S.; Higuera, P.E.; Walsh, J.E. [et al.]. 2010. Tundra burning in Alaska: linkages to climatic change and sea ice retreat. Journal of Geophysical Research. 115: G04002.

Isaak, D.J.; Luce, C.H.; Rieman, B.E. [et al.]. 2010. Effects of climate change and wildfire on stream temperatures and salmonid thermal habitat in a mountain river network. Ecological Applications. 20: 1350–1371.

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.

Johnson, M.C.; Peterson, D.L.; Raymond, C.L. 2007. Guide to fuel treatments in dry forests of the Western United States: assessing forest structure and fire hazard. Gen. Tech. Rep. PNW-686. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 322 p.

Jorgenson, M.T.; Yoshikawa, K.; Kanevskiy, M. [et al.]. 2008. Permafrost characteristics of Alaska. Proceedings of the ninth international conference on permafrost. Fairbanks, AK: University of Alaska. 29: 121–122.

Joslin, J.D.; Wolfe, M.H.; Hanson, P.J. 2000. Effects of altered water regimes on forest root systems. New Phytologist. 147: 117–129.

Kashian, D.M.; Romme, W.H.; Tinker, D.B. [et al.]. 2006. Carbon storage on landscapes with stand-replacing fires. BioScience. 56: 598–606.

Keeley, J.E.; Aplet, G.; Christensen, N.L. [et al.]. 2009. Ecological foundations for fire management in North America. Gen. Tech. Rep. PNW-779. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 92 p.

Kindschy, R.R. 1994. Pristine vegetation of the Jordan Crater kipukas: 1978–91. In Monsen, S.B.; Kitchen, S.G., eds. Proceedings, ecology and management of annual rangelands. Gen. Tech. Rep. INT-313. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station: 85–88.

Kinnard, C.; Zdanowicz, C.M.; Fisher, D.A. [et al.]. 2011. Reconstructed changes in Arctic sea ice over the past 1,450 years. Nature. 479: 509–513.

Knutson, T.R.; Zeng, F.; Wittenberg, A.T. 2013. Multimodel assessment of regional surface temperature trends: CMIP3 and CMIP5 twentieth-century simulations. Journal of Climate. 26: 8709–8743.

Konrad, C.P. 2006. Location and timing of river-aquifer exchanges in six tributaries to the Columbia River in the Pacific Northwest of the United States. Journal of Hydrology. 329: 444–470.

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.

Larsen, P.H.; Goldsmith, S.; Smith, O. [et al.]. 2008. Estimating future costs for Alaska public infrastructure at risk from climate change. Global Environmental Change. 18: 442–457.

Lieutier, F. 2004. Mechanisms of resistance in conifers and bark beetle attack. In: Wagner M.R.; Clancy, K.M.; Lieutier, F.; Paine, T.D., eds. Mechanisms and deployment of resistance in trees in insects. Boston: Kluwer Academic: 31–78.

Link, S.O. 2006. *Bromus tectorum* cover mapping and fire risk. International Journal of Wildland Fire. 15: 113–119.

Littell, J.S., McAfee, S.; O'Neel, S. [et al.]. 2017. Snow and ice. In: Hayward, G.D.; Colt, S.; McTeague, M.; Hollingsworth. T., eds. Climate change vulnerability assessment for the Chugach National Forest and the Kenai Peninsula. Gen. Tech. Rep. PNW-950. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 29–78.

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. Douglas-fir growth in mountain ecosystems: water limits tree growth from stand to region. Ecological Monographs. 78: 349–368.

Loehman, R.A.; Keane, R.E.; Holsinger, L.M.; Wu, Z. 2017. Interactions of landscape disturbances and climate change dictate ecological pattern and process: spatial modeling of wildfire, insect, and disease dynamics under future climates. Landscape Ecology. 32: 1447–1459.

Logan, J.A.; Powell, J.A. 2009. Ecological consequences of forest-insect disturbance altered by climate change. In Wagner, F.H., ed. Climate warming in western North America. Salt Lake City, UT: University of Utah Press: 98–109.

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.; Gritzner, J.; Grant, G.E.. [et al.]. 2019. Climate change, water, and roads 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: 55–102. Chapter 4.

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

Luce, C.; Staab, B.; Kramer, M. [et al.]. 2014. Sensitivity of summer stream temperatures to climate variability in the Pacific Northwest. Water Resources Research. 50: 3428–3443.

Lynn, K.; Daigle, J.; Hoffman, J. [et al.]. 2013. The impacts of climate change on Tribal traditional foods. Climatic Change. 120: 545–556.

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.

Mantua, N.; Tohver, I.; Hamlet, A. 2010. Climate change impacts on streamflow extremes and summertime stream temperature and their possible consequences for freshwater salmon habitat in Washington State. Climatic Change. 102: 187–223.

Marlier, M.E.; Xiao, M.; Engel, R. [et al.]. 2017. The 2015 drought in Washington State: a harbinger of things to come? Environmental Research Letters. 12: 114008.

Matthews, W.J.; Marsh-Matthews, E. 2003. Effects of drought on fish across axes of space, time and ecological complexity. Freshwater Biology. 48: 1232–1253.

McKelvey, K.S.; Copeland, J.P.; Schwartz, M.K. [et al.]. 2011. Climate change predicted to shift wolverine distributions, connectivity, and dispersal corridors. Ecological Applications. 21: 2882–2897.

McKenzie, D.; Gedalof, Z.; Peterson, D.L.; Mote, P. 2004. Climatic change, wildfire, and conservation. Conservation Biology. 18: 890–902.

Melgoza, G.; Nowak, R.S. 1991. Competition between cheatgrass and two native species after fire: implications from observations and measurements of root distribution. Journal of Range Management. 44: 27–33.

Melvin, A.M.; Larsen, P.; Boehlert, B. [et al.]. 2017. Climate change damages to Alaska public infrastructure and the economics of proactive adaptation. Proceedings of the National Academy of Sciences. 114: E122–E131.

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.

Milne, B.T.; Gupta, V.K.; Restrepo, C. 2002. A scale-invariant coupling of plants, water, energy, and terrain. EcoScience. 9: 191–199.

Morton, J.M.; Huettmann, F. 2017. Moose, caribou, and Sitka black-tailed deer. In: Hayward, G.H.; Colt, S.; McTeague, M.L.; Hollingsworth, T.N., eds. Climate change vulnerability assessment for the Chugach National Forest and the Kenai Peninsula. Gen. Tech. Rep. PNW-950. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 265–295.

Mote, P.W.; Abatzoglou, J.T.; Kunkel, K.E. 2014. Climate variability and change in the past and the future. In: Dalton, M.M.; Mote, P.W.; Snover, A., eds. Climate change in the Northwest: implications for our landscapes, waters, and communities. Washington, DC: Island Press: 25–40.

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

Naiman, R.J.; Decamps, H.; Pollock, M. 1993. The role of riparian corridors in maintaining regional biodiversity. Ecological Applications. 3: 209–212.

National Research Council. 1996. Upstream: salmon and society in the Pacific Northwest. Washington, DC: The National Academies Press. 472 p.

Overland, J.; Hanna, E.; Hanssen-Bauer, I. [et al.]. 2014. Air temperature. In: Arctic Report Card 2014. https://www.pmel.noaa.gov/arctic/news-story/arctic-report-card-2014. [Date accessed: December 9, 2017].

Paerl, H.S.; Huisman, J. 2008. Blooms like it hot. Science. 320: 57–58.

Parent, M.B.; Verbyla, D. 2010. The browning of Alaska's boreal forest. Remote Sensing. 2: 2729–2747.

Pastick, N.J.; Duffy, P.; Genet, H. [et al.]. 2017. Historical and projected trends in landscape drivers affecting carbon dynamics in Alaska. Ecological Applications. 27: 1383–1402.

Pauli, J.N.; Zuckerberg, B.; Whiteman, J.P. 2013. The subnivian: a deteriorating seasonal refugium. Frontiers in Ecology and the Environment. 11: 260–267.

Paustian, S. 2010. Channel type user guide for the Tongass National Forest, southeast Alaska. R10-TP-26. Juneau, AK: U.S. Department of Agriculture, Forest Service, Alaska Region. 185 p.

Person, D.K.; Kirchhoff, M.; Van Ballenberghe, V. [et al.]. 1996. The Alexander Archipelago wolf: a conservation assessment. Gen. Tech. Rep. PNW-384. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 42 p.

Peterson, D.L.; Halofsky, J.E. 2018. Adapting to the effects of climate change on natural resources in the Blue Mountains, USA. Climate Services. 10: 63–71. https://doi.org/10.1016/j.cliser.2017.06.005.

Peterson, D.L.; Halofsky, J.; Johnson, M.C. 2011. Managing and adapting to changing fire regimes in a warmer climate. In: McKenzie, D.; Miller, C.; Falk, D., eds. The landscape ecology of fire. New York: Springer: 249–267.

Pollock, M.M.; Beechie, T.J.; Wheaton, J.M. [et al.]. 2014. Using beaver dams to restore incised stream ecosystems. Bioscience. 64: 279–290.

Potyondy, J.P.; Geier, T.W. 2011. Watershed condition classification technical guide. FS-978. Washington, DC: U.S. Department of Agriculture, Forest Service. 41 p.

Preisler, H.K.; Grulke, N.E.; Heath, Z.; Smith, S.L. 2017. Analysis and out-year forecast of beetle, borer, and drought-induced tree mortality in California. Forest Ecology and Management. 399: 166–178.

Prestemon, J.P.; Kruger, L.; Abt, K.L. [et al.]. 2016. Economics and societal considerations of drought. In: Vose, J.; Clark, J.; Luce, C.; Patel-Weynand, 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, Washington Office: 253–281.

Rahel, F.J.; Olden, J.D. 2008. Assessing the effects of climate change on aquatic invasive species. Conservation Biology. 22: 521–533.

Raymond, C.L.; Peterson, D.L.; Rochefort, R.M., eds. 2014. Climate change vulnerability and adaptation in the North Cascades region, Washington. Gen. Tech. Rep. PNW-892. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 279 p.

Raymondi, R.R.; Cuhaciyan, J.E.; Glick, P. [et al.]. 2014. Water resources: implications of changes in temperature and precipitation. In: Dalton, M.M.; Mote, P.W.; Snover, A., eds. Climate change in the Northwest: implications for our landscapes, waters, and communities. Washington, DC: Island Press: 41–66.

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. 113: 9557–9562.

Riordan, B.; Verbyla, D.; McGuire, A.D. 2006. Shrinking ponds in subarctic Alaska based on 1950–2002 remotely sensed images. Journal of Geophysical Research. 111: G04002.

Runyon, J.B.; Butler, J.L.; Friggens, M.M. 2012. Invasive species and climate change. In: Finch, D.M., ed. Climate change in grasslands, shrublands, and deserts of the interior American West: a review and needs assessment. Gen. Tech. Rep. RMRS-285. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 97–115.

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.

Scenarios Network for Alaska and Arctic Planning (SNAP). [N.d.]. https://www.snap.uaf.edu/tools/data-downloads. [Data accessed: December 9, 2017].

Schnorbus, M.; Werner, A.; Bennett, K. 2014. Impacts of climate change in three hydrologic regimes in British Columbia, Canada. Hydrological Processes. 28: 1170–1189.

Shepherd, T.G. 2014. Atmospheric circulation as a source of uncertainty in climate change projections. Nature Geoscience. 7: 703–708.

Simmons, E.A.; Scudder, M.G.; Morgan, T.A. [et al.]. 2016. Oregon's forest products industry and timber harvest 2013 with trends through 2014. Gen. Tech. Rep. PNW-942. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 58 p.

Sohn, J.A.; Saha, S.; Bauhus, J. 2016. Potential of forest thinning to mitigate drought stress: a meta-analysis. Forest Ecology and Management. 380: 261–273.

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

Stewart, B.C.; Kunkel, K.E.; Stevens, L.E. [et al.]. 2013. Regional climate trends and scenarios for the U.S. National Climate Assessment: Part 7, Climate of Alaska. NOAA Tech. Rep. NESDIS 142-7. Washington, DC: National Oceanic and Atmospheric Administration. 60 p.

Sun, L.; Kunkel, K.E.; Stevens, L.E. 2015. Regional surface climate conditions in CMIP3 and CMIP5 for the United States: differences, similarities, and implications for the U.S. National Climate Assessment. NOAA Tech. Rep. NESDIS 144. Washington, DC: National Oceanic and Atmospheric Administration. 111 p.

Tape, K.; Sturm, M.; Racine, C. 2006. The evidence for shrub expansion in Northern Alaska and the Pan-Arctic. Global Change Biology. 12: 686–702.

Tape, K.D.; Gustine, D.D.; Ruess, R.W. [et al.]. 2016. Range expansion of moose in Arctic Alaska linked to warming and increased shrub habitat. PLoS ONE 11: e0152636.

Tausch, R.J.; Svejcar, T.; Burkhardt, J.W. 1994. Patterns of annual grass dominance on Anaho Island: implications for Great Basin vegetation management. In: Monsen, S.B.; Kitchen, S.G., comps. Symposium on ecology, management, and restoration of Intermountain annual rangelands; 1992 May 18021; Boise, ID. Gen. Tech. Rep. INT-313. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station: 120–125.

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.

Taylor, P.C.; Maslowski, W.; Perlwitz, J.; Wuebbles, D.J. 2017. Arctic changes and their effects on Alaska and the rest of the United States. In: Wuebbles, D.J.; Fahey, D.W.; Hibbard, K.A., eds. Climate Science Special Report: Fourth National Climate Assessment, vol. 1. Washington, DC: U.S. Global Change Research Program: 443–492.

Temperli, C.; Bugmann, H.; Elkin, C. 2012. Adaptive management for competing forest goods and services under climate change. Ecological Applications. 22: 2065–2077.

Tohver, I.; Hamlet, A.F.; Lee, S. 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.

U.S. Department of Agriculture, Forest Service (USDA FS). 2012. National best management practices for water quality management on National Forest System lands. Vol. 1: National Core BMP Technical Guide. FS-990a. Washington, DC: U.S. Department of Agriculture, Forest Service. 165 p.

U.S. Department of Agriculture, Forest Service (USDA FS). 2016a. Tongass land and resource management plan: final environmental impact statement, plan amendment. Volume 1. R10-MB-769h. Anchorage, AK: U.S. Department of Agriculture, Forest Service, Alaska Region.

U.S. Department of Agriculture, Forest Service (USDA FS). 2016b. Tongass land and resource management plan. R10-MB-769j. Anchorage, AK: U.S. Department of Agriculture, Forest Service, Alaska Region.

U.S. Department of Agriculture, Forest Service; U.S. Department of the Interior, Bureau of Land Management (USDA and USDI). 1994. Record of decision for amendments to Forest Service and Bureau of Land Management planning documents within the range of the northern spotted owl. Washington, DC: U.S. Department of Agriculture, Forest Service and U.S. Department of the Interior, Bureau of Land Management. 248 p.

Vernon, M.J.; Sherriff, R.L.; van Mantgem, P.; Kane, J.M. 2018. Thinning, tree-growth, and resistance to multi-year drought in a mixed-conifer forest of northern California. Forest Ecology and Management. 422: 190–198.

Vose, J.M.; Miniat, C.F.; Luce, C.H. 2016. Ecohydrological implications of drought. In: Vose, J.M.; Clark, J.S.; Luce, C.H.; Patel-Weynand, 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, Washington Office: 231–251.

Vose, R.S.; Easterling, D.R.; Kunkel, A.N. [et al.]. 2017. Temperature changes in the United States. In: Wuebbles, D.J.; Fahey, D.W.; Hibbard, K.A. [et al.], eds. Climate Science Special Report: Fourth National Climate Assessment, vol. 1. Washington, DC: U.S. Global Change Research Program: 185–206.

Walsh, J.E.; Bhatt, U.S.; Littell, J.S. [et al.]. 2018. Downscaling of climate model output for Alaskan stakeholders. Environmental Modeling and Software. 110: 38–51. https://doi.org/10.1016/j.envsoft.2018.03.021.

Wendler, G.; Shulski, M. 2009. A century of climate change for Fairbanks, Alaska. Arctic. 62: 295–300.

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.

Young, A.M.; Higuera, P.E.; Duffy, P.A.; Hu, F.S. 2017. Climatic thresholds shape northern high-latitude fire regimes and imply vulnerability to future climate change. Ecography. 40: 606–617.