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Effects of Drought on Forests and Rangelands in the United States:

Translating Science Into Management Responses

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Abstract

Most regions of the United States are projected to experience a higher frequency of severe droughts and longer dry periods as a result of a warming climate. Even if current drought regimes remain unchanged, higher temperatures will interact with drought to exacerbate moisture limitation and water stress. Observations of regional-scale drought impacts and expectations of more frequent and severe droughts prompted a recent state-of-science synthesis (Vose et al. 2016). The current volume builds on that synthesis and provides region-specific management options for increasing resilience to drought for Alaska and Pacific Northwest, California, Hawai'i and U.S.-Affiliated Pacific Islands, Interior West, Great Plains, Northeast and Midwest, and Southeast.

Ecological drought refers to the negative impacts of meteorological drought on ecosystem services, generally focused on observable changes (e.g., forest mortality, soil loss in rangelands), but less observable responses (e.g., lower plant productivity) can have observable changes and economic consequences over the long term. The magnitude of these impacts depends on the severity, duration, frequency, and spatial extent of drought events. A wide range of management options is available for minimizing the adverse impacts of drought when they occur, facilitating postdrought recovery, and creating ecosystem conditions that reduce negative impacts of future droughts. For forests, a common theme among regions is reducing water demand by managing stands at a lower density and favoring species that either require less water or can tolerate drought. Responses to hydrological drought include restoring riparian areas and wetlands to improve functionality, ensuring that aquatic habitats for fish and other organisms provide refugia and passage during low streamflow conditions, and carefully managing consumptive uses for livestock grazing, recreation, agriculture, and drinking water during droughts.

For drought management to be effective, timely implementation is needed across large spatial scales, facilitated by coordination among agencies and stakeholders. Optimal responses can be developed by integrating existing policies and practices with new information and by timely reporting of current conditions. The following strategic actions will help institutionalize awareness of drought effects and drought responses in public and private land management: (1) establish and maintain relationships with providers of drought information, (2) include drought in collaborative efforts among agencies and stakeholders, (3) revise best management practices as needed, (4) implement drought in relevant planning processes, (5) establish long-term monitoring of drought effects, and (6) share information on effectiveness of drought responses. If drought-informed practices are institutionalized as part of agency operations, then planning and management will be more effective, and "crisis management" in response to drought can be avoided.

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Keywords: adaptation, ecological drought, forests, hydrological drought, rangelands, resilience.

Contents

Executive Summary

This report informs and guides natural resource managers as they evaluate management options to minimize drought impacts, help forest and rangelands recover from drought, and create forests and rangelands better adapted to future drought conditions. An overall conceptual framework and development of organizational structure and chapter content were facilitated by a series of virtual and in-person workshops. Teams of experts used a national-scale drought synthesis (Vose et al. 2016), combined with more recent scientific literature and their best professional judgments, to link scientific evidence with regionally appropriate discussions of risks, vulnerabilities, and management options.

Drought has shaped ecological processes and influenced human and biological communities for millennia and will continue to do so. Climate change will influence future drought characteristics (frequency, severity, timing), and some regions of the United States will experience a higher frequency of severe droughts and longer dry periods. In areas where meteorological drought is common, forest and rangeland species have the capacity to survive most droughts through a variety of mechanisms that mitigate drought impacts and facilitate recovery (e.g., deep rooting, leaf shedding, stomatal regulation). However, new drought regimes (e.g., droughts combined with warmer temperatures) may overwhelm this capacity, causing lower vegetation productivity and increasing vegetation mortality, with far-reaching effects on ecosystem conditions and services.

Areas where droughts are currently uncommon may be especially vulnerable because species that are not well adapted to drought may be greatly affected by even minor droughts. Secondary impacts of drought, such as more frequent and larger wildfires and large-scale insect outbreaks, may have even greater impacts (magnitude and spatial extent) than direct drought effects. Hydrological drought is a major concern in areas dependent on reliable flows of surface water for aquatic species and habitats, groundwater recharge, and drinking water supply.

Droughts can have substantial impacts on the economy at local and regional scales. The timber products industry can be affected by drought-related mortality and reduced productivity, leading to reduced wood supply and an increase in market price. Drought in rangelands reduces forage and water available for livestock grazing and reduces overall vegetative land cover, which can lead to soil loss from wind and water erosion with long-term effects on rangeland productivity. Altered water quantity following drought may have little impact on economics, although degraded water quality after disturbances like fire can substantially disrupt municipal water supply and treatment in ways that may force substantial public investment in water infrastructure to avoid supply interruptions.

This report provides important guidance for evaluating management options to minimize drought impacts, such as reduced forage and water (top) and degraded water quality after disturbances like fire (bottom).

Photos: Lance Cheung, USDA and Chris Stewart, USDA Forest Service

Restoring riparian areas helps to maintain water quality and quantity during drought events (top), as well as critical habitat for culturally and economically valuable species (bottom).

Photos: USDA Forest Service and Don MacDougall, USDA Forest Service

Changing drought conditions in the remainder of the 21st century will present significant challenges for natural resource managers as they plan and implement actions to increase the adaptive capacity of the Nation's forests and rangelands to resist and recover from current and future droughts. The combination of warmer temperatures and more variable precipitation regimes across most areas of the United States suggests that although the nature of drought will differ among and within regions, most forests and rangelands will be affected by more frequent and/or intense drought by the end of the 21st century.

Most chapters in this publication discuss management options for minimizing the adverse impacts of drought when they occur, facilitating postdrought recovery, and creating ecosystem conditions that might help minimize impacts of future droughts. For forests, a common theme is reducing water demand by managing stands at a lower density and favoring species that either require less water or can tolerate drought. Responses to hydrological drought include restoring riparian areas and wetlands to improve functionality, ensuring that aquatic habitats for fish and other organisms provide refugia and passage during low streamflow conditions, and carefully managing consumptive uses for livestock grazing, recreation, agriculture, and drinking water supplies during droughts.

For drought management strategies to be most effective, timely implementation is needed across large spatial scales. Optimal responses can be developed by integrating existing policies and practices with new information and by timely reporting of current conditions. Coordination by Federal agencies with other agencies and stakeholders is needed for effective management of drought effects across large landscapes. If drought-informed thinking is institutionalized as part of agency operations, then planning and management will be more effective, and "crisis management" in response to drought can be avoided.

Regionally specific drought issues and management options include the following:

ALASKA AND PACIFIC NORTHWEST

- Water is important for wildlife and people, providing critical habitat for salmon, which are culturally and economically valuable species.
- Across both Alaska and the Pacific Northwest, rising temperatures, decreasing snowpack, and less summer water availability will affect both people and ecosystems in the future.
- 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.
- Limiting livestock grazing, fishing, and recreation in key habitats, and removing physical and biological barriers to fish movement will help fish survive when streamflow is low.

- In dry forests characterized by historically frequent fire, resilience to drought and fire can be increased by mitigating the effects of past fire exclusion by decreasing stand densities and hazardous fuels.
- Addressing altered fire regimes, overgrazing, and invasive species will help to maintain rangeland productivity and ecosystem resilience under changing conditions.

CALIFORNIA

- Extreme droughts will become the norm by the middle of the 21st century, but even moderate droughts can have significant, long-lasting effects on the structure and function of ecosystems.
- Management options for addressing drought impacts vary by ecosystem, but goals are to (1) shift systems back within the natural range of variation (including disturbance regimes) to the degree possible and (2) facilitate a transition to plant species better adapted to future droughts.
- In forests and woodlands, drought management focused on the use of mechanical thinning and prescribed burning will decrease stand densities and promote the growth and vigor of desirable tree species.
- In chaparral, frequent disturbances are stressors, so soil disturbances need to be limited as much as possible to reduce the spread of invasive, nonnative annual plants that promote wildfires.
- In grasslands, prescribed fire may be useful to manage nonnative species and increase perennial plant cover to make grasslands more drought resilient. In rangelands used for livestock grazing, conservative stocking rates, supplemental feeding, and resting pastures should be considered during times of drought.
- As the frequency and magnitude of droughts increase, our ability to better quantify and project impacts on ecological and human systems, and to develop and implement appropriate management actions, will become more critical.

An entomologist checks dead ponderosa pine trees for pine bark beetle infestations in the Sequoia National Forest, CA.

Photo: Lance Cheung, USDA

HAWAI‘I AND U.S.-AFFILIATED PACIFIC ISLANDS

- Drought increases the risk of wildfire in grasslands and savanna vegetation, which then increases the vulnerability of adjacent forest. The capacity of native forests to recover afterward can be reduced by the rapid establishment of nonnative species, many of which increase the probability of future fires.
- Preparing for wildfire before a drought is critical to mitigate drought impacts. Preparation includes (1) building up or maintaining fire suppression and emergency responder capacity and readines and (2) preparedness by individuals, households, communities, and large landowners and land managers.
- Extreme drought reduces streamflow and groundwater levels. Lower groundwater levels exacerbate the potential for saltwater intrusion and can degrade drinking water wells and nearshore and marine ecosystems that rely on the discharge of fresh groundwater.

Pacific Island communities rely on traditional knowledge and community-based support during water shortages (top). Rangeland management to address ecosystem stressors helps maintain productivity and benefits native ungulates (bottom).

Photos: Forest and Kim Starr, Starr Environmental, Bugwood.org. and USDA

- Management options for preparing for water shortages include increasing water capture and storage capacity, improving delivery efficiencies, securing alternative water sources, improving end-user efficiencies, and providing education and outreach.
- Many communities in Hawai‘i and the U.S.-Affiliated Pacific Islands rely on traditional knowledge developed over thousands of years and on the resulting community-based approaches, practices, tools, and institutions that have supported communities during drought periods from the distant past into the present.
- Management will benefit from efforts to engage multiple interacting stressors: invasive species, altered fire regimes, altered climate regimes, insects, and pathogens.

INTERIOR WEST

- The diversity of climate, biogeography, and socioeconomics in the Interior West means that drought occurrence and effects will vary greatly from north to south and from year to year.
- The first, best, and often least costly means of increasing resilience to drought are to reduce existing stressors and improve the current condition (“health”) of ecosystems.
- Pre-emptive actions that create benefits for multiple resources are valuable, especially actions that increase the quantity and duration of water availability.
- Reconnecting floodplains with side channels and restoring populations of American beaver contribute to retaining water during the summer, benefit water supply for agriculture and municipal watersheds, maintain productivity of riparian areas, and maintain high-quality fish habitat.
- In dry forests, the effects of past fire exclusion can be addressed by reducing stand densities and hazardous fuels to increase resilience to drought and fire.
- In rangelands, management responses to altered fire regimes, overgrazing, and invasive species will help maintain productivity and benefit livestock grazing, native ungulates, and many animal species.

GREAT PLAINS

- Rangeland management differs based on local conditions, but core principles remain, primarily restoration or maintenance of diverse native species that nurture belowground ecosystem health and facilitate a range of species tolerances to meet changing conditions, including drought.
- Protection of the soil resource will maintain water-holding capacity and support vegetation cover, thus attenuating drought effects.
- Wildfire and variable-intensity grazing are primary disturbances in rangelands and provide mechanisms to increase vegetation heterogeneity.
- Although economic downturns provide disincentives to reducing stocking rates, delayed response to drought may degrade rangelands if high stocking levels are decoupled from forage production, resulting in long-term productivity declines, which makes retention of a core herd more challenging.

- Information about drought scale, severity, and forecasts improves decisions on how to balance short-term gains and losses against risk of damage to future productivity.
- Communication among livestock owners, grazing association boards, governmental agencies, and other stakeholders will help achieve favorable outcomes during drought years, facilitating a return to profitability and sustainability.

NORTHEAST AND MIDWEST

- Based on climate change projections, future forest responses to drought could include mortality of sensitive species, shifts in forest composition toward more drought-tolerant species (including nonnative species), and potential migration of tree species into more suitable habitats outside of current geographic ranges.
- Such drought-related effects could affect many ecosystem services, including timber and nontimber products, water supply, carbon sequestration, wildlife habitat, and cultural benefits.
- Forest thinning may be an important management strategy to enhance resilience during drought, even in humid parts of the Northeast.
- Using silvicultural systems that promote high species diversity may enhance the sustainability of forest production under changing climate regimes.
- To promote the establishment of individuals that are more likely to survive and adapt to frequent future drought, seeding and planting genotypes or species considered better adapted to soil moisture deficit is preferred over natural regeneration.
- Although water resources are typically not the primary forest management objective, existing best forest management practices are designed to maintain water supply and quality.

SOUTHEAST

- Projections of increased drought frequency and duration in many areas of the Southeast will present challenges for land managers to reduce the likelihood of wildfire occurrence and area burned.
- Management options to reduce fire risk in the Southeast have mostly focused on reducing fuel loads through frequent prescribed burning. Additional actions include reducing fuel loading through planting at lower densities, thinning natural stands and existing plantations, reducing live and downed fuels mechanically with mastication treatments, and reducing live fuels with herbicide.
- Thinning or other preventive silvicultural practices that improve pine vigor may help mitigate drought-related impacts by southern pine beetle and other bark beetles.

Forest thinning is an important management strategy to enhance drought resilience (top). Prescribed burning and planting at lower densities are management options that can reduce fuel loads and fire risk (middle and bottom).

Photos: Eli Sagor, University of Minnesota, Bugwood.org, Chris Evans, University of Illinois, Bugwood.org, and Jared M. Dort, USDA Forest Service

Informed management decisions require active experiments on drought management practices (top). Collaborative efforts that include drought considerations will help to institutionalize awareness of drought effects and management responses (middle and bottom).

Photos: Sandy Kase, USDA Forest Service, Jose Witt, Friends of Nevada Wilderness, and Peter M. Fredin, Vail Resorts

- Planting or regenerating more drought-tolerant species (e.g., longleaf pine instead of loblolly pine) could also help reduce drought-related impacts.
- The restoration of longleaf pine and shortleaf pine ecosystems are broad efforts organized across the historic range of both ecosystems. Both longleaf pine and shortleaf pine provide numerous benefits for responding to current and future climate change, including resistance to wildfire, higher productivity during drought periods, and higher disease and pest resistance.
- Thinning can increase water availability for tree growth by reducing stand transpiration and canopy interception.

The following strategic actions will help to institutionalize awareness of drought effects and drought responses in public and private land management:

- Establish and maintain relationships with providers of drought information.
- Include drought in collaborative efforts among agencies and stakeholders.
- Revise best management practices as needed.
- Implement drought in relevant planning processes.
- Establish long-term monitoring of drought effects.
- Share information on effectiveness of drought management practices.

Effective management of drought effects requires that resource managers access information on drought and disturbance, anticipate future conditions, develop robust responses, and implement those responses in a timely way. Being informed enough to take effective action requires a combination of (1) ongoing monitoring of parameters that are critical for making timely decisions, (2) longer term monitoring (e.g., 5–10 years) to determine the success or failure of past management decisions, and (3) active experiments that test the effectiveness of new or revised drought management practices.

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CHAPTER 1

Managing Effects of Drought: Introduction and Definition of Key Terms and Concepts

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In the most basic terms, drought is a lack of water. A place can be dry (e.g., a desert) or wet (e.g., a rain forest), but droughts can occur in both dry and wet locations as events in time. The consistently dry seasons experienced in many parts of the United States (e.g., the dry summers of much of the Western United States) would not merit the designation of "drought" per se; however, interannual variation in the duration and magnitude of dry periods can affect forests and rangelands (Seneviratne et al. 2012, Wilhite and Buchanan-Smith 2005). Therefore, particularly long dry periods within times of the year that are normally dry would be designated as drought. Drought has shaped ecological processes and influenced human and biological communities throughout the millennia and will continue to do so. It is an important disturbance process for the ecology of forests and rangelands, so is not "bad" in and of itself, but changing drought regimes present challenges for ecological communities and land managers.

Although it is difficult to quantitatively project how climate change will influence future drought characteristics (i.e., frequency, severity, timing), many global climate models project that some regions of the United States will experience a higher frequency of severe droughts and longer dry periods (IPCC 2014, Wuebbles et al. 2017) (chapter 2). Even if current drought regimes remain unchanged, higher temperatures interact with drought to exacerbate moisture limitation and water stress (Adams et al. 2009, Breshears et al. 2005).

Recent observations of regional-scale drought impacts, and expectations of more frequent and severe droughts in the future across many areas of the United States, prompted a state-of-the-science synthesis (Vose et al. 2016a) that provides a foundation for how future droughts may affect forest and rangeland ecosystems. The purpose of the current volume is to build on that synthesis and provide region-specific adaptation options for natural resource managers to increase resilience to drought, thus minimizing impacts and facilitating recovery after droughts occur.

GOALS OF FOREST MANAGEMENT

There is a long history of active forest and grassland management in the United States. Among the primary goals of management is to sustain or enhance the quality and quantity of ecosystem services provided by forests and rangelands. In the early 20th century, education and training of resource professionals were critical to meeting the needs of the Nation to restore degraded forest lands in the Eastern United States following a period of resource extraction and poor logging practices. Indeed, a primary objective of early forest management was improvement of watershed conditions for sustaining water quality and supply, including mitigation of drought (Zon 1927). The ability to successfully restore and sustainably manage forests and grasslands in the United States is evident by the contribution of both sectors to the national and global economy. For example, the timber products industry is directly responsible for 1.2 million U.S. jobs and over $72 billion in labor income; economic activity associated with the forest sector generates an additional 4 million jobs with $210 billion of associated labor income (Prestemon et al. 2016).

In addition to the value of wood products, U.S. forests and rangelands provide many ecosystem services that are difficult to quantify in economic terms but are nonetheless important. Examples include recreation, clean water, wildlife habitat, biodiversity, and climate mitigation. Forest and rangeland systems are inherently resilient to environmental stressors and disturbances, although that resilience has limits (McDowell et al. 2016), so the ability to achieve these management goals will be challenged by changing environmental conditions such as drought. Our expectation is that a better understanding of drought effects and implications for forest and rangeland values will help land managers anticipate responses and inform management actions that increase adaptive capacity to current and future drought (chapter 10).

DROUGHT AS A DRIVER OF ECOLOGICAL PROCESSES

Forest and rangeland biota already have some level of adaptive capacity to periods of dry conditions. A key unknown is whether current species in a given location and associated ecosystem processes will be able to endure more severe (or different) droughts in the future (Clark et al. 2016, Schlesinger et al. 2016, Vose et al. 2016a). Understanding adaptive traits of species and ecosystems is an important component of developing management options. Long-term studies (e.g., plot re-measurements and dendrochronology) provide strong evidence for evaluating responses to drought at the individual-species level, and more recent physiological studies provide a mechanistic basis for understanding species differences in drought sensitivity (McDowell et al. 2016).

As leaves become drier due to a lack of available moisture in the soil to rewet them at night, stomata will close when the evaporative demand of the air (a function of warm temperatures and low humidity) becomes too high. When stomata close, plants are unable to fix carbon dioxide, leading to metabolic stress. Under severe water stress, hydraulic failure can occur, interrupting the flow of water up the stem to the leaves (McDowell et al. 2016). Such failures can be partially repaired by plants, but much of the damage can be permanent.

In addition, species differ in their allocation to roots, mycorrhizal associations, and xylem anatomy, contributing to varied drought tolerance among species (Mackay et al. 2015, McDowell et al. 2016, Phillips et al. 2016). This ecological and physiological knowledge underpins science-based management of forests and rangelands in response to current and future drought regimes. Furthermore, recent large-scale tree mortality events in response to drought, drought plus elevated temperatures ("hot drought"), and drought-mediated insect outbreaks and wildfires suggest that shifting drought characteristics are altering forest structure and function at broad scales, with negative impacts on ecosystem services (Vose et al. 2016a; chapter 4).

ECOLOGICAL DROUGHT AS A COMPONENT OF STRESS COMPLEXES

As noted above, drought effects rarely occur in isolation from other disturbances and stressors. Insects and invasive species capitalize on drought stress in trees, which can lead to forest mortality (Breshears et al. 2005; chapters 3, 4, 6, 9). Severe moisture stress reduces both chemical and physical defenses of trees to insects, and droughts are often precursors to severe outbreaks (Creeden et al. 2014, Kolb et al. 2016, Raffa et al. 2008). Insects also benefit from the increased nutritional content of drought-stressed trees, making both defoliating and boring insect outbreaks more potent during drought conditions. Some fungal infections may be hampered by drier conditions, although many species may benefit from drought-related damage after moist conditions return. Insect attacks and fungal pathogens can further impair plant defenses against drought mortality. Prolonged and severe moisture stress can ultimately have negative feedbacks on insect populations simply through reduced food production and quality.

The spatial extent of wildfires is higher during years with extended drought (Heyerdahl et al. 2008, Morgan et al. 2008; chapters 3, 4, 6, 9), and multiple meteorological drought indices offer some predictive capability for area burned by fire at short time scales (days to months). Drought can, inversely, limit the amount of fuels, particularly in more arid locations, creating an outcome in which wet conditions preceding the dry season are associated with a larger extent of fire (Abatzoglou and Kolden 2013; Littell et al. 2009, 2018). Forest fires that occur in moist years tend to be less widespread (in part because they are easier to control), and severity patterns in these fires are controlled by topographic factors affecting soil moisture distributions (Dillon et al. 2011).

Drought conditions cause browning on leaves of this flowering dogwood (*Cornus florida* L.). (Photo by John Ruter, University of Georgia, Bugwood.org)

However, fires are more likely to escape control during drought years, leading to greater area burned. Although the fractional area of high severity is similar between drought and non-drought years, severity patterns show greater continuity and less discrimination based on topography in drought years. In other words, in the worst fire years, local "fire refugia" like north-facing slopes or riparian areas tend to have high-severity burns just like the surrounding hillsides, and low-severity burning tends to occur around the edges of the fire or in large patches where the fire burned in cooler or moister conditions (e.g., during the night). Land management and fire management activities that affect fuel loading can influence the spread and severity of fires (chapter 10).

Cheatgrass (*Bromus tectorum*) infestation reduces habitat quality for both vegetation and animals. (Photo by Chris Evans, University of Illinois, Bugwood.org)

Invasive species create challenges for forest and rangeland plant and animal species, often reducing ecosystem services (e.g., biodiversity, carbon storage), and drought can increase invasion success for some species and locations (chapter 5). For example, the spread of cheatgrass (*Bromus tectorum*) and other nonnative annual plants into shrub-steppe ecosystems has reduced dominance by sagebrush (*Artemisia* spp.) and reduced habitat quality for both vegetation and animals (e.g., greater sage-grouse [*Centrocercus urophasianus*]) (chapters 6, 7). Cheatgrass and sagebrush are both well adapted to frequent drought, but cheatgrass is adapted to frequent fire disturbances and sagebrush is not.

CHARACTERIZING ECOLOGICAL DROUGHT

Drought has generally been framed into four classes (Wilhite and Glantz 1985)—**meteorological drought**, **hydrological drought**, **agricultural drought**, and **socioeconomic drought**—which address periods of dry weather that negatively affect a particular resource or sector. More recent efforts address **ecological drought**, a similar concept focused on ecosystem responses. These classes are not mutually independent, but refer to different ways to measure, identify, or conceptualize drought conditions. Most types of drought are associated with meteorological conditions that result in a lack of water, such as a low precipitation or excess demand from evapotranspiration (ET).

Meteorological drought definitions refer to atmospheric components of the water balance, between precipitation and ET, where low precipitation and high evapotranspirative demand lead to a relative lack of water (chapter 2). **Hydrological**, **agricultural**, and **socioeconomic drought** are filters placed on meteorological drought to frame how they affect human demands and values for water, including food production, electrical power production, recreation, and wildlife conservation.

Ecological drought relates to the negative impacts of meteorological drought on ecosystem services. The effects of dry conditions on ecological processes often include tradeoffs, however, and some biota benefit from drought primarily because other biota are more negatively impacted. Interrupting normal drought-related disturbances can actually harm some ecosystems and reduce their resilience to future drought, as exemplified by fire exclusion in dry forest ecosystems in the Western United States (chapters 3, 4, 6). Nevertheless, evolving drought conditions can be so atypical in terms of characteristics or context that it is useful to frame **ecological droughts** as those that are outside of conditions for which current vegetation is adapted. The focus of **ecological drought** is generally on observable changes such as large-scale forest mortality, but less observable responses (such as slower tree growth or altered species composition) can have observable changes (and economic consequences) over the long term.

Key drought characteristics that drive ecological responses to drought are:

- **Severity** (defined as degree of moisture deficit)
- **Frequency** of a given level of deficit
- **Temporal patchiness** (duration and short-term variability)
- **Spatial coherence** (spatial distribution across the landscape)

The most direct measures of drought **severity** for terrestrial and aquatic ecosystems are measures such as soil moisture, streamflow, and fuel moisture, which express spatial and temporal integration of precipitation and ET. The **frequency** of a given level of drought severity is critical for understanding the ecological role of drought because the relationship of the frequency of mortality-inducing drought to regeneration or recovery times is a fundamental descriptor of ecosystem dynamics. At one end of the spectrum, species that mature more slowly than the frequency at which mortality-inducing weather events occur may not be well adapted to the local climate. At the other end of the spectrum, species that take advantage of frequent disturbance may not compete well with species that are more competitive when disturbance is infrequent.

Relationships between **frequency** and **severity** are commonly embedded within adaptations to drought and disturbance. For example, it is unusual for severe wildfire or insect outbreaks to occur frequently (e.g., every few years) because it is difficult to regrow sufficient vegetation (fuel or food, depending on the disturbance) to sustain the next severe event. The role of high-frequency, low-severity fire in thick-barked ponderosa pine (*Pinus ponderosa*) stands in maintaining low fuel connectivity is a well understood adaptation in drought-prone (and fire-prone) forests (chapters 3, 4, 6). Similarly slow-growing trees adapted to arid sites (e.g., bristlecone pine [*Pinus longaeva*]) are another example of how isolation created by frequent drought builds a degree of resilience to disease, insects, and fire spread.

Temporal patchiness describes drought duration and variability, such as the contrasts between multiple consistently dry years versus alternating wet and dry years (or growing seasons), or a long sequence of dry days. Both ends of this spectrum can have substantial effects on ecological processes and disturbance regimes. For example, high contrasts in moisture over relatively short (seasonal to interannual) time scales can increase the severity of drought-related stressors such as wildfire and insects (chapters 8, 9). This was previously noted for how wet winters and springs promote heavy growth of annual grasses, leading to more severe and larger fires during the following dry summer in shrublands (Abatzoglou and Kolden 2011, Littell et al. 2009). Substantial growth in a forest in a wet year contrasted to dry conditions the next year can lead to increased moisture stress because of increased leaf area, along with greater food abundance for defoliating insects. Exceptionally long dry periods can cause stress and in some cases mortality, even in long-lived trees.

Severe meteorological droughts with large **spatial coherence** (i.e., they occur over large spatial scales) are sometimes termed “megadroughts” because they may encompass multiple regions of the United States at a given time (Coats et al. 2014, Cook et al. 2014). Drought at this scale can potentially affect fire suppression strategies or response to insect outbreaks, although smaller spatial scales are also relevant because a particular drought may have different effects on different landscapes (e.g., north versus south aspect, side slope versus valley).

COMMON DROUGHT METRICS

Drought severity and duration are connected because the longer a place goes without rain, the greater the opportunity for ET to continue to dry the soil. Although the several dimensions of drought are important to consider for strategically managing landscapes for drought, several duration-severity metrics are commonly used to describe droughts as they progress in time and can be used to inform responses to developing or ongoing drought (chapter 2). Three of the most common metrics used to characterize meteorological drought are the Standardized Precipitation Index (SPI) (McKee et al. 1993), Palmer Drought Severity Index (PDSI) (Palmer 1965), and Keetch-Byram Drought Index (KBDI) (Keetch and Byram 1968).

The SPI is a relatively simple approach to characterizing drought, in which an anomaly occurs when the amount of precipitation (in this case, lower precipitation) differs (determined as a Z-score, or number of standard deviations above or below the mean) from the long-term mean for a specific location (McKee et al. 1993). The index is applicable only at a local scale, relative to mean precipitation over the period of interest.

The PDSI is related to water balance (difference between incoming precipitation and ET) of a relatively thin, two-layer soil incorporating estimates of evaporation and runoff. The precipitation component is relatively straightforward, and runoff is computed based on the water-holding capacity of the soil column (porosity at field capacity). Evapotranspiration is drawn from the two layers of soil independently, with the thin top layer being available for direct evaporation, while the second soil layer retains water for transpiration. Evapotranspiration is calculated based on air temperature using the Thornthwaite method (Thornthwaite 1948). Because drier soils evapotranspire less than moist soils, a seasonal

Forest (wetter sites) and rangeland (drier sites) are juxtaposed in the Blue Mountains, Oregon. (Photo by Dave Powell, USDA Forest Service [retired], Bugwood.org)

Shortleaf pine (*Pinus echinata*) is resistant to wildfire, pests, and disease. (Photo by Chris Evans, University of Illinois, Bugwood.org)

adjustment to the Thornthwaite estimate is used for well-watered soils. Derivations of the PDSI include computing ET with the Penman-Monteith (Monteith 1965) equation, which improves ET estimates under some conditions.

The KBDI (Keetch and Byram 1968) is absolute in nature and not locally indexed. It is based on an exponential decay conceptualization of soil moisture in fuels. Precipitation minus interception (constant) rewets fuels, and daily loss is calculated (in tables) as a function of the daily air temperature and the previous day's drought index. As the index approaches its driest extreme, the effect of further drying is diminished asymptotically.

The use of these metrics in real-time decision making is aided by the fact that they have been used in resource management for decades, so many land managers have become familiar with what a particular value might mean for affected resources in a given location (e.g., U.S. Drought Monitor; https://droughtmonitor.unl.edu). Unfortunately, the physical basis for some metrics limits their utility as measures of future drought, particularly those that do not use an energy balance approach for estimating ET (Milly and Dunne 2017). However, the dimensions of drought listed above (e.g., frequency, duration, severity), along with an overall warming context, frame a thoughtful approach for considering future drought challenges that is not constrained by the limitations of individual metrics (Abatzoglou and Kolden 2011, Luce et al. 2016).

ECONOMIC CONSEQUENCES OF DROUGHT

Droughts can have substantial impacts on the economy. Most obvious are droughts that reduce local, national, and global food and water supplies. The timber products industry, which represents 2 percent of the U.S. economy (Prestemon et al. 2016), can be affected by drought-related mortality and reduced productivity, leading to reduced wood supply and a corresponding increase in market price. Market-scale effects will be more pronounced when larger areas are affected by drought. The timber products industry can be a much bigger player in local, often rural economies, and disruptions in wood supply reduce employment, income, and the economic base of such locales. Frequent wood supply interruptions in an area can lead to disinvestment of milling infrastructure (Insley and Lei 2007, Sims 2011), leading to more persistent economic consequences in rural communities.

Drought in rangelands reduces forage and water available for livestock grazing and reduces overall vegetative land cover, which can lead to soil loss from wind and water erosion with long-term effects on rangeland productivity (Finch et al. 2016; chapters 3, 6, 7). Because animal stocking rates are generally determined by expected precipitation, degradation can occur quickly if drought occurs and grazing persists. Although soil conservation practices and modern irrigation have reduced the impact of episodic droughts, the effects of severe drought are a significant concern in communities where livestock grazing contributes to the local economy (Prestemon et al. 2016).

Forest and rangeland ecosystems also help regulate water supply by stabilizing surface flow (i.e., reducing streamflow extremes) and allowing more subsurface recharge (chapters 3, 6, 7, 8). In addition to the direct effects of reduced streamflow and groundwater recharge during drought, lower growth and mortality of vegetation may occur. Extensive mortality may increase overall streamflow after the drought ends (Vose et al. 2016b), although that response is not a certainty (e.g., Adams et al. 2012). Altered water quantity following drought may have little impact on economics, although degraded water quality after disturbances like fire can substantially disrupt municipal water supply and treatment in ways that may force substantial public investment in water infrastructure to avoid supply interruptions (Emelko et al. 2011).

Forest and rangeland management is greatly affected by drought, perhaps most acutely in management of wildfires. Spatially and temporally extensive droughts in the Western United States are a likely contributor to a recent (since around 1980) increase in area burned by wildfire in dry forests (Abatzoglou and Kolden 2013, Holden et al. 2018, Westerling et al. 2003). Larger and more frequent wildfires have become difficult to suppress (Stavros et al. 2014, Yang et al. 2015), resulting in higher suppression costs (Prestemon et al. 2008). The cost of fire suppression has also been partially driven by the high cost of protecting property in the wildland-urban interface.

ADAPTING TO DROUGHT

What is Adaptation?

Adaptation is an ecological term that implies a "natural" adjustment in forest and rangeland ecosystems in response to environmental stressors and disturbances. For drought, adaptation management is the purposeful implementation of management actions to minimize drought impacts, enhance recovery after drought, or facilitate transitions of ecosystems to conditions better suited to survive future droughts (chapters 3, 4, 5, 6, 7, 8, 9). The concept of using adaptation strategies to sustainably manage forests and rangelands is not new to land managers. Climatic variability and associated disturbances have challenged managers to continuously adapt management actions to adjust to changing environmental conditions, changing societal demands, and unanticipated stressors such as invasive species. It is likely that all ecosystems will experience drought at one time or another, and the likelihood of increasing drought occurrence and severity in some regions of the United States suggests that drought exposure will become more frequent and more damaging for some ecosystems.

In areas where droughts are relatively frequent, ecosystems have adjusted "naturally" with physiological and morphological adaptive measures that impart some level of resistance to drought. Examples include lower plant density, higher proportion of species with low water requirements, species with leaf traits that prevent desiccation, deep rooting, and fire-resistant characteristics in fire-prone locations. In contrast, species adapted to wetter environments may be more vulnerable to drought because they have developed adaptive traits that prioritize competitive growth over water conservation, and hence they may have a limited capacity to adapt to increasingly droughty conditions. In either case, extreme and perhaps unprecedented droughts, defined in the context of geographically specific climate regimes, may have substantial impacts on the structure and function of forest and rangeland ecosystems.

Historical and current biophysical context is an important factor in evaluating risks to future droughts and can constrain (or increase) potential adaptation options. In addition, successful and sustainable drought adaptation actions require understanding which ecosystem characteristics provide resilience to drought and which characteristics decrease resilience. In some cases, past management has decreased drought resilience. For example, fire exclusion in ponderosa pine forests has resulted in higher stand densities and fuel loadings, making these forests more vulnerable to wildfire and insect outbreaks than in much of their past history (Agee and Skinner 2005; chapters 3, 4, 6).

Cold-water fish species in the West have some degree of drought resilience because streams affected by post-fire debris flows or desiccated channels can be repopulated by migratory members of the population, providing an advantage over non-migratory species (Dunham et al. 2003, Rieman and Clayton 1997; chapters 3, 6). Land managers are learning how to augment rather than hamper natural drought adaptations, thus acknowledging the dynamic nature of ecosystems (e.g., Penaluna et al. 2018).

Resistance, Resilience, and Response Options to Facilitate Transitions

Millar et al. (2007) proposed three primary adaptive strategies in response to climatic variability and change: increase resistance, increase resilience, and facilitate transitions. **Resistance options** are intended to create ecosystem conditions that are better able to resist change and therefore **minimize impacts**. For drought, examples may include management efforts to prevent drought-mediated disturbances such as insect outbreaks and wildfires. Options include reducing stand density with thinning to maintain lower fuel loads and increase overall tree health and vigor (chapters 3, 4, 6, 9).

Resilience options are intended to promote a return to a prior condition following disturbance, thus **facilitating recovery**. For drought, examples include favoring (through planting or selective cutting) species that are more drought tolerant, and creating and maintaining high species and structural diversity. Thinning and harvest that break up fuel (for fire) and food (for insects) continuity (Hessburg et al. 2015, Logan and Powell 2001) reduce spread during events and encourage smaller patches that are more easily seeded by surviving vegetation.

Response options designed to **facilitate transitions** move the ecosystem from current to new conditions, in **anticipation** of creating ecosystem structure and functions that are better adapted to **future conditions**. Examples include preferentially planting drought-tolerant species or genotypes in areas where drought is expected to worsen.

Resistance options are intended primarily as a short-term strategy in a warming climate, whereas resilience can be effective for longer time scales, and transition response options are long-term strategies once neither resistance nor recovery is an available option. These different options should not be considered mutually exclusive; for example, some resistance management actions may also impart resilience (and vice versa), and transformation of some areas or aspects of an ecosystem may allow persistence of others for a longer period.

The Maintain-Repair-Engineer Spectrum

Although there are broad goals of resistance, resilience, or transitioning, Rieman et al. (2010) argue that the choices in the landscape range from (1) a largely passive role in maintaining an already resilient/resistant ecosystem (transitioning on its own), to (2) restoring/repairing an area in the direction of resilient/resistant condition or toward a transition, to (3) aggressive management of conditions and outcomes in order to actively provide resilience/resistance or transition. This spectrum is primarily about level of effort and sustainability given a large expanse of forests and rangelands, but it has other implications as well. Wilderness and surrounding remote areas with mostly passive management are examples of places where extensive intervention is not feasible, and in some cases, less important to maintain functions and processes that provide desired ecosystem services.

At the other end of the spectrum are places where natural dynamics associated with drought could pose a hazard to isolated populations of rare biota or places of human habitation, requiring intensive and ongoing management efforts to substitute for natural dynamics that sustain particular conditions. Between these extremes are places that might require some short-term management effort to facilitate conditions that have long-term resilience. Different forests have different pathways through which they have arrived to current circumstances. Some forests have been so altered by historical management (or lack thereof) or by altered land use (e.g., residential construction) that intervention is now necessary (e.g., establishment of longleaf pine [*Pinus palustris*] forests) (chapters 5, 9). Other forests may only recently have begun to show reduced health due to shifts in climate.

In this framework, desirable landscape conditions are relatively resilient to natural and evolving dynamics driven by drought. At the same time, there is an acknowledgment that the specific values to be maintained or protected need to be directly identified, whether they be genetic diversity, ecosystem function, or some economic provisioning service. Do we need to protect species or populations? Are we looking simply for a forest ecosystem, even if it is a new mix of species? How much effort can we afford to meet these goals? Ultimately, any efforts at resilience and resistance for a given landscape will need to yield to some transition, and decisions need to be made about (1) which values and conditions are critical and (2) the costs and benefits of management interventions to sustain those values and conditions. It will likely be easier to maintain resilience for “a forest” than for a forest with a particular distribution and abundance of species (chapter 10).

Doing Things Versus Learning Things

Although much is known about options for managing forests and rangelands in response to current and anticipated drought, there is still a high level of uncertainty, and surprises are likely. This uncertainty suggests a need for monitoring and ongoing learning to adjust management actions and goals over time. Specifically, effective management requires that managers are an intelligent component of the ecosystem who are able to learn and use information on trends and responses to disturbance, anticipating future conditions and developing robust management decisions over time (chapter 10). This is especially challenging because changing drought regimes may create conditions that are different than those observed at any time in the past. The ability to anticipate responses, and to change course if anticipated responses do not occur, will be critical for effectively sustaining ecosystem services.

Being informed enough to take effective action requires a combination of (1) ongoing monitoring to track what affects timely decisions (e.g., being ready to prepare a postdrought recovery action in a timely way), (2) monitoring that can detect the success or failure of previous plans, and (3) active experiments that anticipate that one idea will work but others will fail (chapter 10). If we look at adaptation in a Darwinian sense, no species is already adapted to new conditions, and it is the populations and genes that can cope with evolving conditions that are ultimately successful—in other words, those that can **learn**.

The following chapters in this volume provide regionally specific management options for minimizing drought impacts, facilitating postdrought recovery, and managing in anticipation of future drought conditions based on current knowledge. The intent is to provide general guidance for land managers to combine with their local knowledge, experiences, management objectives, and current constraints. In most cases, species, ecosystems, and human communities will likely be best served by a full range of management intensities, from intensive management responses to "observe, evaluate, and respond." Learning strategies will hopefully range from **thoughtful management**, in which management options are implemented and management actions are modified based on observed responses, to **adaptive management** (*sensu* Walters 1986) in which experimental management is applied with rigorous modeling and monitoring.


Drought damage. (Photo by Petr Kapitola, Central Institute for Supervising and Testing in Agriculture, Bugwood.org)

PURPOSE AND APPROACH FOR REGIONAL CHAPTERS

The purpose of this report is to inform and guide natural resource managers as they evaluate management options to minimize drought impacts, help forests and rangelands recover from drought, and create forests and rangelands better adapted to future drought conditions. An overall conceptual framework and development of organizational structure and chapter content were facilitated by a series of virtual and in-person workshops. Teams of experts used a national-scale drought synthesis (Vose et al. 2016a), combined with more recent scientific literature and their best professional judgments, to link scientific evidence with regionally appropriate discussions of risks, vulnerabilities, and management options.

Chapter 2 describes projections of potential changes in drought in the United States as a frame of reference. The remaining chapters are organized by regions: Alaska and Pacific Northwest (chapter 3), California (chapter 4), Hawai'i and U.S.-Affiliated Pacific Islands (chapter 5), Interior West (chapter 6), Great Plains (chapter 7), Midwest and Northeast (chapter 8), and Southeast (chapter 9). Authors were provided a general framework and guidelines for writing but retained flexibility to organize and develop chapters to address key issues and challenges specific to each region.

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CHAPTER 2

Projected Drought for the Conterminous United States in the 21st Century

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BACKGROUND

Measuring and Defining Long-Term Trends of Drought

Several metrics are used to quantify the lack of available water in an environment and identify drought occurrences. Each metric focuses on different effects of water deficits, such as agricultural, meteorological, hydrological, ecological, or socioeconomic drought (Vose et al. 2016). Thirteen drought indices were developed and used in the United States in the 20th century, and some are still commonly used (Heim 2002). Zargar et al. (2011) described 74 indices used to characterize droughts.

Many of the climatic parameters needed to calculate these indices are based on observed values and are available in digital formats at fine spatial resolutions (Abatzoglou 2013, Daly et al. 2008). Other parameters are downscaled from future projections at temporal resolutions, either monthly (Thrasher et al. 2013) or daily (Maurer et al. 2014). Indices that use remotely sensed data to document past or near real-time droughts are not suited to model potential future drought conditions. This chapter focuses on the climate-based indices most conducive to projecting future conditions.

Regardless of the metric used to define drought, the ability to access past and projected future climate data provides information for multiple types of users: modelers seeking to improve climatic models, researchers and decision makers who need assessments on the current and potential future vulnerability of sectors affected by droughts, and the interested public wanting information on how climatic conditions may change. Although much research has focused on future changes in precipitation and temperature, few studies have examined potential changes in drought events for the United States (but see Cook et al. 2015, Dai 2012, Ryu and Hayhoe 2017). Regardless of scale, it is a challenging task to model complex, interconnected processes that regulate climatic patterns. Although modeling outputs may not align precisely with observed data, the resulting general trends provide insights into aspects of the climate system that influence observed changes and thus help to improve and refine modeling techniques (Hoskins et al. 2008). Individual and ensembles of models that indicate repeated periodic extreme events for one or more locations help to develop risk assessments (O'Neill et al. 2017).

In this chapter, we present some of the challenges associated with spatial modeling of drought in the past and into the future, and we examine some potential results from downscaled projections for the conterminous United States. The results are presented for the seven geographic regions used by the most recent U.S. National Climate Assessment (USGCRP 2017).

INDICES AND CLIMATIC DRIVERS FOR EXAMINING DROUGHT

Several indices related to drought are derived from climatic information; some also require soil properties. Examples include precipitation only (McKee et al. 1993), precipitation and temperature (Heddinghaus and Sabol 1991, Palmer 1965), precipitation and soil moisture (Keetch and Byram 1968, McGuire and Palmer 1957), and precipitation, temperature, and soil moisture (van der Schrier et al. 2013, Wells et al. 2004). These examples are not exhaustive, but they are generally the better known and more widely used indices applied in the United States and elsewhere.

Palmer Drought Severity Index

The Palmer Drought Severity Index (PDSI) (Palmer 1965) has been widely used to incorporate precipitation and temperature into a water balance model to classify meteorological and hydrological droughts. In response to criticisms of spatial incomparability on the original PDSI (Alley 1984, Guttman et al. 1992), it was modified by Heddinghaus and Sabol (1991) and updated by Wells et al. (2004) to account for local normal conditions via a self-calibrating approach.

Potential evapotranspiration (PET) is used to determine how much soil moisture could be lost under specified temperature conditions. Potential evapotranspiration is used by PDSI and other indices (e.g., standardized precipitation evapotranspiration index [Vicente-Serrano et al. 2010], moisture index [Koch et al. 2013]). Opinions vary on the best way to calculate PET. A key issue is whether temperature-only-based methods (e.g., Thornthwaite 1948) are sufficient, or if process-based methods like the Penman-Monteith model (Burke et al. 2006) are needed. Another issue is whether solar radiation and vapor pressure deficit are needed to calculate PET, especially when predicting future climate model outputs. Both Dai (2011) and van der Schrier et al. (2013) swapped the Thornthwaite model with the Penman-Monteith model and found little effect on the resulting classification of drought by the PDSI. However, Milly and Dunne (2017) conducted a comprehensive study of several methods of calculating PET and projecting into the future on a global scale. For the period 1981–2000 compared to a multi-model mean, temperature-based methods of calculating evapotranspiration resulted in future projections with a higher percentage of change, and process-based methods (e.g., Penman-Monteith) had a lower percentage of change. We chose to use the Penman-Monteith approach to calculating PET because it is less biased than other methods.

Limitations and challenges with PDSI and time-series data—Palmer's (1965) original equation used the Thornthwaite (1948) method to calculate PET, where temperatures below 32 °F do not result in positive values of PET. The PDSI in this case therefore assumes that evapotranspiration does not occur under freezing conditions. However, PDSI is usually calculated using weekly or monthly climate data, and temperatures can fluctuate (above and below freezing) on smaller time scales. Therefore, snowmelt functions have been incorporated to account for delayed changes in soil moisture (Dai et al. 2004, Yan et al. 2014). These functions generally accumulate a snowpack when monthly temperatures are <32 °F and release a portion of the stored water when monthly temperature is above some threshold, usually above freezing.

Another common issue with many of the currently used drought and aridity indices (e.g., PDSI, standardized precipitation evapotranspiration index) is that they produce location-based, time series datasets that are not conducive for examining and interpreting thousands of locations over multiple periods. We sought a method to simply evaluate long-term drought that could be applied across the conterminous United States at a relatively fine scale. As a historic example, Marcovitch (1930) measured the severity of drought as a function of the length of consecutive days with temperatures >90 °F, weighted by total monthly precipitation for the period June through September. This index results in a single value that was originally intended to define conditions that were favorable or unfavorable for the Mexican bean beetle (*Epilachna varivestis*), but it could also be modified to represent normal conditions by averaging among many years. Although interesting, this index has limited value because an arbitrary threshold of 90 °F is used to define drought, but this criterion ignores soil moisture or water-holding capacity. Nonetheless, the notion of combining multiple time slices (e.g., months) has merit when visually representing drought conditions, which we sought to replicate in the analysis reported here. By aggregating time series data into a weighted value, such as the frequency of drought events weighted by their intensity, a single value can represent the relative droughtiness of a location over a given time.

In this chapter, we present indices that capture past and projected future drought periods as well as potential periods of excessive moisture. We present these indices for each of four 30-year periods from 1980 to 2099, showing the projected increase in drought conditions over much of the conterminous United States, especially under climate change scenarios with higher levels of greenhouse gas emissions (e.g., RCP 8.5, in which humans do not aggressively pursue a substantial reduction of inputs that influence atmospheric warming).

Cumulative Drought and Moisture Severity Indices

Two cumulative indices, the cumulative drought severity index (CDSI) and the cumulative moisture severity index (CMSI), were derived from the frequency of monthly drought (CDSI) and excessive moisture (CMSI) events, weighted by their intensity (Peters et al. 2015). Intensity was defined by seven self-calibrated PDSI (scPDSI) classes (Wells et al. 2004), three of drought, three of excessive moisture, and one of normal moisture. To represent the increase of intensity, each cumulative month received a weighting. Extreme drought (scPDSI <-3.9) or extremely moist (scPDSI >3.9) received a weighting of 3; severe drought (scPDSI -3.9 to -3.0) or a very moist spell (scPDSI 3.0 to 3.9) received a weighting of 2; moderate drought (scPDSI -2.9 to -2.0) or unusually moist spell (scPDSI 2.0 to 2.9) received a weighting of 1. Normal conditions were assumed when monthly scPDSI values ranged from -1.9 to +1.9 and received a zero weighting. Using the four 30-year periods of 1980–2009, 2010–2039, 2040–2069, and 2070–2099, CDSI and CMSI values were calculated from monthly scPDSI data derived from the climate and drought indices tools (National Integrated Drought Information System 2018) and accumulated for the 360 months in each 30-year period. The calibration period (1960–2010) can also influence the later periods by truncating the range of conditions representative of "normal" for a location, resulting in more extreme conditions (Dai and Zhao 2017). For this chapter, we examined how conditions might differ going forward for trees that were established over the last few decades (1960–2010).

Data Sources

Climate: current and future projections—Monthly precipitation, temperature, and mean PET were acquired from the climate data prepared for the Resources Planning Act (RPA) 2020 Assessment (Joyce et al. 2018). These data included the general circulation model (GCM) and representative concentration pathway (RCP) combinations of HadGEM2-ES365 4.5 (Had 4.5) and 8.5 (Had 8.5), IPSL-CM5A-MR 8.5 (IPSL 8.5), and MRI-CGCM3 4.5 (MRI 4.5) for a historical period of 1960–2005. Projections were modeled for the period 2006–2099. These GCM-RCP combinations represent four potential future conditions: hot-wet (HW) (Had 4.5), hot-slightly dry (HSD) (Had 8.5), hot-dry (HD) (IPSL 8.5), and warm-wet (WW) (MRI 4.5). These projections were statistically downscaled by Abatzoglou and Brown (2012) to ~4-km^2 grids.

In addition to using the climate data to calculate monthly scPDSI values, mean 30-year total annual and summer (June/July/August) precipitation and summer maximum temperature values were summarized across the conterminous United States for the periods of 1980–2009, 2010–2039, 2040–2069, and 2070–2099.

Soil-available water supply—Soil-available water supply (AWS) to a depth of 59 inches was obtained from the State soil survey geographic database (STATSGO) and aggregated to approximately 2.5- x 2.5-mile grids (fig. 2.1). The self-calibrated PDSI algorithm (Wells et al. 2004) partitions the available soil moisture, a static variable, into two bins: a top layer having a capacity to hold 1 inch of soil moisture, and a lower layer equal to any remaining soil moisture. Incorporating information about the soil's capacity to hold water to a depth of 59 inches produces PDSI values that are more relevant to the impact of drought on tree species, which access soil moisture much deeper than most agricultural and grassland vegetation. Across the conterminous United States, AWS ranges from 0 to 32 inches, with generally higher values, >8 inches, in the Central Plains region and along portions of East and West coasts (fig. 2.1).

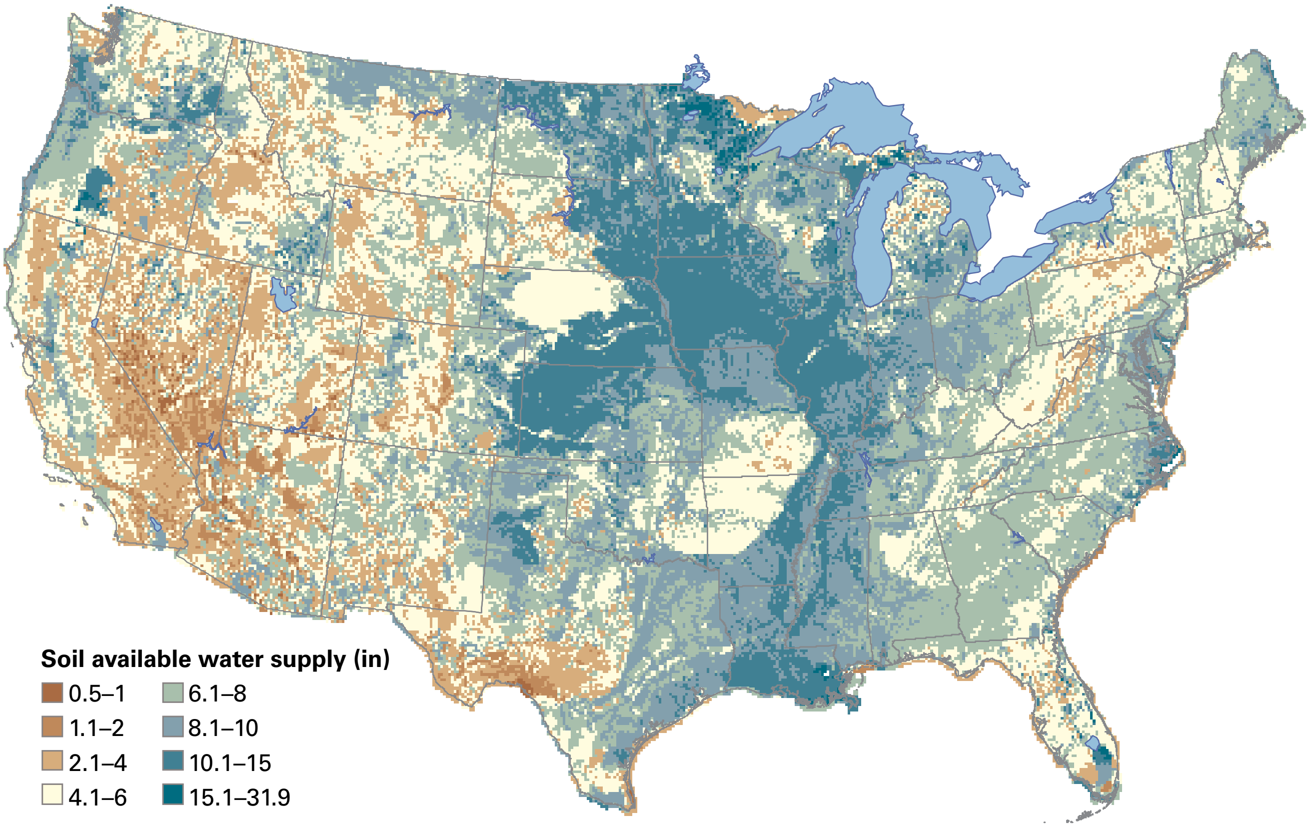

Figure 2.1—Soil-available water supply to a depth of 59 inches, derived from the U.S. Department of Agriculture, Natural Resources Conservation Service gridded State soil survey geographic database mapped across the conterminous United States at approximately 2.5- × 2.5-mile (1/24-degree) grids.

REGIONAL ANALYSES—ASSESSMENT OF TRENDS

To further evaluate the trends across the conterminous United States, we used the regions in the fourth National Climate Assessment (NCA4) (USGCRP 2017) to break out the patterns geographically with the drought inputs and indices. The NCA4 divides the United States into seven regions by State boundaries. For each, we present the mean values from four GCM-RCP scenarios for some precipitation, temperature, and drought metrics (tables 2.1–2.7).

Water Balance (Precipitation—Annual, June/July/August)

All seven U.S. regions show an increase in annual precipitation by the end of the 21st century for the WW, HW, and HSD scenarios, but a lessening of annual precipitation for all regions except the Northeast and Northwest under the HD scenario (tables 2.1–2.7). On the other hand, summer precipitation, most important for vegetative growth, is projected to decrease by the end of the century for almost all regions and scenarios except the WW scenario. As one example, in the Northern Plains under the HSD scenario, annual precipitation is projected to increase by 9.6 percent, but summer precipitation is projected to decrease by 28.7 percent; coupled with an 18.9-percent increase in temperature, this yields a 470-percent increase in the CDSI (table 2.3).

Although these increases in precipitation under the WW, HW, and HSD scenarios, if realized, could mitigate some of the effects of projected warmer temperatures, seasonal shifts in precipitation and reductions to snowpacks can exacerbate warming by reducing soil moisture at critical times in plant growth, producing physiological stress on plants. The rate at which precipitation is projected to change over the three periods varied among regions, where some regions are expected to experience increases in summer precipitation during the 2010–2039 period and then reductions during the middle and later portions of the century.

Summer Temperatures (Maximum Temperature—June/July/August)

All regions and all scenarios show marked increases in mean maximum summer temperatures, increasing throughout the century (tables 2.1–2.7). These increases were most severe in the HSD scenario (up to a 19.6-percent increase in the Northwest by 2099, rising from 77.7 to 92.9 °F), followed by HD, HW, and finally, WW, which had only a 2.6- to 4.3-percent increase in maximum summer temperatures. Each of the seven U.S. regions is projected to experience differences in the amount and rate of warming, especially under RCP 8.5, which may result in especially intensified drought conditions in some locations due to a concomitant reduction in summer precipitation. Northern regions are generally expected to experience larger changes in maximum summer temperatures by century's end (tables 2.1–2.4) compared to southern regions (tables 2.5–2.7). But because the southern zones are already relatively hot, conditions in these locations could become very stressful for many organisms, including humans, at times when monthly average maximum summer temperatures reach 100.6–105.4 °F (see also Matthews et al. 2018). Thus, the "hot droughts" already documented in the Southwest (Allen et al. 2015) will be exacerbated there and may be observed in other parts of the Nation.

Cumulative Drought Severity and Moisture Severity Indices (CDSI/CMSI)

Monthly scPDSI values, used to derive the CDSI and CMSI, were examined as a percentage of each region's area experiencing five conditions under the four GCM-RCP scenarios: extreme drought (scPDSI <-3.9), severe drought (-3.9 to -3.0), moderate drought (-2.9 to -2.0), near-normal (-1.9 to 1.9), unusual moist spell (2.0 to 2.9), very moist spell (3.0 to 3.9), and extremely moist (>3.9) (fig. 2.2). Figure 2.2 shows changes in PDSI among the four 30-year periods, with increased drought conditions during the two later periods (2040–2069, 2070–2099) for all regions. Concomitantly, except for three regions (Northern Plains, Southwest, Southeast) under the WW scenario, all regions and scenarios showed a decline in cumulative moisture severity by end of the 21st century (tables 2.1–2.7). Although drought frequency and/or intensity is projected to increase regardless of scenario over this century, reductions to the near-normal and moisture surplus conditions varied regionally and by scenario. The two wet scenarios (WW, HW) retain the most near-normal conditions, whereas the two dry scenarios (HSD, HD) vary among near-normal and moisture surplus conditions (fig. 2.2).

The CDSI was derived by weighting the frequency of monthly self-calibrated PDSI values representing drought conditions as moderate (1), severe (2), and extreme (3). Projections indicate more frequent and/

Table 2.1—Midwest region summary (range, mean, and percentage change from current) of annual and summer (June/July/August) precipitation, mean summer maximum temperature, cumulative drought severity index, and cumulative moisture severity index, for four 30-year periods (1980–2009, 2010–2039, 2040–2069, 2070–2099)

MIDWEST															
Potential future condition[a]	Annual precipitation (in)			Summer precipitation (in)			Summer temperature (°F)			Cumulative drought severity index			Cumulative moisture severity index		
	RANGE	MEAN	% CHANGE	RANGE	MEAN	% CHANGE	RANGE	MEAN	% CHANGE	RANGE	MEAN (median)	% CHANGE	RANGE	MEAN (median)	% CHANGE
1980–2009															
WW	20–52	35.4		8–15	11.6		69.0–91.5	82.4		4–247	75 (74)		2–227	76 (68)	
HW	21–53	35.3		8–15	11.5		69.3–92.6	83.1		9–185	99 (99)		38–291	146 (145)	
HSD	21–53	35.2		8–15	11.4		69.5–92.5	83.3		1–174	71 (67)		49–307	168 (169)	
HD	19–52	36.3		8–16	12.2		69.6–91.8	82.8		0–30	4 (3)		39–340	180 (185)	
2010–2039															
WW	21–52	36.5	3.0	7–15	12.0	3.0	69.7–91.8	82.9	0.7	-105–250	50 (46)	66.5	-138–180	34 (48)	45.0
HW	22–50	36.4	3.2	7–15	11.1	-3.8	71.9–96.5	86.2	3.8	-141–50	-40 (-35)	-40.1	-203–155	-36 (-40)	-24.8
HSD	20–55	37.1	5.2	7–14	10.9	-4.1	72.4–97.3	87.1	4.6	-147–110	-31 (-37)	-43.7	-128–129	-40 (-45)	-24.0
HD	19–49	34.8	-4.1	7–15	10.9	-10.8	71.1–94.8	85.4	3.1	-12–61	9 (4)	225.5	-177–84	-62 (-65)	65.8
2040–2069															
WW	21–53	38.0	7.3	9–17	13.0	11.8	71.6–93.2	84.1	2.1	-163–147	32 (40)	42.7	-147–231	37 (36)	49.0
HW	19–55	37.3	5.8	7–14	10.0	-13.4	74.2–100.2	89.9	8.2	-106–308	26 (11)	26.2	-270–50	-83 (-84)	-57.0
HSD	20–49	35.3	0.2	5–12	8.5	-25.3	75.7–105.7	92.8	11.5	-65–283	59 (51)	82.2	-288–61	-128 (-133)	-76.2
HD	19–50	34.1	-5.9	6–14	10.2	-16.1	75.3–98.7	89.6	8.2	3–181	54 (45)	1,388.4	-305–24	-144 (-149)	-80.3
2070–2099															
WW	21–51	36.4	2.6	8–16	12.1	4.2	73.2–93.9	85.3	3.5	-97–244	98 (100)	131.5	-169–186	-3 (-1)	-4.2
HW	19–54	37.1	5.1	6–15	10.2	-11.5	77.2–101.7	92.3	11.1	-67–283	80 (77)	81.3	-279–37	-83 (-81)	-57.20
HSD	21–54	38.4	9.0	5–12	8.4	-26.1	81.8–108.8	98.4	18.1	-29–342	125 (115)	175.2	-305–35	-121 (-123)	-72.10
HD	20–50	33.0	-9.2	6–12	9.4	-23.1	80.5–105.0	95.1	14.9	185–404	289 (281)	7,383.8	-340– -16	-167 (-171)	-92.90

[a] Potential future conditions (represented by corresponding climate scenarios):
WW=warm-wet (MRI-CGCM3 4.5), HW=hot-wet (HadGEM2-ES365 4.5), HSD=hot-slightly dry (HadGEM2-ES365 8.5), and HD=hot-dry (IPSL-CM5A-MR 8.5).

Table 2.2—Northeast region summary (range, mean, and percentage change from current) of annual and summer (June/July/August) precipitation, mean summer maximum temperature, cumulative drought severity index, and cumulative moisture severity index, for four 30-year periods (1980–2009, 2010–2039, 2040–2069, 2070–2099)

NORTHEAST															
Potential future condition[a]	**Annual precipitation (in)**			**Summer precipitation (in)**			**Summer temperature (°F)**			**Cumulative drought severity index**			**Cumulative moisture severity index**		
	RANGE	MEAN	% CHANGE	RANGE	MEAN	% CHANGE	RANGE	MEAN	% CHANGE	RANGE	MEAN (median)	% CHANGE	RANGE	MEAN (median)	% CHANGE
1980–2009															
WW	32–89	46		9–23	13		59.5–88.3	79.0		22–174	88 (89)		15–323	109 (104)	
HW	31–86	45		8–22	13		59.9–88.8	79.5		1–178	55 (55)		29–266	127 (123)	
HSD	31–86	45		8–23	12		60.0–89.0	79.7		0–192	33 (26)		16–241	96 (85)	
HD	32–89	46		8–23	12		59.9–88.6	79.4		0–58	10 (7)		60–284	136 (129)	
2010–2039															
WW	32–90	47	2.0	8–22	12	-5.4	60.6–89.6	79.7	0.9	-108–167	2 (-14)	2.3	-248–123	0 (6)	-0.3
HW	32–91	47	3.4	8–26	13	5.7	62.4–91.4	82.5	3.8	-104–119	7 (4)	12.3	-193–85	-26 (-15)	-20.7
HSD	33–93	49	8.4	8–24	13	3.5	62.6–91.8	82.7	3.7	-101–30	-8 (-5)	-23.4	-97–219	33 (34)	34.4
HD	32–86	45	-0.8	9–24	13	6.4	62.1–90.8	81.6	2.7	-30–121	23 (18)	224.8	-128–63	-27 (-29)	-19.6
2040–2069															
WW	31–88	46	-0.1	7–21	12	-7.0	61.9–91.0	81.1	2.6	-102–238	75 (74)	84.9	-298–114	-56 (-59)	-51.9
HW	32–95	48	6.0	7–26	12	-1.8	65.4–94.8	85.8	7.9	-125–159	65 (76)	117.0	-226–73	-74 (-78)	-58.6
HSD	30–93	46	3.6	6–25	12	-3.9	67.2–99.3	87.9	10.3	-27–213	95 (99)	291.0	-229–48	-63 (-48)	-64.9
HD	33–91	47	3.0	8–24	13	5.4	65.8–93.9	85.2	7.3	31–157	91 (92)	886.4	-220–26	-64 (-56)	-46.8
2070–2099															
WW	33–93	47	2.5	8–23	12	-3.2	62.5–91.4	81.7	3.4	-42–207	57 (47)	64.6	-219–100	-14 (-12)	-12.8
HW	33–92	47	5.3	8–26	13	1.2	67.6–96.7	87.9	10.7	-8–222	112 (111)	202.4	-215–66	-79 (-72)	-62.0
HSD	34–99	50	11.8	7–27	12	-1.5	74.3–104.4	94.5	18.6	12–280	176 (178)	538.9	-232–58	-49 (-32)	-50.8
HD	33–94	48	4.7	8–24	12	0.4	70.2–99.0	90.1	13.4	97–349	210 (210)	2,033.8	-247–53	-93 (-86)	-68.7

[a] Potential future conditions (represented by corresponding climate scenarios):
WW=warm-wet (MRI-CGCM3 4.5), HW=hot-wet (HadGEM2-ES365 4.5), HSD=hot-slightly dry (HadGEM2-ES365 8.5), and HD=hot-dry (IPSL-CM5A-MR 8.5).

Table 2.3—Northern Plains region summary (range, mean, and percentage change from current) of annual and summer (June/July/August) precipitation, mean summer maximum temperature, cumulative drought severity index, and cumulative moisture severity index, for four 30-year periods (1980–2009, 2010–2039, 2040–2069, 2070–2099)

NORTHERN PLAINS															
Potential future condition[a]	Annual precipitation (in)			Summer precipitation (in)			Summer temperature (°F)			Cumulative drought severity index			Cumulative moisture severity index		
	RANGE	MEAN	% CHANGE	RANGE	MEAN	% CHANGE	RANGE	MEAN	% CHANGE	RANGE	MEAN (median)	% CHANGE	RANGE	MEAN (median)	% CHANGE
							1980–2009								
WW	5–106	18.8		2–14	6.6		53.2–90.9	80.8		20–230	118 (122)		5–176	61 (61)	
HW	5–106	19.3		2–15	6.6		54.3–91.4	81.0		1–165	54 (46)		18–197	83 (77)	
HSD	5–107	19.2		1–15	6.6		54.5–91.5	81.1		0–154	47 (33)		8–237	82 (75)	
HD	5–104	19.1		2–15	6.4		54.6–91.5	82.0		0–110	18 (12)		7–266	86 (79)	
							2010–2039								
WW	5–106	19.2	2.2	2–14	6.8	1.9	54.9–91.7	81.9	1.4	-120–184	14 (10)	12.3	-98–97	-12 (-14)	-19.4
HW	6–104	20.7	7.4	2–14	6.8	2.4	57.7–94.4	84.4	4.2	-129–134	19 (24)	34.6	-141–177	22 (14)	26.9
HSD	6–110	21.3	10.6	2–14	7.0	5.7	57.1–95.0	84.6	4.2	-98–95	9 (8)	19.3	-174–163	36 (37)	43.6
HD	6–105	19.4	1.2	2–14	6.6	2.5	56.3–94.2	84.2	2.6	-34–84	16 (13)	88.4	-140–124	2 (3)	2.2
							2040–2069								
WW	6–104	19.9	5.8	2–15	7.0	5.8	55.6–92.5	82.6	2.2	-119–196	30 (32)	25.7	-111–122	5 (4)	8.1
HW	5–112	20.3	5.2	2–13	5.9	-10.3	60.7–97.4	87.8	8.5	-83–243	107 (108)	198.3	-164–79	-26 (-16)	-31.5
HSD	6–111	20.3	5.5	1–11	5.4	-18.3	62.9–100.2	90.1	11.0	-31–194	90 (92)	190.3	-189–57	-46 (-40)	-56.1
HD	5–113	18.7	-2.5	2–13	5.5	-13.8	61.3–99.3	89.0	8.6	3–190	77 (72)	430.3	-239–64	-64 (-58)	-74.8
							2070–2099								
WW	6–109	20.3	8.0	2–14	6.9	4.3	56.8–93.7	83.8	3.6	-137–204	39 (42)	32.8	-106–159	24 (24)	39.4
HW	5–113	20.2	4.9	1–12	5.5	-16.3	62.6–98.5	90.0	11.1	-37–351	155 (160)	288.2	-182–75	-47 (-44)	-57.0
HSD	5–112	21.1	9.6	1–10	4.7	-28.7	69.0–106.8	96.4	18.9	7–377	222 (243)	470.5	-237–91	-53 (-49)	-64.8
HD	5–113	18.6	-2.6	1–16	5.8	-10.1	65.7–104.6	93.3	13.8	33–476	271 (259)	1,510.8	-256–42	-71 (-64)	-82.8

[a] Potential future conditions (represented by corresponding climate scenarios):
WW=warm-wet (MRI-CGCM3 4.5), HW=hot-wet (HadGEM2-ES365 4.5), HSD=hot-slightly dry (HadGEM2-ES365 8.5), and HD=hot-dry (IPSL-CM5A-MR 8.5).

Table 2.4—Northwest region summary (range, mean, and percentage change from current) of annual and summer (June/July/August) precipitation, mean summer maximum temperature, cumulative drought severity index, and cumulative moisture severity index for four 30-year periods (1980–2009, 2010–2039, 2040–2069, 2070–2099)

NORTHWEST															
Potential future condition[a]	Annual precipitation (in)			Summer precipitation (in)			Summer temperature (°F)			Cumulative drought severity index			Cumulative moisture severity index		
	RANGE	MEAN	% CHANGE	RANGE	MEAN	% CHANGE	RANGE	MEAN	% CHANGE	RANGE	MEAN (median)	% CHANGE	RANGE	MEAN (median)	% CHANGE
	1980–2009														
WW	6–249	34.8		1–17	3.5		39.9–91.8	77.3		4–155	65 (64)		12–242	104 (102)	
HW	6–239	33.1		1–18	3.3		40.0–92.7	77.7		11–169	78 (75)		18–209	89 (87)	
HSD	6–241	33.1		1–17	3.0		39.9–92.8	77.7		1–204	59 (60)		20–216	105 (107)	
HD	7–247	35.0		1–18	3.7		40.1–93.0	78.1		0–190	21 (17)		15–294	123 (120)	
	2010–2039														
WW	6–247	34.6	-0.7	1–19	3.8	9.7	40.8–93.3	78.4	1.5	-110–108	11 (10)	17.2	-206–109	-35 (-35)	-34.3
HW	7–243	34.4	3.9	1–16	3.0	-7.1	43.5–96.2	81.2	4.5	-138–80	-30 (-31)	-38.7	-130–96	-28 (-35)	-31.7
HSD	7–247	35.9	8.5	1–15	3.0	-1.7	44.1–95.9	81.5	4.8	-170–113	-33 (-35)	-55.6	-197–148	-18 (-25)	-17.6
HD	7–247	35.1	0.4	1–18	4.0	9.0	42.6–94.8	80.3	2.8	-115–176	34 (26)	163.5	-175–74	-32 (-31)	-26.0
	2040–2069														
WW	7–255	34.8	-0.1	1–18	3.6	3.0	42.0–94.6	79.6	3.0	-41–190	62 (62)	95.1	-189–89	-29 (-30)	-27.6
HW	6–253	34.9	5.5	1–13	2.7	-16.6	47.1–99.6	84.6	8.8	-98–140	38 (39)	48.9	-184–87	-32 (-31)	-36.4
HSD	7–257	34.8	5.2	1–14	2.4	-21.2	48.2–101.9	86.4	11.2	-144–196	41 (40)	70.5	-188–114	-68 (-67)	-65.2
HD	7–266	37.1	6.0	1–17	3.5	-4.2	46.6–99.8	84.6	8.3	-135–178	54 (52)	259.4	-253–185	-56 (-56)	-45.4
	2070–2099														
WW	6–256	35.0	0.4	1–19	3.6	2.1	43.1–95.5	80.6	4.3	-35–230	89 (92)	136.2	-210–104	-24 (-24)	-22.7
HW	7–263	35.4	7.0	1–13	2.9	-10.9	48.3–101.6	86.4	11.2	-123–308	132 (130)	169.6	-165–169	-17 (-16)	-19.1
HSD	7–240	34.4	4.0	0–11	2.2	-28.8	54.6–108.2	92.9	19.6	-148–355	185 (180)	316.3	-210–218	-75 (-83)	-72.2
HD	8–257	36.8	5.0	1–20	3.9	7.5	50.3–103.9	88.5	13.3	-116–306	185 (190)	894.1	-269–126	-59 (-53)	-47.6

[a] Potential future conditions (represented by corresponding climate scenarios):
WW=warm-wet (MRI-CGCM3 4.5), HW=hot-wet (HadGEM2-ES365 4.5), HSD=hot-slightly dry (HadGEM2-ES365 8.5), and HD=hot-dry (IPSL-CM5A-MR 8.5).

Table 2.5—Southeast region summary (range, mean, and percentage change from current) of annual and summer (June/July/August) precipitation, mean summer maximum temperature, cumulative drought severity index, and cumulative moisture severity index for four 30-year periods (1980–2009, 2010–2039, 2040–2069, 2070–2099)

SOUTHEAST															
Potential future condition[a]	Annual precipitation (in)			Summer precipitation (in)			Summer temperature (°F)			Cumulative drought severity index			Cumulative moisture severity index		
	RANGE	MEAN	% CHANGE	RANGE	MEAN	% CHANGE	RANGE	MEAN	% CHANGE	RANGE	MEAN (median)	% CHANGE	RANGE	MEAN (median)	% CHANGE
1980–2009															
WW	36–95	52.4		8–29	14.5		69.7–93.7	89.5		16–256	103 (106)		0–253	83 (82)	
HW	37–93	51.1		9–29	13.7		70.6–94.9	90.5		4–270	91 (87)		18–272	120 (114)	
HSD	36–93	50.8		9–29	13.8		70.7–95.0	90.5		1–216	62 (54)		5–240	117 (113)	
HD	36–96	53.0		8–30	14.4		70.3–94.1	89.8		0–173	19 (7)		54–255	138 (130)	
2010–2039															
WW	36–94	53.0	1.2	8–32	14.6	0.6	70.4–94.5	90.1	0.6	-113–153	8 (8)	7.9	-169–146	-10 (-15)	-11.8
HW	37–93	50.7	-0.8	7–30	13.4	-1.8	73.9–98.5	93.7	3.6	-153–127	-6 (-8)	-6.2	-200–108	-54 (-51)	-44.9
HSD	40–105	55.5	9.1	8–30	14.2	3.1	74.2–98.7	93.8	3.7	-171–119	-10 (-6)	-17.0	-155–246	45 (47)	39.0
HD	36–91	49.8	-6.0	8–30	14.2	-1.4	72.6–97.0	92.2	2.6	-119–95	33 (39)	172.9	-188–41	-72 (-65)	-52.1
2040–2069															
WW	39–98	54.7	4.5	9–33	15.5	7.0	71.8–95.8	91.3	2.1	-149–147	19 (23)	18.8	-170–155	9 (15)	10.5
HW	38–104	53.5	4.7	6–30	12.4	-9.1	77.0–101.4	96.6	6.8	-105–240	53 (54)	58.4	-191–87	-37 (-33)	-30.7
HSD	36–96	48.7	-4.1	4–26	10.6	-22.9	81.0–106.6	100.6	11.2	-34–296	120 (122)	195.1	-225–58	-86 (-80)	-73.4
HD	36–92	48.5	-8.6	8–29	14.5	0.3	75.4–100.9	95.3	6.2	-72–221	110 (111)	572.5	-224–74	-72 (-61)	-52.6
2070–2099															
WW	37–101	55.8	6.6	8–35	15.1	3.9	72.1–96.3	91.8	2.6	-187–229	12 (-9)	11.9	-194–203	30 (36)	35.9
HW	37–104	53.9	5.4	6–27	12.5	-8.5	78.1–101.9	97.7	8.0	-63–278	51 (44)	56.7	-209–112	-49 (-41)	-40.9
HSD	37–99	51.1	0.4	5–23	10.5	-23.6	85.2–109.2	103.9	14.8	-63–352	154 (156)	250.1	-227–34	-93 (-86)	-79.7
HD	33–85	45.5	-14.1	7–30	13.2	-8.6	80.5–106.7	100.6	12.0	65–452	305 (319)	1,587.2	-253–19	-117 (-110)	-85.0

[a] Potential future conditions (represented by corresponding climate scenarios):
WW=warm-wet (MRI-CGCM3 4.5), HW=hot-wet (HadGEM2-ES365 4.5), HSD=hot-slightly dry (HadGEM2-ES365 8.5), and HD=hot-dry (IPSL-CM5A-MR 8.5).

Table 2.6—Southern Plains region summary (range, mean, and percentage change from current) of annual and summer (June/July/August) precipitation, mean summer maximum temperature, cumulative drought severity index, and cumulative moisture severity index for four 30-year periods (1980–2009, 2010–2039, 2040–2069, 2070–2099)

SOUTHERN PLAINS															
Potential future condition[a]	Annual precipitation (in)			Summer precipitation (in)			Summer temperature (°F)			Cumulative drought severity index			Cumulative moisture severity index		
	RANGE	MEAN	% CHANGE	RANGE	MEAN	% CHANGE	RANGE	MEAN	% CHANGE	RANGE	MEAN (median)	% CHANGE	RANGE	MEAN (median)	% CHANGE
							1980–2009								
WW	8–68	29.6		4–17	8.7		74.5–102.8	93.0		23–260	127 (128)		12–166	81 (81)	
HW	8–67	29.1		3–17	8.1		75.4–103.3	93.8		60–254	137 (136)		3–182	86 (90)	
HSD	8–67	28.6		3–16	8.3		75.4–103.3	93.7		48–238	127 (126)		11–186	93 (94)	
HD	9–69	30.6		4–20	9.7		74.7–102.4	93.0		0–69	20 (17)		63–278	163 (162)	
							2010–2039								
WW	8–69	30.0	1.2	4–20	9.5	9.3	75.4–103.7	93.7	0.8	-130–130	11 (12)	8.3	-144–131	-38 (-41)	-47.0
HW	8–66	30.1	3.5	3–16	7.8	-3.7	77.7–105.7	96.3	2.7	-150–43	-63 (-65)	-46.0	-125–130	-7 (-4)	-7.8
HSD	7–75	30.6	7.1	3–16	7.9	-5.3	78.8–106.7	97.1	3.6	-174–103	-39 (-32)	-30.7	-95–102	-5 (-6)	-5.4
HD	8–61	26.2	-14.6	3–16	8.0	-16.8	77.6–106.8	96.3	3.6	-2–143	50 (47)	253.4	-255–36	-119 (-122)	-73.0
							2040–2069								
WW	8–72	31.8	7.6	4–22	10.3	18.8	77.8–105.4	95.2	2.4	-116–184	32 (31)	25.0	-80–133	9 (4)	11.3
HW	8–71	29.5	1.4	3–15	7.5	-7.8	79.3–107.1	98.6	5.2	-98–163	37 (43)	27.0	-150–71	-36 (-36)	-41.8
HSD	8–60	26.8	-6.2	3–14	5.8	-31.0	81.8–109.5	101.6	8.4	-21–280	131 (134)	102.8	-162–83	-63 (-73)	-67.6
HD	6–52	23.6	-23.1	3–15	7.4	-23.3	82.4–110.3	100.3	7.9	80–307	156 (152)	783.4	-254–-36	-140 (-139)	-85.5
							2070–2099								
WW	10–68	31.3	5.7	4–19	9.5	10.2	76.9–105.5	95.7	2.9	-127–242	7 (3)	5.6	-128–134	-11 (-13)	-13.7
HW	9–72	31.2	7.3	4–17	8.1	-0.9	80.3–107.1	99.2	5.8	-139–144	1 (2)	1.0	-143–128	-16 (-20)	-18.9
HSD	8–67	29.9	4.6	4–15	6.8	-18.4	85.0–112.5	103.9	10.9	-108–253	57 (48)	44.6	-153–74	-43 (-37)	-46.0
HD	4–48	21.1	-31.0	2–13	6.4	-33.6	88.9–116.2	105.7	13.8	293–551	430 (433)	2,161.4	-277–-63	-158 (-155)	-97.0

[a] Potential future conditions (represented by corresponding climate scenarios):
WW=warm-wet (MRI-CGCM3 4.5), HW=hot-wet (HadGEM2-ES365 4.5), HSD=hot-slightly dry (HadGEM2-ES365 8.5), and HD=hot-dry (IPSL-CM5A-MR 8.5).

Table 2.7—Southwest region summary (range, mean, and percentage change from current) of annual and summer (June/July/August) precipitation, mean summer maximum temperature, cumulative drought severity index, and cumulative moisture severity index for four 30-year periods (1980–2009, 2010–2039, 2040–2069, 2070–2099)

SOUTHWEST															
Potential future condition[a]	Annual precipitation (in)			Summer precipitation (in)			Summer temperature (°F)			Cumulative drought severity index			Cumulative moisture severity index		
	RANGE	MEAN	% CHANGE	RANGE	MEAN	% CHANGE	RANGE	MEAN	% CHANGE	RANGE	MEAN (median)	% CHANGE	RANGE	MEAN (median)	% CHANGE
	1980–2009														
WW	3–166	16.5		0–17	3.5		51.7–114.2	86.8		24–308	143 (134)		2–189	65 (61)	
HW	2–159	16.0		0–15	3.0		52.0–114.8	87.6		4–342	126 (120)		6–193	63 (60)	
HSD	2–156	15.6		0–14	2.8		51.9–114.8	87.6		0–331	106 (96)		6–178	61 (59)	
HD	3–168	17.2		0–19	3.7		52.3–114.7	87.5		0–186	20 (6)		2–261	90 (88)	
	2010–2039														
WW	3–158	17.0	3.2	0–17	3.4	-2.8	52.8–115.8	88.0	1.4	-239–137	-15 (-9)	-10.4	-137–123	10 (11)	14.8
HW	3–165	17.1	6.9	0–15	3.1	5.1	55.5–117.5	90.4	3.2	-113–161	12 (13)	9.3	-86–158	25 (25)	38.6
HSD	3–175	17.6	13.0	0–14	3.0	7.9	55.7–117.6	90.8	3.6	-234–132	-21 (-20)	-20.1	-102–161	27 (25)	44.0
HD	3–163	17.9	4.0	0–19	4.1	10.2	54.3–116.5	89.4	2.1	-103–177	13 (5)	67.3	-113–142	19 (20)	21.0
	2040–2069														
WW	3–163	16.9	2.3	0–16	3.5	-1.7	53.9–116.9	89.4	2.9	-117–267	52 (48)	36.6	-153–109	-4 (-2)	-5.5
HW	3–159	16.8	4.7	0–19	3.1	5.1	58.3–119.7	92.8	6.0	-148–221	34 (40)	26.8	-153–79	-18 (-17)	-28.7
HSD	2–156	15.5	-0.3	0–14	2.8	-0.9	59.8–121.2	94.8	8.1	-75–277	100 (107)	95.1	-153–57	-34 (-32)	-55.4
HD	3–167	15.5	-9.7	0–12	2.8	-23.9	58.2–121.1	94.3	7.8	-42–298	124 (117)	629.1	-247–90	-56 (-54)	-62.6
	2070–2099														
WW	3–161	18.3	11.0	0–22	3.9	10.6	55.2–117.9	89.9	3.6	-209–184	-31 (-27)	-21.6	-152–155	8 (8)	12.8
HW	3–157	17.2	7.2	0–18	3.2	9.3	59.5–121.0	93.9	7.2	-165–307	58 (62)	45.6	-144–129	-9 (-8)	-13.8
HSD	3–163	17.4	11.8	0–15	3.1	9.5	63.4–124.7	98.4	12.3	-104–387	124 (119)	117.2	-155–193	-23 (-25)	-37.0
HD	3–168	15.0	-13.0	0–8	1.8	-50.0	61.5–124.5	98.5	12.6	-56–615	304 (284)	1,541.7	-261–92	-64 (-67)	-71.7

[a] Potential future conditions (represented by corresponding climate scenarios):
WW=warm-wet (MRI-CGCM3 4.5), HW=hot-wet (HadGEM2-ES365 4.5), HSD=hot-slightly dry (HadGEM2-ES365 8.5), and HD=hot-dry (IPSL-CM5A-MR 8.5).

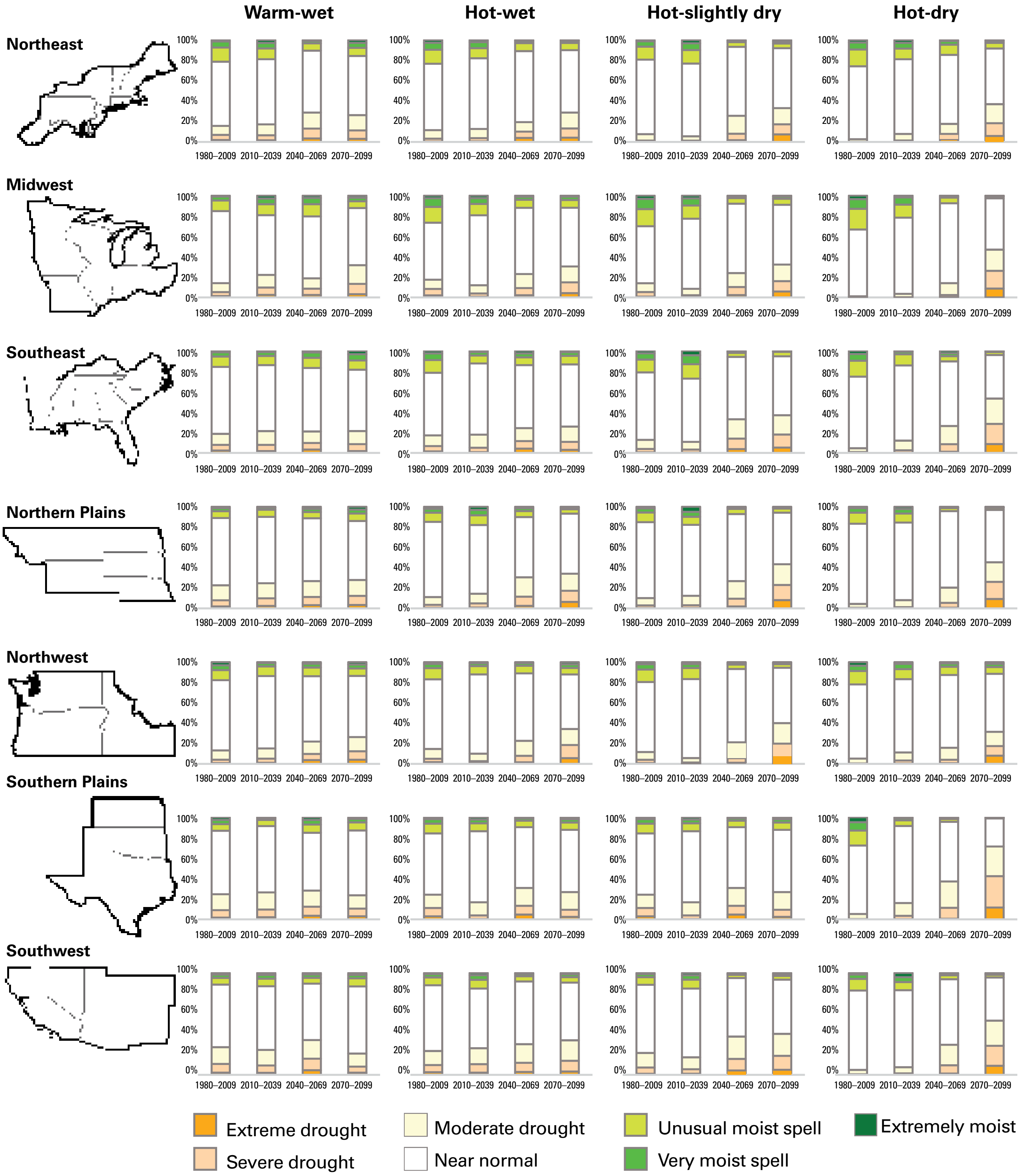

Figure 2.2—Palmer Drought Severity Index (PDSI) as the percentage of a 30-year period by area of each National Climate Assessment region, under four climate change scenarios (see text). Scenarios: warm-wet (WW), hot-wet (HW), hot-slightly dry (HSD), hot-dry (HD). Dates: historical (1980–2009), early century (2010–2039), mid-century (2040–2069), and late century (2070–2099).

or intense drought conditions in the conterminous United States by the end of the 21st century under all four GCM-RCP scenarios (tables 2.1–2.7). Compared to the baseline period, many regions could experience little change in droughts during 2010–2039, even under the two dry scenarios (HSD, HD) (figs. 2.5 and 2.6). However, CDSI values are projected to increase by middle to late century in all regions. Under the WW scenario, regional changes in CDSI in the first period (1980–2009) show either little change or some decreases (i.e., less drought), except in the Southern Plains and Southwest (fig. 2.3). Nevertheless, under all four GCM-RCP scenarios, the three later periods (2010–2039, 2040–2069, 2070–2099) project increases as much as <2 to thirteenfold by 2070 and <2 to seventy-threefold by 2100 with the HD scenario resulting in CDSI values much greater than twofold. The only exception is for the Southwest, which shows less drought in 2070–2099 under the WW scenario, despite sizeable increases in CDSI under the other three scenarios (tables 2.1–2.7). Under the two dry scenarios (HSD, HD), all regions show comparatively larger potential increases of CDSI for mid-century under the HSD scenario and for late century under the HD scenario, both indicating more drought if humans do not curtail greenhouse gas emissions.

The CMSI is the inverse of CDSI, weighting the frequency of monthly conditions with excess soil moisture. CMSI generally shows a lessening of excessive moisture conditions throughout the 21st century under the HW, HSD, and HD scenarios. However, the Midwest, Northeast, Northern Plains, and Southeast are projected to experience slight increases in the frequency and/or intensity of excess moisture conditions during the first period (1980–2009) (figs. 2.3–2.6), but stark reductions for the rest of the century (2010–2039, 2040–2069, and 2070–2099). Three regions could experience little change throughout the century: higher CMSI values for the WW scenario in the Northern Plains, Southeast, and Southwest. However, averaged across all regions, CMSI values are projected to decrease under all four scenarios by the end of the century.

DISCUSSION

Evaluating downscaled climate projections is a widely used practice to help inform management decisions and develop policies. However, uncertainties are associated with the GCMs, RCPs, and downscaling methods, and these must be considered when interpreting such data. Therefore, the model results and trends presented here are a guide, not precise trajectories. Nonetheless, the four GCM-RCP scenarios used in this evaluation represent bookends between warmer-to-hot and drier-to-wetter conditions. All scenarios show increasing maximum summer temperatures, sometimes by up to 15 °F.

Precipitation estimates are more uncertain in the climate models. For example, under the HSD scenario, the largest increases in annual precipitation are projected for the Northeast and Southwest regions during the last 30 years of the 21st century (2070–2099); this same scenario projects the lowest increases in annual precipitation in the Northwest and Southeast during the same period. All models suggest that important seasonal shifts in precipitation are likely, especially less precipitation during the summer months. Coupled with warmer summer temperatures, less summer precipitation could intensify and prolong physiological drought conditions, leading to additional tree mortality due to “hot droughts” (Allen et al. 2015).

Drought Projections

Based on projections from four GCM-RCP scenarios, the conterminous United States could experience much warmer temperatures and seasonal reductions in precipitation. The CDSI suggests that more frequent and/or intense droughts are likely in the middle to latter parts of the 21st century. Compared to the baseline period of 1980–2009, the 2010–2039 period shows little of the widespread increase in CDSI projected by the end of the century. Some regions may even experience fewer or less intense droughts during this period due to projected increases in precipitation. However, all regions show marked increases in drought conditions after 2040.

The models presented here use the process-based Penman-Monteith method to calculate PET. Although this method is less biased than others (Milly and Dunne 2017), it could show increasing uncertainty into the future because several of the underlying parameters (e.g., relative humidity, vapor pressure deficit) are modeled with uncertainty and at broad spatial scales. Therefore, these projections of CDSI also carry increasing uncertainty as we move into the latter decades of this century. Using four GCM-RCP scenarios, we have presented a range of possible drought conditions for the rest of the century. Regardless of scenario or region, however, drought conditions are likely to increase spatially and temporally.

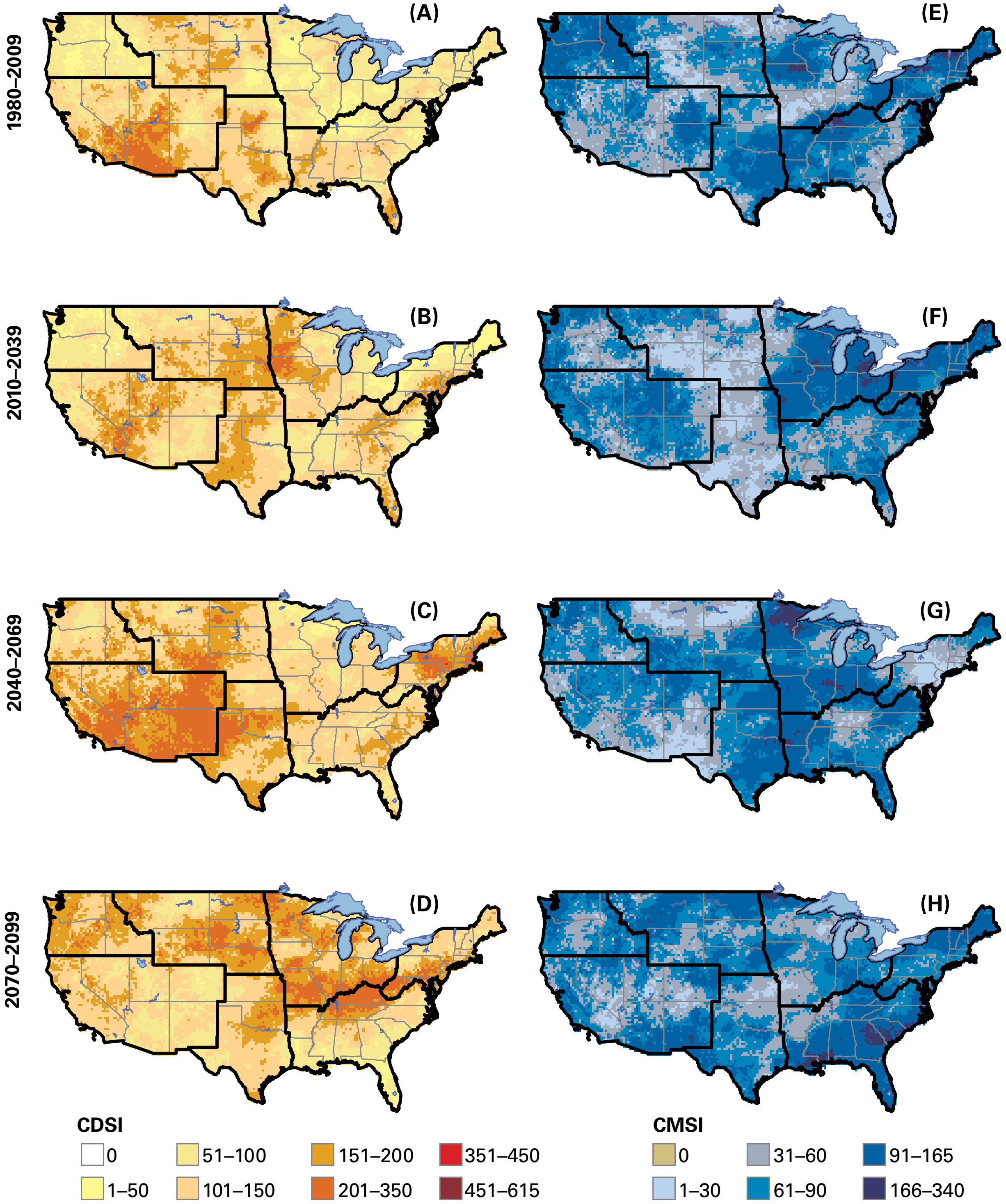

Figure 2.3—Cumulative drought severity index (CDSI) (A–D) and cumulative moisture severity index (CMSI) (E–H), derived from self-calibrated Palmer Drought Severity Index values calculated for the warm-wet (WW, MRI-CGCM3 4.5) scenario (see text). Changes in drought and moisture surplus, respectively, are shown for four 30-year periods: 1980–2009 (A,E), 2010–2039 (B,F), 2040–2069 (C,G), and 2070–2099 (D,H). National Climate Assessment regions are outlined in bold.

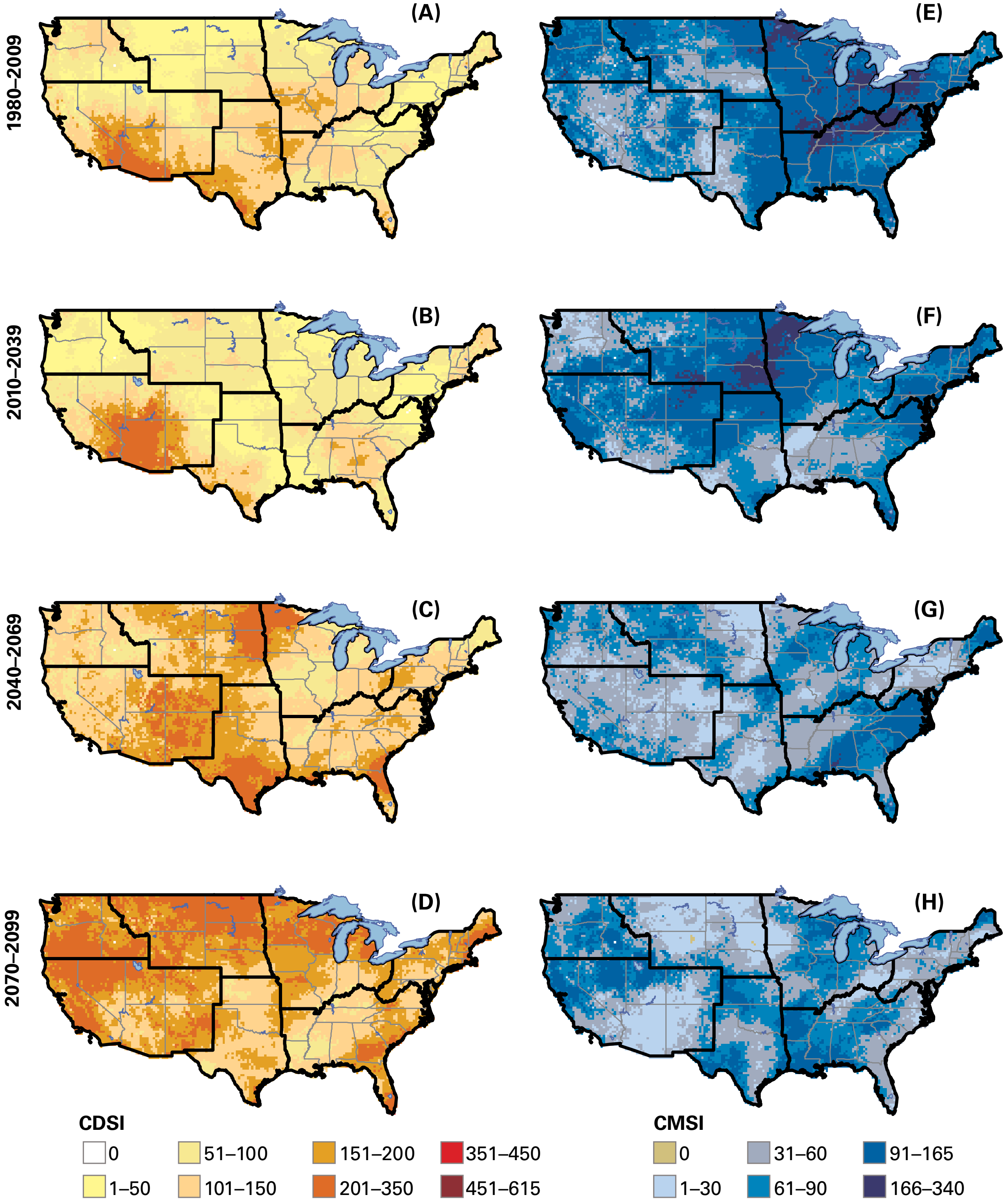

Figure 2.4—Cumulative drought severity index (CDSI) (A–D) and cumulative moisture severity index (CMSI) (E–H), derived from self-calibrated Palmer Drought Severity Index values calculated for the hot-wet (HW, HadGEM2-ES365 4.5) scenario (see tables). Changes in drought and moisture surplus, respectively, are shown for four 30-year periods: 1980–2009 (A,E), 2010–2039 (B,F), 2040–2069 (C,G), and 2070–2099 (D,H). National Climate Assessment regions are outlined in bold.

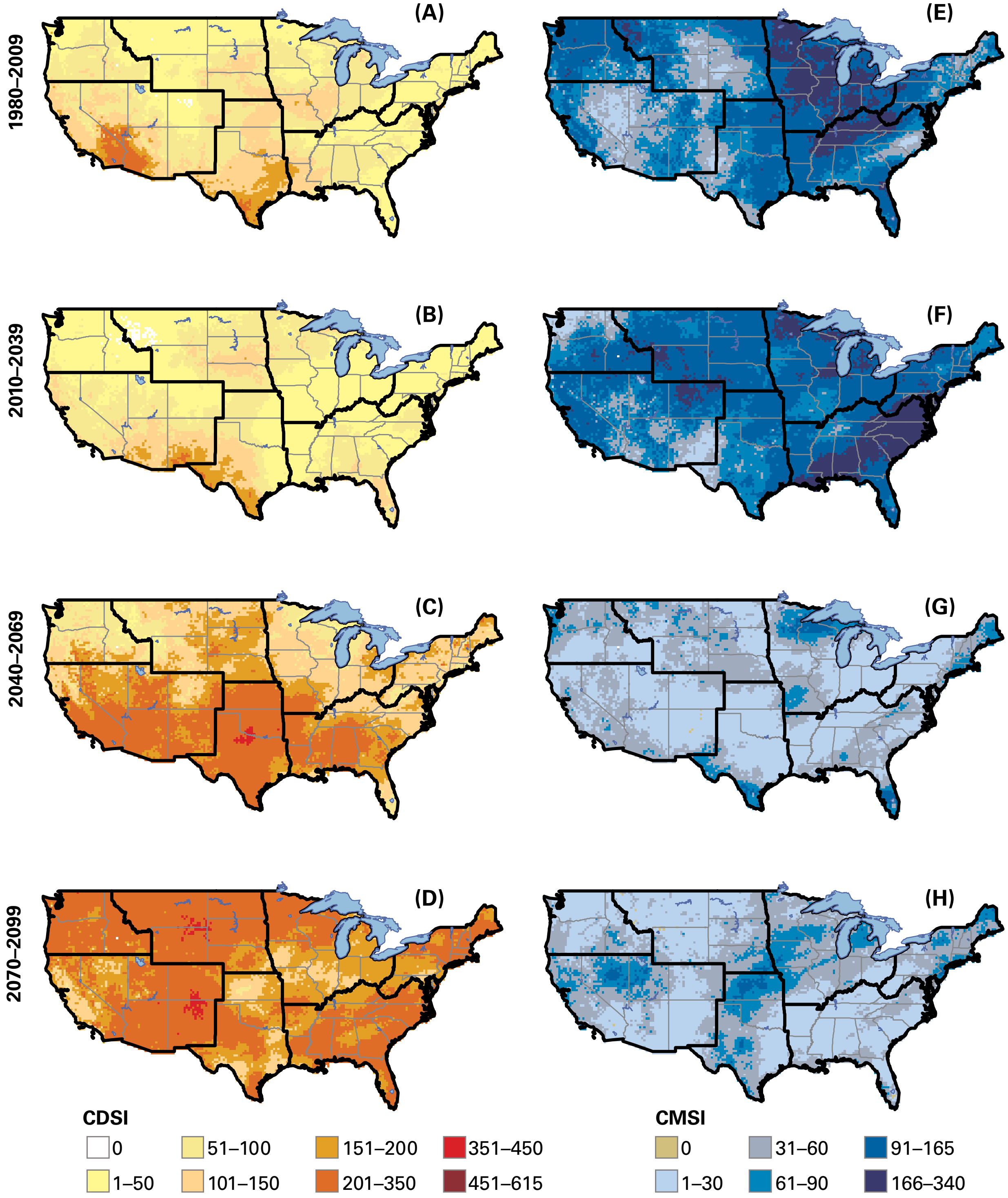

Figure 2.5—Cumulative drought severity index (CDSI) (A–D) and cumulative moisture severity index (CMSI) (E–H), derived from self-calibrated Palmer Drought Severity Index values calculated for the hot-slightly dry (HSD, HadGEM2-ES365 8.5) scenario (see tables). Changes in drought and moisture surplus, respectively, are shown for four 30-year periods: 1980–2009 (A,E), 2010–2039 (B,F), 2040–2069 (C,G), and 2070–2099 (D,H). National Climate Assessment regions are outlined in bold.

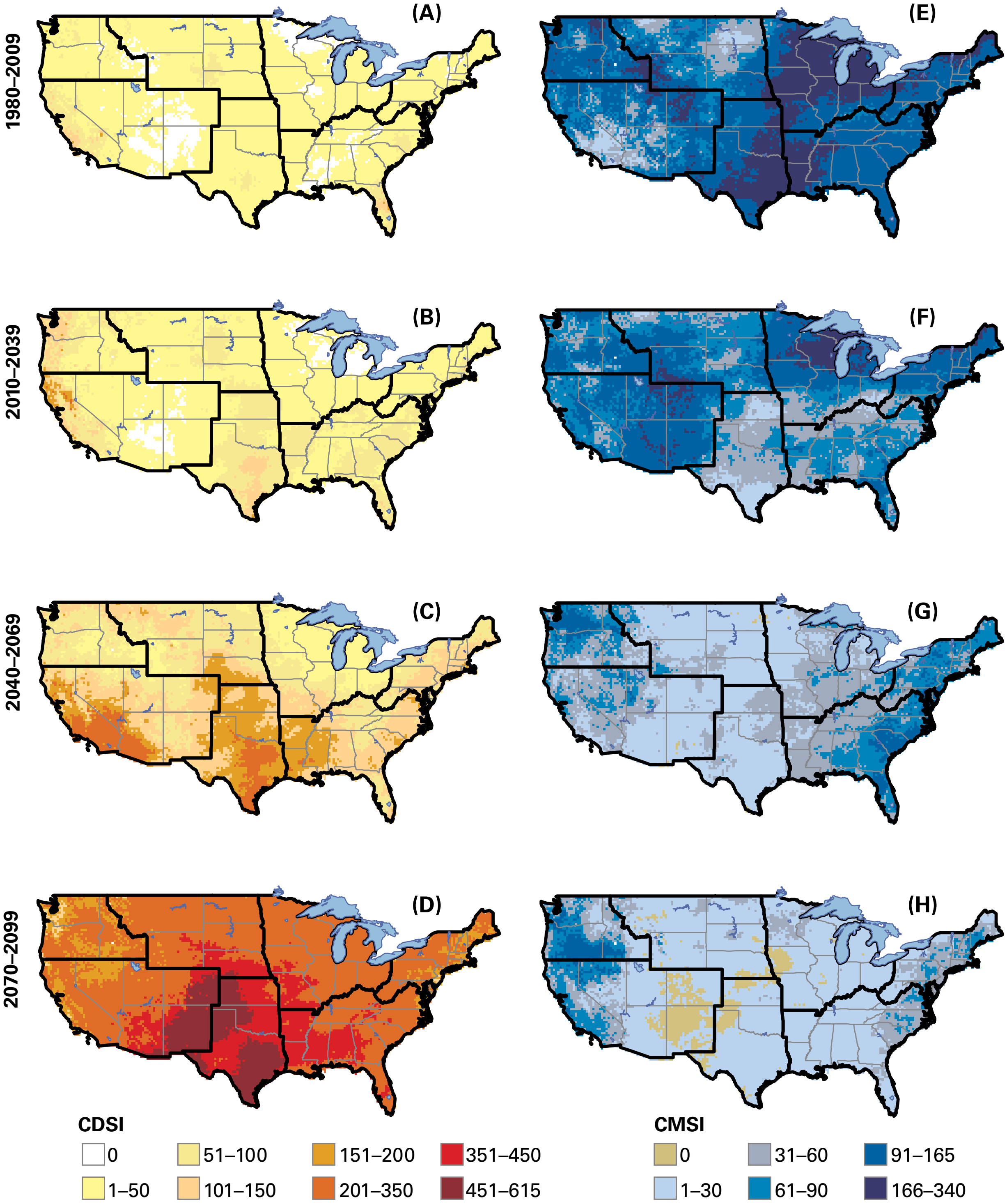

Figure 2.6—Cumulative drought severity index (CDSI) (A–D) and cumulative moisture severity index (CMSI) (E–H), derived from self-calibrated Palmer Drought Severity Index values calculated for the hot-dry (HD, IPSL-CM5A-MR 8.5) scenario (see text). Changes in drought and moisture surplus, respectively, are shown for four 30-year periods: 1980–2009 (A,E), 2010–2039 (B,F), 2040–2069 (C,G), and 2070–2099 (D,H). National Climate Assessment regions are outlined in bold.

Effects on Forests and Grasslands

Much of the literature on meteorological droughts focuses on soil moisture conditions within the top few inches, which is essential for shallow-rooted species, especially agricultural crops. However, the effects of drought differ for deep-rooted species such as trees and some grassland species. Therefore, it is important to consider a deeper soil moisture profile when parameterizing drought indices. We have attempted to address this issue by using a deeper soil horizon for soil-available water supply, but additional modifications may be necessary for this and other indices. The ability of trees to access water in deeper horizons during droughts is critical for survival.

Stress from drought can compound increased stress from other sources (e.g., competitors, disease, fire, pests), reducing the ability of trees to cope with overall physiological stress (Allen et al. 2015, Clark et al. 2016, Luce et al. 2016) and potentially resulting in the Manion decline spiral (Manion 1991). For example, the effects of drought and bark beetles on tree stress are well understood in the Western and Southeastern United States (Kolb et al. 2016). However, little is known about how forest composition in the Eastern United States might be affected by drought combined with insect outbreaks (e.g., Asian longhorned beetle [*Anoplophora glabripennis*], emerald ash borer [*Agrilus planipennis*], gypsy moth [*Lymantria dispar*], hemlock woolly adelgid [*Adelges tsugae*], mountain pine beetle [*Dendroctonus ponderosae*], southern pine beetle [*D. frontalis*]) and pathogens (e.g., oak wilt [*Ceratocystis fagacearum*], sudden oak death [*Phytophthora ramorum*], white pine blister rust [*Cronartium ribicola*]). Increasing numbers of nonnative species add to stress in native forests because nonnatives are often more competitive than natives during drought conditions. Although effects of drought on ecosystems in arid to semiarid regions of the Western United States have been well documented (Pederson et al. 2014), more droughts in the temperate Eastern United States in the future may produce novel climatic conditions and unknown effects on forests.

Concentrations of atmospheric CO_2 are expected to increase during the 21st century, although plant species responses over large regions to such increases is uncertain (Allen et al. 2015, Swann et al. 2016). This uncertainty can also influence the amount and even the direction of change for species evaluated in vulnerability assessments, depending on the metrics used to define drought conditions and the role of CO_2 enrichment in the analysis (Burke and Brown 2007, Swann et al. 2016).

Evaluation of GCM projections—Time will tell whether GCM projections are accurate, but regardless of the outcome, resource managers can make better informed decisions by examining a range of potential scenarios. The projections presented here include ranges of warming and wetting that are within the bounds of other model ensembles. Diversity of species composition and structure can help to reduce the overall effects of drought on forests (Clark et al. 2016). Therefore, evaluations of GCM projections should not only focus on how disturbances may change, but also consider which species might be favored by newly suitable habitat or increased resources (Iverson et al. 2008, 2011, 2017; Matthews et al. 2011).

Long-term soil moisture data—Some drought indices require information related to soil moisture, and spatial datasets related to soil characteristics are improving and becoming more available. Because of completeness and computational issues, we chose to use the older, coarse-level STATSGO data for the conterminous United States evaluation, and we found that it does not heavily influence the regional calculations of PDSI and CDSI/CMSI. This dataset does not provide long-term measures of soil moisture. Satellite-based imagery of soil moisture conditions can help to identify trends from around 1980 to the present (Nicolai-Shaw et al. 2017), but these data are of limited value in highly vegetated regions and represent only a series of snapshots along a timeline.

CONCLUSIONS

Analyzing future projections of drought under multiple climate change scenarios can provide insights on how regional temperatures, precipitation, and drought may change throughout this century, compared to baseline conditions of the period 1980–2009. The projections often show minimal changes in the next few decades, followed by large changes in the second half of the century. These changes will likely negatively affect plant growth and survival, leading to changes in forest composition and structure. These expected changes are larger under the two dry scenarios, especially the hot-dry scenario, emphasizing the value of reducing greenhouse gas emissions.

These projections of drought, considered in light of the model's uncertainties, can help managers prioritize strategies that may allow ecosystems to adapt to newer conditions. Forest management activities have the ability to shape the next forest over the course of this century, and the effects of different climate conditions must be considered to ensure that management goals are achieved.

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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

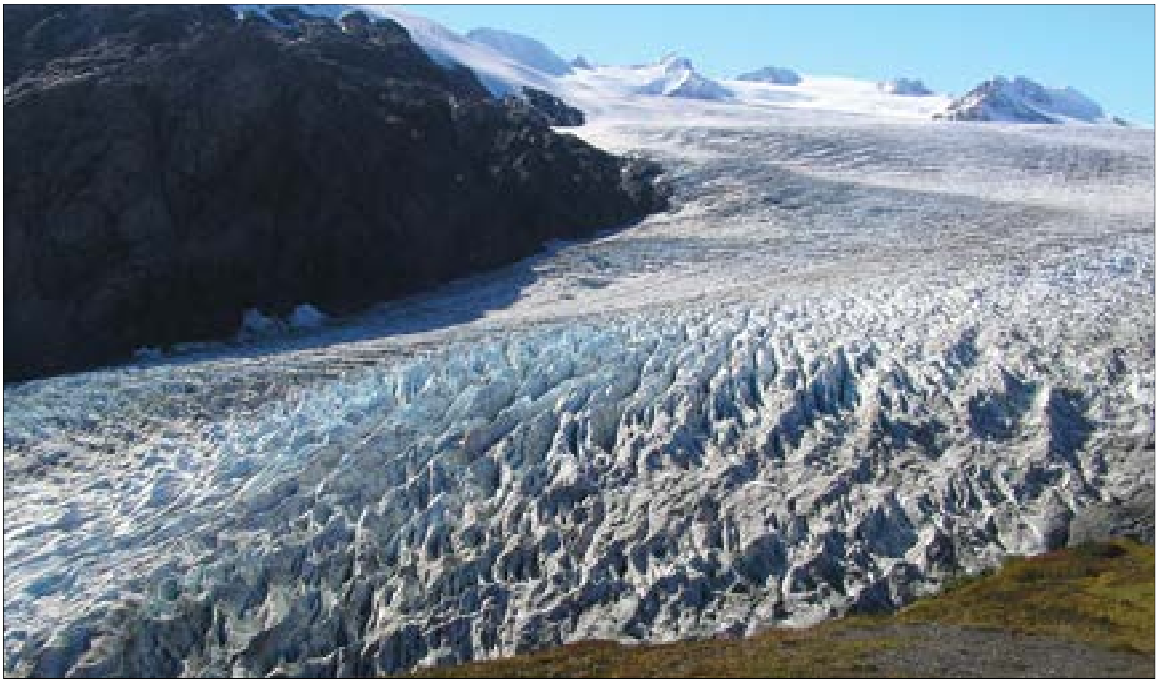

Figure 3.1—Exit Glacier (Kenai Fjords National Park) is an iconic example of the ongoing retreat of glacial ice in southern Alaska. Note recently exposed rock and soil in the foreground that has become vegetated. (Photo from https://commons.wikimedia.org/wiki/File:1055_-_exit_glacier.jpg)

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

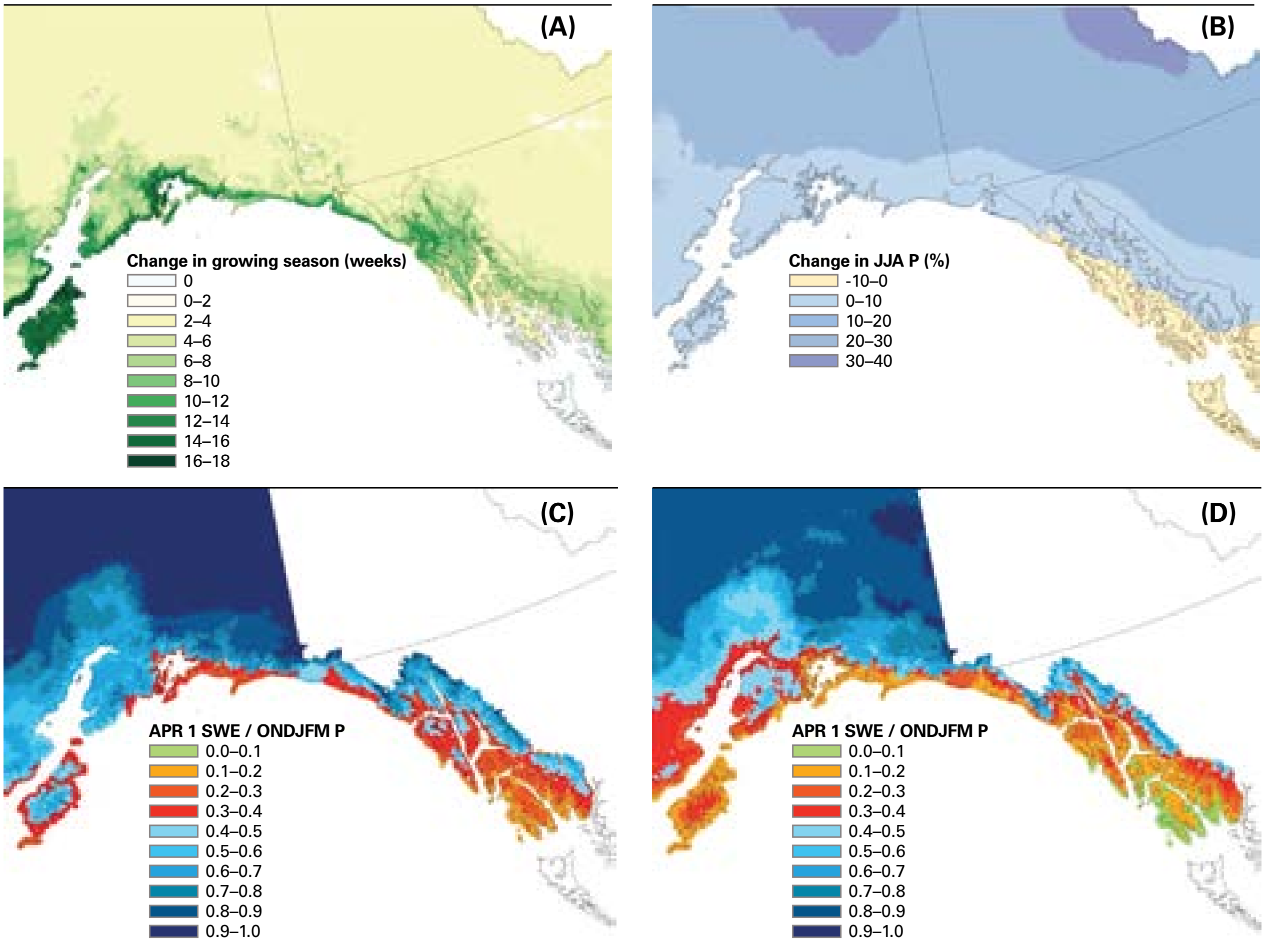

Figure 3.2—Projected changes in ecologically relevant climate variables for southcentral and southeast Alaska, comparing 2040–2069 climatology to 1970–1999. Changes are based on a five-GCM average (NCAR CCSM4, NOAA GFDL-CM3, NASA GISS-E2-R, IPSL-CM5ALR, MRI-CGCM3) for the Representative Concentration 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

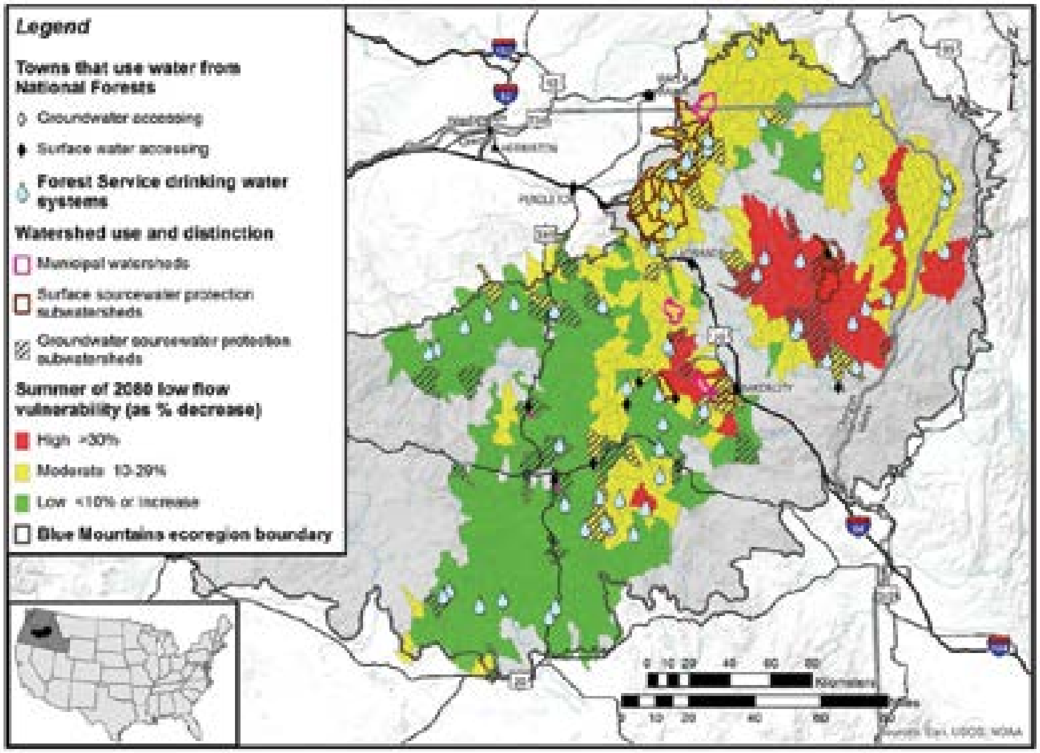

Figure 3.3—Projected risk of summer water shortage in the Blue Mountains region of Washington and Oregon, based on low streamflows for 2080. The Variable Infiltration Capacity model was used to calculate differences between historical streamflow data (1915–2006) and streamflow projections for the A1B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

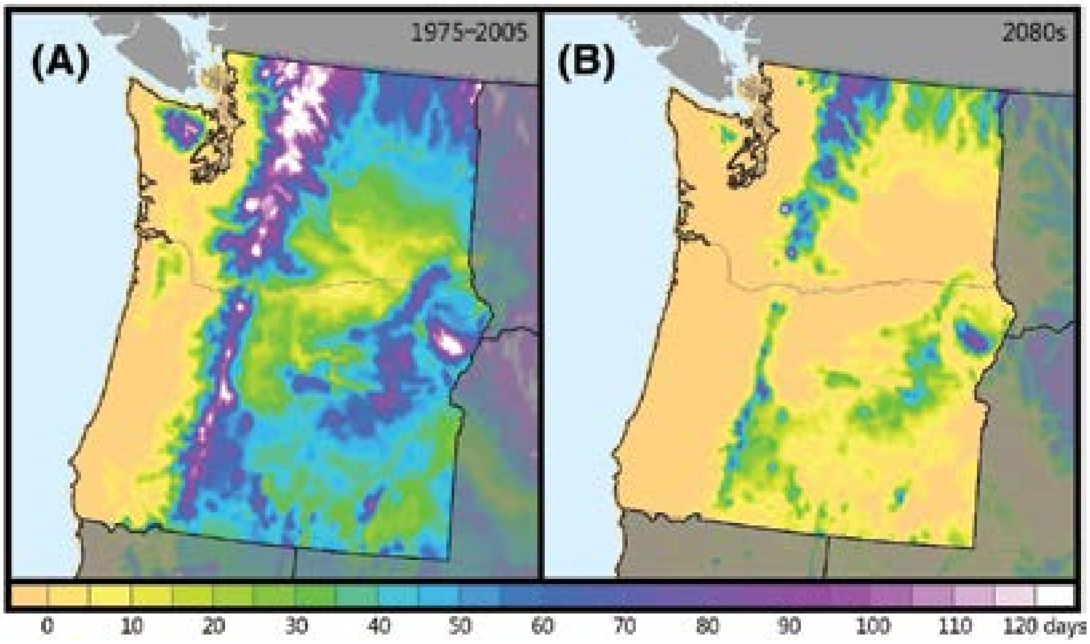

Figure 3.4—Modeled snow residence time in Washington and Oregon for (A) a historical period (1975–2005) and (B) projected for the 2080s with the Representative Concentration Pathway (RCP) 8.5 emissions scenario. Snow residence time will decrease in the Pacific Northwest in the future, particularly east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

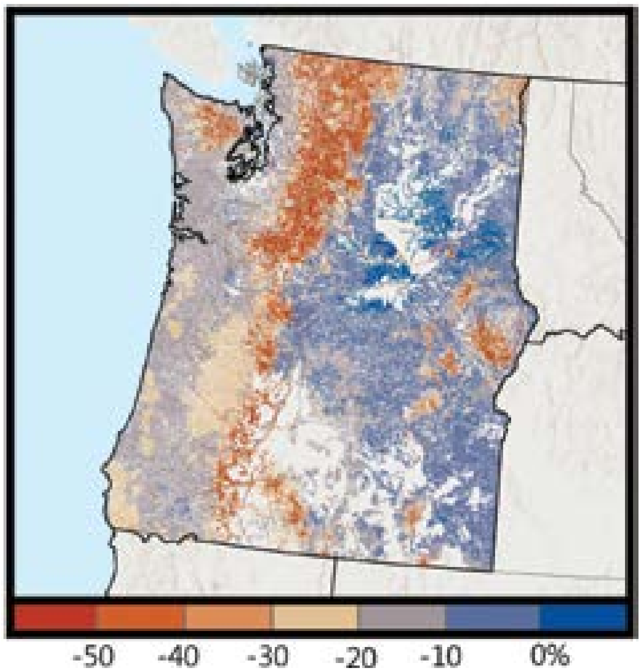

Figure 3.5—Projected change in mean summer streamflow in Washington and Oregon between historical (1977–2006) and future (2080s) time periods for the Representative Concentration Pathway (RCP) 8.5 emissions scenario. The largest reductions are shown in the mountainous areas, likely influenced by reduction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

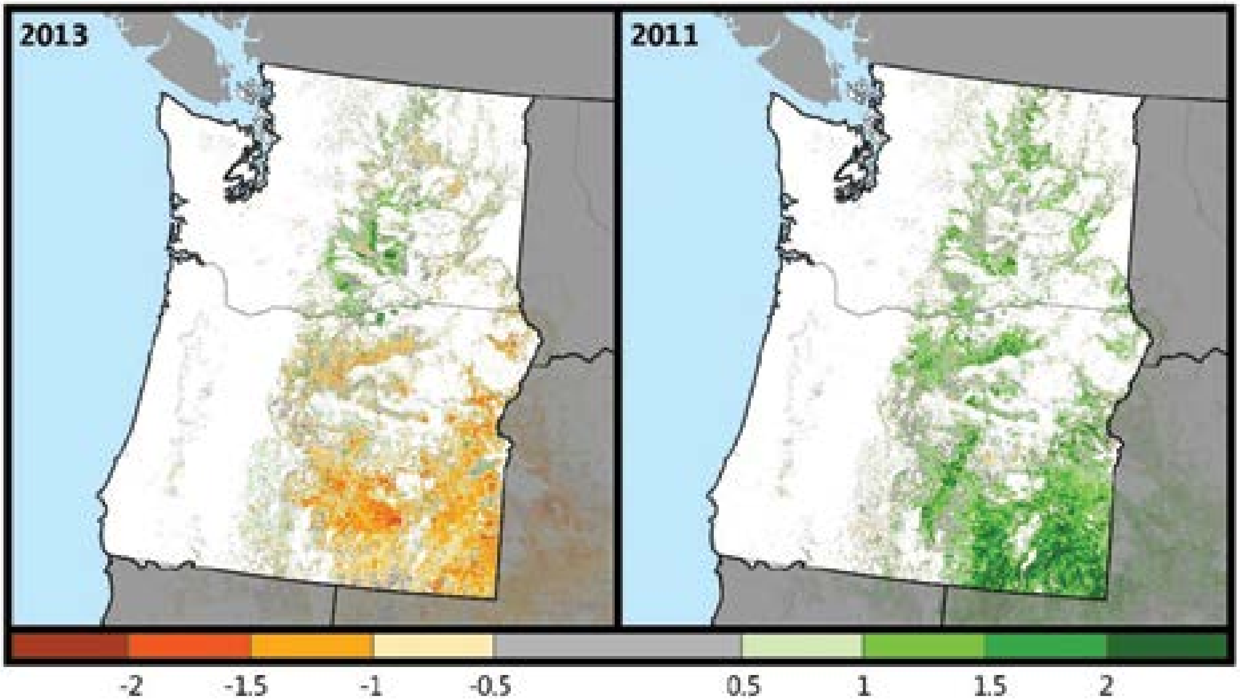

Figure 3.6—Relative rangeland productivity (z-scores) for Washington and Oregon, illustrating the standard deviation from the mean. Left (2013) represents a drought year with lower rangeland productivity. Right (2011) represents above-average moisture and productivity. For a more detailed map on rangeland 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.

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CHAPTER 4

Managing Effects of Drought in California

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INTRODUCTION

The State of California illustrates how society can be affected by drought. As the sixth largest economy in the world (California Legislative Analyst's Office 2016), California is home to 39.3 million people, with agricultural and forestry sectors of national and international significance. California also has the largest population living in the wildland-urban interface of any U.S. State (11.3 million people). Although climates in California range widely, from desert to subarctic, much of the climate is described as Mediterranean-type, characterized by an annual dry period with hot, dry summers, followed by an annual wet period with cool, moist winters. Mediterranean-type climates are rare not just in the United States but also globally, and found in California, the Cape Region of South Africa, southwest and southern Australia, central Chile, and lands bordering the Mediterranean Sea (Esler et al. 2018).

California receives almost all (>95 percent) of its precipitation in the form of rain and high-elevation (>6,000 feet) snow between October and May, around 66 percent of it during the core rainy-season months of December to March (Swain et al. 2016). Shortage of precipitation in the wet season affects water supply for the entire year. This characteristic poses a unique challenge to organisms that live in California, and it requires special considerations regarding land management actions (Brooks et al. 2002).

HOW ARE DROUGHTS EXPRESSED IN CALIFORNIA?

Droughts have had an important influence on California for millennia (Cook et al. 2007). For example, in forests, droughts have contributed to widespread bark beetle outbreaks, extensive tree mortality, reduced tree growth, and increased wildfire hazard (Fettig et al. 2019, Stephens et al. 2018), all of which in turn affect biogeochemical cycling (Goetz et al. 2012) and hydrological processes (Guardiola-Claramonte et al. 2011). In rangelands, droughts have reduced productivity, altered nutrient cycling, increased wildfire hazard, and increased susceptibility to invasive plants (Vose et al. 2016). California leads the Nation in agricultural crop receipts at $47 billion (USD) (CDFA 2016). Recent droughts caused losses of $2.7 billion and 21,000 jobs in 2015 (Howitt et al. 2015), and $603 million and 4,700 jobs in 2016 (Medellin-Azuara et al. 2016). Unlike forestry, the agricultural sector can mitigate some of the effects of drought by relying on groundwater reserves and extensive irrigation networks (Marston and Konar 2017). For example, droughts in January 2007–December 2009 and October 2012–September 2016 depleted, respectively, an estimated 4 cubic miles and 10 cubic miles of groundwater (Xiao et al. 2017).

The most recent drought in California (2012–2016) was characterized by large precipitation deficits and abnormally high temperatures during both the wet and dry seasons; winter 2014–2015 was the warmest in the meteorological record (Aghakouchak et al. 2014). Although consecutive years of drought and associated stress on vegetation are not uncommon in California (fig. 4.1), this event was the most severe in the last 1,200 years (Griffin and Anchukaitis 2014) and may foreshadow future drought events in the State. For example, the Forest Service, U.S. Department of Agriculture (USFS) Aerial Detection Survey (ADS) reported extensive tree mortality (29 million trees in 2015) in the central and southern Sierra Nevada, where drought effects were most pronounced. As a result, Governor Jerry Brown declared a state of emergency and established a task force to address the issue. Winter 2015–2016 brought near-normal precipitation to much of California, but drought stress remained high in many forests. Aerial Detection Survey estimated that an additional 62 million trees died in 2016 and 27 million trees in 2017 (http://www.fs.fed.us/news/releases/new-aerial-survey-identifies-more-100-million-dead-trees-california), bringing the total to 129 million trees from 2010 to 2017 (CDFFP 2018) (fig. 4.2).

The 2012–2016 drought was mostly a result of natural variability in the climate system associated with a persistent ridge of high atmospheric pressure over the northeast Pacific (Seager et al. 2015, Williams et al. 2015), although warming was a contributing factor. Williams et al. (2015) reported that a lack of precipitation was the primary driver in 2012–2014, but that warming accounted for 8–27 percent of the observed drought anomaly during that period. They concluded that although natural variability dominates the system, human-induced warming did and will continue to increase the likelihood of extreme droughts in California.

Put simply, warming amplifies water limitations. Higher temperatures not only result in higher levels of potential evapotranspiration (PET, the amount of evaporation and plant transpiration that would occur if sufficient water was available) (Mann and Gleick 2015) or climatic water deficit (CWD, evaporative demand exceeding available soil moisture computed as PET minus actual

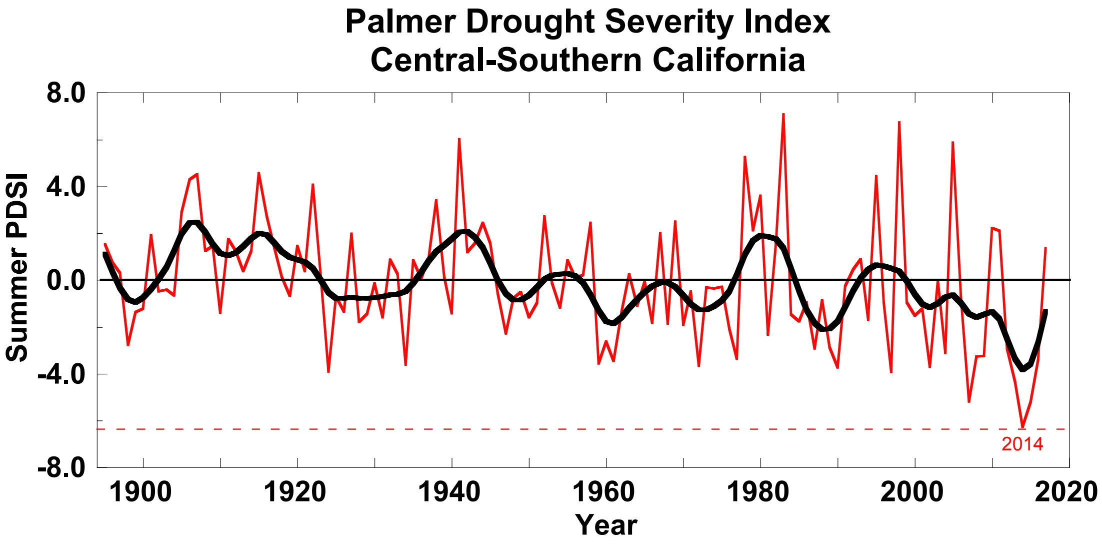

Figure 4.1—Palmer Drought Severity Index (PDSI) values for central and southern California from 1895 to 2017 (red); the black smoothing line denotes decadal-scale variability. Year 2014 is noted as the lowest value for the period. Three-month PDSI values ending in August were obtained for California State Climate Divisions 4–7 (NOAA Divisional Climate Data, https://www.ncdc.noaa.gov/cag), and an area-weighted average was calculated. Figure modified from Griffin and Anchukaitis (2014; fig. 1a).

Figure 4.2—California experienced a period of severe drought during 2012–2016. In 2015, the USFS Aerial Detection Survey (ADS) reported extensive tree mortality in the central and southern Sierra Nevada, estimating that over 29 million trees were killed. Winter 2015–2016 brought near-normal precipitation to much of California, but drought stress remained high in many areas. The ADS reported that an additional 62 million trees died in 2016 and 27 million trees in 2017, bringing the total to 129 million trees killed from 2010 to 2017. (Photo of Sequoia National Forest, April 2017, by C. Fettig, USDA Forest Service)

evapotranspiration) and thus plant stress, but reduced snowfall and snowpack (Berg and Hall 2017, Luo et al. 2017). Although precipitation deficits were largely responsible for producing the agricultural drought, the effects of high temperatures over high-elevation areas (e.g., >6,000 feet) during the wet season were as much or more harmful to snowpack than were precipitation deficits (Luo et al. 2017).

FUTURE DROUGHTS

Global climate models project that California will experience more frequent severe droughts, causing significant reductions in snowpack (Berg and Hall 2017, Diffenbaugh et al. 2015). Using 21st century projections of warming and the Representative Concentration Pathway (RCP) 8.5 emissions scenario (a business-as-usual scenario based on high human population growth, slow income growth, and modest rates of technological change and energy improvements), total snowpack is projected to decline by 85 percent during this century (Berg and Hall 2017). Mountain snowpack is a critical resource in California, supplying water for multiple uses throughout much of the State. For example, runoff from snowpack in the Sierra Nevada provides over 50 percent of the annual water supply and about 15 percent of the electrical power supply (Rheinheimer et al. 2012).

Drought presents significant challenges for natural resource managers, and future droughts will likely exert even greater impacts (Allen et al. 2010, Fettig et al. 2013, Millar and Stephenson 2015). Managers can intervene by altering plant structure and composition, increasing annual water yield, and conducting public outreach and education regarding water conservation. A good example of outreach is the Drought Early Warning System (DEWS), which uses partnerships among Federal, Tribal, State, local, and academic partners to make climate and drought science more accessible and to improve our capacity to forecast and respond to droughts (National Integrated Drought Information System 2017) (box 4.1). Other useful resources include the California Climate Tracker (Desert Research Institute 2017) and the Climate at a Glance Resource (NOAA 2017) (box 4.1).

Strong environmental gradients in California result in wide variation in ecosystems, drought sensitivities, and constraints and opportunities for management responses. Below we consider the effects of drought on several major ecosystems, highlighting management options that minimize undesirable impacts and facilitate

BOX 4.1
Additional Resources on Drought in California

Cal-Adapt—Tools for developing climate projections and adaptation plans. http://cal-adapt.org

California Climate Tracker—Tool that facilitates mapping of recent and historical temperature and precipitation data (Desert Research Institute 2017). https://wrcc.dri.edu/monitor/cal-mon

California Drought Portal—Information on drought conditions and water conservation measures within the State. http://www.drought.ca.gov

California Rangeland Conservation Coalition—Resources for ranchers wishing to restore stock ponds, improve rangeland health, or promote resilience, including assistance with locating funding sources and navigating the permitting process. http://carangeland.org/our-work/projects

California Tree Mortality Task Force—Resources of relevance to the recent large-scale tree mortality event in California. http://www.fire.ca.gov/treetaskforce

Climate at a Glance—Tool for mapping recent and historical temperature anomalies on an interactive 5°- x 5°-map (NOAA 2017). https://www.ncdc.noaa.gov/cag

Effects of Drought on Forests and Rangelands in the United States: A Comprehensive Science Synthesis—Publication on the scientific foundation of our understanding of droughts in forests and rangelands. https://doi.org/10.2737/WO-GTR-93b

National Integrated Drought Information System for California—Information on current drought conditions in the State with links to early warning systems and management plans. https://www.drought.gov/drought/states/california

National Seed Strategy for Rehabilitation and Restoration—Guidance for large-scale ecological restoration, with sections emphasizing drought and rangelands. https://www.blm.gov/programs/natural-resources/native-plant-communities/national-seed-strategy

Our Forests Are Changing—Information on the Forest Service response to drought-induced tree mortality in California. https://www.fs.usda.gov/main/catreemortality/home

Restoration Manual for Annual Grassland Systems in California—Information on restoration of California grasslands, including drought hardiness of common grassland species. http://ucanr.edu/blogs/lnrblog/blogfiles/45083.pdf

Seedlot Selection Tool—An interactive, web-based mapping tool to help resource managers match seedlots to planting sites. https://seedlotselectiontool.org

UC Rangelands "Managing for Drought"—A collection of drought resources for rangeland managers. http://rangelands.ucdavis.edu/drought

USDA California Climate Hub "Drought Impacts on Rangelands"—A two-page summary on the effects of drought on California rangelands. http://caclimatehub.ucdavis.edu/wp-ontent/uploads/sites/320/2016/03/factsheet5_rangelands.pdf recovery from droughts. Other ecosystems and sectors (e.g., crop production agriculture) that are heavily affected by drought are beyond the scope of this review. Increasing our adaptive capacity to drought has critical ecological and social components.

MONTANE AND SUBALPINE FORESTS

In montane and subalpine forests, understory herbs are affected by drought, with fewer individuals germinating; those that do germinate may have a truncated period for flowering, seed set, and senescence. Trees, with deeper roots and greater carbohydrate reserves, are more tolerant of short-term droughts, but for droughts of more than a year, growth often decreases, reducing photosynthate production and making trees increasingly susceptible to insects and pathogens that can weaken or kill large overstory individuals. Bark beetles, often key mortality agents of trees in montane and subalpine forests (Fettig 2016) (table 4.1), prey on specific tree species, so mortality varies among tree species. A nonlinear relationship exists between drought intensity and bark beetle outbreaks in the Western United States: moderate drought reduces bark beetle population performance and subsequent tree mortality, but intense drought increases bark beetle performance and tree mortality (Kolb et al. 2016). In some cases, insecticides, semiochemicals, or other tactics may be used to protect individual trees, such as sugar pines (*Pinus lambertiana*) resistant to white pine blister rust (*Cronartium ribicola*), or small stands of trees (usually <25 acres) during periods of elevated populations of bark beetles associated with drought (Fettig and Hilszczański 2015).

Many montane forests in California that experience drought historically had frequent (<30-year), low-intensity (generally surface) fire regimes that kept stand density low, buffering them from drought-induced stress (North et al. 2016). For example, mixed-conifer forests historically averaged 64 stems per acre (range 24–133 stems per acre), 152 square feet of basal area per acre (91–235 square feet per acre), and 20–40 percent canopy cover, with about half of the forest area in gaps (Safford and Stevens 2017). With the advent of effective fire exclusion (roughly 1940 and later), many mixed-conifer forests now have 2–6 times more stems, about 1.5 times more basal area, 50–80 percent canopy cover, and few gaps (Collins et al. 2017, Knapp et al. 2013). With so many “straws in the ground,” competition for scarce soil moisture is often acute even before drought occurs, and it becomes severe enough in some forests to contribute to large-scale tree mortality events during multiyear droughts (Young et al. 2017). Shrubs are able to capture and take up soil moisture at much lower concentrations than most trees, buffering them from stress except during severe droughts that persist for several years (Hurteau and North 2008). As a result, plant composition may shift toward a greater dominance of shrubs in drought-affected forests.

Minimizing Drought Impacts

Reducing stand densities will increase the resilience of montane and subalpine forests to drought and other disturbances exacerbated by drought (Fettig et al. 2007, Kolb et al. 2016, North et al. 2015). The main density reduction tools are fire and mechanical thinning. Fire management consists of either prescribed burning or wildfires that are allowed to burn under appropriate weather conditions (i.e., managed wildfire) (table 4.2). Compared to fire, mechanical thinning can more precisely meet desired management objectives and

Table 4.1—Bark beetles that cause significant levels of tree mortality in montane and subalpine forests in California

COMMON NAME	SCIENTIFIC NAME	PRIMARY HOST(S)
California fivespined ips	*Ips paraconfusus*	*Pinus coulteri, P. lambertiana, P. ponderosa*
Fir engraver	*Scolytus ventralis*	*Abies concolor*
Jeffrey pine beetle	*Dendroctonus jeffreyi*	*P. jeffreyi*
Mountain pine beetle	*D. ponderosae*	*P. contorta, P. lambertiana, P. ponderosa*
Pine engraver	*I. pini*	*P. contorta, P. jeffreyi, P. lambertiana, P. ponderosa*
Western pine beetle[a]	*D. brevicomis*	*P. coulteri, P. ponderosa*

[a] Species responsible for much of the tree mortality that occurred during the 2012–2016 drought in California.

Note: The impacts of these species are exacerbated by intense droughts.

Table 4.2—Strategies that minimize undesirable drought effects and facilitate recovery of drought-affected landscapes in select California ecosystems

ECOSYSTEM	DROUGHT MANAGEMENT STRATEGIES
Montane and subalpine forests	• Reduce stand densities and fuel loads through prescribed burning, managed wildfires, and mechanical thinning. • Maintain appropriate stand densities and fuel loads through prescribed burning, managed wildfires, and mechanical thinning. • Use topography and historic fire regimes to drive prescriptions (North 2012, North et al. 2009). • Increase forest heterogeneity. • Salvage dead and dying trees in areas of heavy tree mortality. • Plant drought-tolerant species and genotypes in areas lacking adequate seed sources to rely on natural regeneration. • Prioritize restoration of ecologically sensitive areas (e.g., meadows).
Coast redwood forests	• Maintain appropriate stand densities through prescribed burning and mechanical thinning. • Reduce practices that create forest structures that are too open, thereby losing their ability to capture moisture from fog. • Thin competing vegetation (e.g., Douglas-fir [*Pseudotsuga menziesii*]) to promote growth of residual trees. Variable-density thinning results in structures that best mimic naturally clumped distributions (O'Hara et al. 2010). • Minimize soil disturbance. • Create small gaps for light availability for regenerating seedlings. • Protect old-growth reserves.
Oak woodlands	• Reduce stand densities through prescribed burning and mechanical thinning. • Maintain appropriate stand densities through prescribed burning and mechanical thinning, mimicking strategies used by Native Americans (Anderson 2007). • Create gaps for light availability for regenerating seedlings. • Restore perennial grasses. • Control nonnative annuals. • Graze to reduce moisture competition between the understory and overstory. Protect seedlings and saplings with tree shelters, as appropriate. • In urban trees, consider deep watering of mature oaks.
Chaparral and California (coastal) sage scrub (CSS)	• Avoid creating gaps and soil disturbance which increase susceptibility to invasion by nonnative annuals, increasing drought stress and wildfires. • Focus invasive plant management programs on disturbed areas. • Focus on priority areas (e.g., for slope stabilization) with a high probability of successful restoration.
Grasslands	• Reduce nonnative annuals and woody encroachment through prescribed burning. • Remove nonnative annuals and replace with native grasses and forbs. • Plant diverse seed palettes of drought-hardy species and genotypes. • Avoid overgrazing; provide supplemental feed for livestock as necessary. • Maintain stock ponds.

Note: Reducing the rate of atmospheric warming (through reductions in CO_2 and other greenhouse gas emissions), public outreach and education, monitoring, and adaptive management are important strategies for all ecosystems.

conditions through individual tree marking and removal, but it is often difficult to conduct at large (>500–2,500 acres) scales because of costs, regulatory processes, and legal, operational, and administrative constraints (North et al. 2015) (fig. 4.3).

Numerous studies have documented the effectiveness of reducing stand density in montane and subalpine forests to increase resilience to bark beetles (reviewed by Fettig et al. 2007) and wildfire (reviewed by McIver et al. 2013). For example, Fiddler et al. (1989) showed that thinning significantly reduced the amount of mortality caused by mountain pine beetle (*Dendroctonus ponderosae*) in ponderosa pine (*Pinus ponderosa*) stands in California. No tree mortality occurred in stands of <39 square feet per acre of basal area; this result agrees with the optimal stocking level of 48 square feet per acre (described by Oliver 1979, 1995) to increase resilience of forests to mountain pine beetle and western pine beetle (*D. brevicomis*) in California. Given climate projections of increased levels of drought stress, optimal stocking levels will probably need to be lowered to maintain adequate levels of resilience in the future (Peterson et al. 2011). To that end, the USFS is revising thinning guidelines for management of yellow pines in the Western United States.[1]

Prescribed fire to reduce stand density is less precise than thinning because it occasionally torches and kills all trees in localized patches (generally <40 acres). However, it is much more economical than thinning, can be used at large scales, and is often better at increasing structural heterogeneity (North et al. 2015). Forest heterogeneity may be particularly important for increasing forest resistance and resilience to increasingly frequent and severe wildfire and drought events (Larson and Churchill 2012). Topography can be used within stands and across landscapes to vary tree density, canopy cover, and tree gap and clump size to synchronize forest conditions with soil moisture availability and the local historic fire regime (North et al. 2009) (fig. 4.4). Within stands, managers can consider creating a spatial clump/gap pattern described as "individual trees, clumps of trees, and openings"

Figure 4.3—Thinning is an effective tool to increase the resilience of montane and subalpine forests to drought and other disturbances exacerbated by drought. Thinning reduces competition among trees for nutrients, water, and other resources, thereby increasing vigor. It also affects the microclimate within treated stands, decreasing the effectiveness of chemical cues used during host finding, selection, and colonization by many species of bark beetle. (Photo by C. Fettig, USDA Forest Service)

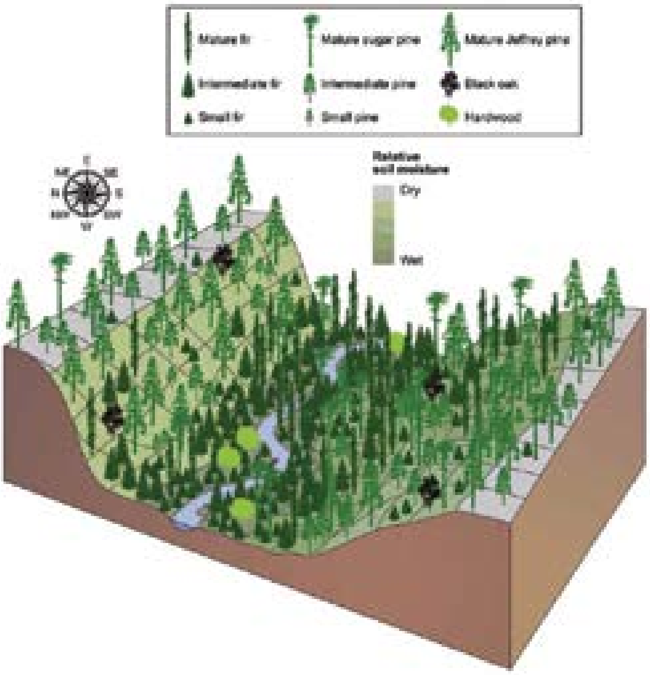

Figure 4.4—Topography can be used within stands and across large landscapes to vary tree density, canopy cover, and tree gap and clump size to increase resilience to drought by synchronizing forest structure with soil moisture availability and local historic fire regimes.

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[1] Unpublished data. On file with: J. Egan, Group Leader and Entomologist, U.S. Department of Agriculture, Forest Service, Forest Health Protection, 26 Fort Missoula Road, Missoula, MT 59804.

(ICO) found in forests that historically had frequent-fire regimes (Fry et al. 2014, Lydersen et al. 2013). More research is needed to determine how tree clump size and density should vary for sites with different CWD to minimize drought stress. Initial studies suggest that to optimize the amount of snowmelt reaching the soil, a tradeoff exists between having sparse enough canopy cover (37–53 percent) to let more snow reach the ground and having small enough opening sizes to reduce solar ablation of the snow surface (Bales et al. 2011, Stevens 2017).

Facilitating Recovery

Restoring montane and subalpine forests after drought-induced tree mortality requires a flexible approach, including a sequence of decisions related to the condition and location of an affected area. For small patches of tree mortality (<50 acres), intervention may be minimal. If green-tree seed sources are not nearby (generally within 800 feet for wind-dispersed conifers), intervention may be limited to planting more drought-tolerant seedlings such as sugar pine, ponderosa pine, and Jeffrey pine (*P. jeffreyi*). In more extensive patches of tree mortality, decisions about salvage harvesting, prescribed burning, planting, and controlling competing vegetation will vary with dead-tree patch size, potential natural seedling recruitment, management goals, and fire hazard.

Where salvage harvesting is used, priority could be placed on whole tree removal in strategic locations where fire management options depend on lower surface fuel loads (North et al. 2009) (table 4.2). In areas not salvaged, safety concerns limit silvicultural treatments such as planting and shrub removal until most snags have fallen to the forest floor (within 10–15 years) (Dunn and Bailey 2015, Knapp 2015). In these areas, accumulated dead fuels will place any naturally recruited or planted trees at risk of complete loss in the event of a wildfire (McGinnis et al. 2010).

Application of prescribed fire or managed wildfire (fig. 4.5) without killing young trees can be difficult (Bellows et al. 2016), especially if surface fuel loading is high. An advantage of prescribed burning is that it can be used when live and woody fuel moistures are high. Such burns are often patchy, allowing at least some conifer regeneration to remain intact. In contrast, areas that burn in high-severity wildfires (hot, dry conditions) within 15–30 years after a drought event are prone to long-term conversion to shrub fields because of the loss of established tree regeneration and seed sources for post-fire conifer regeneration. Surface fuel loading can increase significantly following heavy tree mortality associated with severe drought events, creating concerns about fire hazard in the wildland-urban interface. For example, some have argued that the scale of tree mortality after the 2012–2016 drought in California is so large that the amount and continuity of dry, combustible woody material creates a greater potential for high-severity wildfires (Stephens et al. 2018).

The forests of the Sierra Nevada provide habitat for hundreds of species of animals, many of which merit special protection and management considerations. The California Tree Mortality Task Force (2017; see box 4.1) released recommendations for comprehensive restoration of the Sierra Nevada. This report focused on forests most heavily affected by drought. Two USFS publications helped guide thinking about managing forest structure to emulate the "natural" heterogeneity of mixed-conifer forests and to restore resiliency: *An Ecosystem Management Strategy for Sierran*

Figure 4.5—Prescribed burning is useful for reducing fuels and increasing the resilience of forests to drought stress. (Photo by M. North, USDA Forest Service)

Mixed-Conifer Forests (North et al. 2009) and *Managing Sierra Nevada Forests* (North 2012). Key elements of the task force plan are to:

- Increase the pace and scale of thinning, prescribed burning, and managed wildfire.
- Rebuild the forest products industry in California to facilitate adequate biomass removals.
- Improve forest structure for wildlife habitat.
- Restore ecologically sensitive areas (e.g., meadows).
- Facilitate legislative and administrative reforms that act as barriers to project implementation.
- Implement monitoring and adaptive management.

COAST REDWOOD FORESTS

Coast redwoods (*Sequoia sempervirens*) are the tallest, heaviest, and among the oldest trees on Earth, with some individuals exceeding 2,000 years (Noss 2000) (fig. 4.6). Coast redwoods occur in a narrow coastal belt from southwest Oregon south to Big Sur, CA (Azevedo and Morgan 1974, Carroll et al. 2014, Dawson 1998). Within the redwood forests of northern California, annual water use by large redwoods is high, and largest demands for water occur during summer months when rain is sparse (Fujimori 1977). Fog constitutes 30 percent or more of the total water input each year, serving an important role in ameliorating water deficits (Burgess and Dawson 2004, Corbin et al. 2005). The shallow root structure of coast redwoods, as well as understory herbs and shrubs, benefit from fog drip, particularly during summer months and at sites where deep soil water is unavailable (Dawson 1998).

Coast redwoods tend to be poor regulators of water use, making them sensitive to ambient humidity and the presence or absence of cloud cover (Burgess and Dawson 2004, Johnstone and Dawson 2010). High spring temperatures may constrain growth in redwoods because of increased rates of maintenance respiration, elevated water stress, and decreased gas exchange in more central and southern locations within the range. High summer temperatures, in contrast, may stimulate radial growth in more northern forests, where water

Figure 4.6—Coast redwoods are among the oldest trees on Earth. Mature redwood forests are generally resilient to drought. (Photo courtesy of Redwood State and National Parks)

often is not as limiting (Carroll et al. 2014). During drought, redwood forests continue to tap fog as a water source, and deep, loamy forest soils slowly release the water captured from winter rains. Dependence on fog as a moisture source is highest in those years when winter rainfall is lowest while fog inputs remain normal (Dawson 1998). As summer drought worsens, radial growth of coast redwoods declines (Carroll et al. 2014). Redwood seedlings need moist, cool conditions to germinate and grow, so growth and survival rates are low during droughts (Ambrose et al. 2015).

A study of canopy water content (CWC) and canopy water loss during the 2012–2016 California drought documented major CWC decreases in lowland coastal redwood forests (Asner et al. 2016). Canopy water content is an indicator of progressive drought effects on forest canopies and tree physiological status because it is correlated with leaf water potential during water stress (Nepstad et al. 2002, Vourlitis et al. 2008). Extreme water stress can limit foliar uptake, even in mature redwood foliage (Burgess and Dawson 2004, Limm et al. 2009). Similarly, changes in fog frequency and related climate variables may have important implications for redwood physiology and ecosystem function. Since the 1950s, coastal fog within the redwood belt has declined somewhat, with interannual and multidecadal variations governed largely by ocean-atmosphere circulation and temperature anomalies related to the Pacific Decadal Oscillation (Johnstone and Dawson 2010). Summer low cloudiness has declined by >5 percent (Schwartz et al. 2014). This pattern likely contributes to drought sensitivity, water stress, and reduced survival of plants restricted to the California coast, including redwoods (Fischer et al. 2009, Limm et al. 2009). As temperatures rise and evaporative demand grows, redwoods and other coastal rainforest plants are likely to become increasingly drought-stressed, especially in summer. Summer drought stress is likely even under climate projections of increasing annual precipitation because the increases are expected to occur in winter (Koopman et al. 2014, Walsh et al. 2014).

Minimizing Drought Impacts

Thinning of competing vegetation, such as Douglas-fir (*Pseudotsuga menziesii*), to promote redwoods is thought to minimize effects of drought (Koopman et al. 2014, O’Hara et al. 2010, van Mantgem and Das 2014) (table 4.2). Variable-density thinning results in substantial growth in residual trees (O’Hara et al. 2010) (fig. 4.7) and stand structures that may better mimic the clumped spatial arrangement of stems in old coastal redwood forests (Dagley 2008, van Mantgem and Stuart 2012). However, the optimal level of thinning is uncertain because of the need to balance capturing fog inputs with the need to reduce competing vegetation and enhance the amount of light for regenerating trees. Uncertainty also exists about how thinning intensities should vary with site conditions (e.g., stand slope, aspect, age), how treatment effects may change as stands mature, and how competitive processes might vary across the landscape (van Mantgem and Das 2014).

Figure 4.7—Thinning of competing vegetation, such as Douglas-fir, is thought to minimize effects of drought in coast redwood stands. (Photo by K. O’Hara, University of California)

Facilitating Recovery

Mature redwood forests are generally resilient to climate change, fire, and drought. Coast redwoods can rapidly initiate vigorous sprout growth from lignotubers (underground burls), a characteristic that contributes to their recovery and resilience (Del Tredici 1998, Ramage et al. 2010). However, redwood sprouts will die if light levels are not adequate (O'Hara and Berrill 2010), and seedlings usually fail to establish in deep shade (Peer et al. 1999). The loss of redwood trees to natural disturbances (e.g., wildfire, windthrow, floods, severe drought), extensive timber harvesting, or other land-use practices converts forests to more open habitats reducing fog capture, thus altering the hydrological balance and creating more drought-prone conditions (Dawson 1998, Johnstone and Dawson 2010). The adaptive capacity of redwood forests can be improved by minimizing soil disturbance, protecting and buffering old-growth reserves, reducing competition from other tree species, reducing forest road densities, and reintroducing low-severity fire (table 4.2).

OAK WOODLANDS

California oak woodlands are a widely distributed forest type found on 8.9 million acres, of which 70 percent is privately owned (Waddell and Barrett 2005). The dominant cover types are blue oak (*Quercus douglasii*), canyon live oak (*Q. chrysolepis*), interior live oak (*Q. wislizenii*), California black oak (*Q. kelloggii*), and coast live oak (*Q. agrifolia*) (fig. 4.8). The first fossil record of oaks in California dates back 20 million years, and oaks have been a major element on the landscape for the past 10,000 years (Mensing 2015). This corresponds to the end of the last glaciation, when Native Americans settled in the region and began to play a major role in the distribution and density of oak woodlands through management that enhanced acorn crops, basketry materials, and habitat for some animal species (Anderson 2007). Today, the predominant use of oak woodlands in California is livestock grazing (Allen-Diaz et al. 2007).

Oaks in California are generally well adapted to drought, occurring on some of the lowest rainfall zones in the State. They have extremely deep rooting depth and form mycorrhizal associations to enhance effective root surface area for moisture uptake (Allen 2015). The evergreen oaks (coast live oak, canyon live oak, interior live oak) have a sclerophyllous leaf structure that reduces transpiration loss during the summer drought period (Plumb and Gomez 1983). Deciduous oaks (blue oak, valley oak [*Q. lobata*], black oak) can drop their leaves in late summer to reduce evapotranspiration during severe drought (McCreary 2012). These water conservation features allow oaks to persist during periods of extreme drought (Potter 2016, Stahle et al. 2013).

Fire disturbance has been key to the structure of California oak woodlands for several thousand years (Byrne et al. 1991). Two studies have documented mean fire interval (MFI) in blue oak woodlands. Standiford et al. (2012) found a MFI of 12.8 years from 1850 to 1965, with extensive fire exclusion occurring since that time. McClaran and Bartolome (1989) found MFIs of 25.2 years from 1681 to 1848 and 7.1 years from 1849 to 1948, with no fires since 1949. This study showed the importance of fire in blue oak recruitment, especially from resprouting of top-killed stems; 64–78 percent of all trees became established within 1 year of a fire event. Similar to the MFI of blue oak woodlands for the same period, the MFI of a mixed oak-pine stand in the Sierra Nevada foothills was 7.8 years from 1850 to 1952 (Stephens 1997).

Fire has long been used as a management tool in oak woodlands to maintain more open stand structures, improve large-animal habitat, and enhance desirable vegetation types (Allen-Diaz et al. 2007, Anderson 2007). In the current era of fire exclusion, a statewide

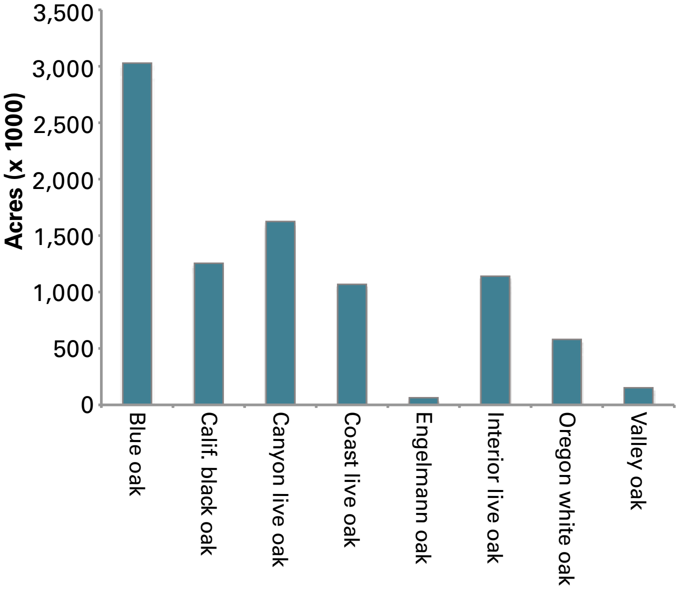

Figure 4.8—Area occupied by oak woodland and forest types in California (Waddell and Barrett 2005).

remeasurement of blue oak woodlands showed a general trend of increasing stand density over the last 50 years (Holzman and Allen-Diaz 1991). Fire also plays a key role in oak recruitment in California (McClaran and Bartolome 1989).

Minimizing Drought Impacts

When designing management strategies to increase the resilience of oak woodlands to drought (fig. 4.9), a necessary step is to create stand structures that ensure adequate soil moisture to both overstory and understory trees (table 4.2). Modern stands are much more prone to tree mortality during the summer dry period than they were historically for two main reasons: the introduction of nonnative annuals in the understory, and denser overstory levels than existed before Euro-American settlement. Both thinning and prescribed fire can help create stand structures that minimize drought impacts.

In a comparison of thinning regimes for blue oak and interior live oak woodlands, thinning to one-third or two-thirds of initial basal area created stand structures with higher individual tree growth, higher acorn production, and enhanced forage production than in unthinned stands (Standiford and McDougald 2015, Standiford et al. 2015). Coast live oak woodlands showed a relatively rapid return to pre-thinned basal area levels, highlighting the need for designs that mimic the role of natural fire intervals in thinned stands (Bonner et al. 2008). Besides thinning alone, thinning and prescribed fire together can be used to minimize drought impacts and to enhance ecosystem values for black oak woodlands, mimicking the strategies used historically by Native Americans (Long et al. 2015). Finally, burning prescriptions can be designed to thin stands and maintain tree vigor during moisture-limiting conditions in blue oak, coast live oak, and black oak woodlands (Fry 2008).

In urban oak woodlands with high amenity values, deep watering of mature oaks near the drip zone may help reduce tree mortality during severe drought conditions (Costello et al. 2011), although the soil zone surrounding the tree trunk must be dry enough to minimize oak crown rot (*Phytophthora* spp.) (Perry 2006). Mistletoe (*Phoradendron villosum*) is a parasitic plant that can cause oak mortality during severe drought conditions (Swiecki and Bernhardt 2006), but control strategies can

Figure 4.9—Mortality of blue oak in the foothills of the southern Sierra Nevada associated with severe drought. (Photo by R. Standiford, University of California)

be used if tree values justify costs (Perry and Elmore 2006). Similarly, colonization by the goldspotted oak borer (*Agrilus auroguttatus*), first associated with dying oaks in eastern San Diego County in 2008 (Coleman and Seybold 2008), exacerbates drought stress in affected trees (Coleman et al. 2011). Irrigation and control measures for these pests are unlikely to be cost effective in wildland settings.

Facilitating Recovery

Restoring perennial grasses can improve soil moisture retention and facilitate oak regeneration (table 4.2). Native perennial moisture regimes have lower soil moisture depletion, resulting in higher survival and growth rates for blue oak seedlings (Welker and Menke 1990). Large-scale replacement of the extensive distribution of nonnative annuals in oak woodland understories is impractical for operational and financial reasons; however, doing so bears consideration in stands that are particularly vulnerable to moisture depletion. Grazing may also help to reduce the effect of moisture competition in some cases (Welker and Menke 1990). In addition, control of annual vegetation around advanced regeneration of blue oak and valley oak, coupled with the use of tree shelters, increases survival and growth of seedlings and saplings, which helps to facilitate recovery after mortality of overstory trees (McCreary et al. 2011).

CHAPARRAL AND CALIFORNIA (COASTAL) SAGE SCRUB

Chaparral and California (coastal) sage scrub (CSS) are widely appreciated by ecologists for their uniqueness and high biodiversity, but they are less appreciated by the general public relative to the more charismatic species and communities in California (e.g., coast redwood forests). Chaparral and CSS occupy extensive areas in the southern and coastal portions of the State (Cleland et al. 2016, Parker et al. 2016). These communities are largely unique to California and in the United States only occur sporadically beyond the State's borders.

Chaparral and CSS communities occur in regions that experience a pronounced summer dry period, often with 4 or more consecutive months of no precipitation. Annual precipitation is about 8–40 inches for chaparral and 10–18 inches for CSS. Chaparral is the most extensive plant community in the State. It is found at low to mid elevations (0–6,600 feet) along the coast and occupies portions of all mountain ranges, with highest abundance in mountain foothills in southern California from San Luis Obispo to the Mexican border (Parker et al. 2016). Important chaparral shrub taxa include chamise (*Adenostoma fasciculatum*), manzanitas (*Arctostaphylos* spp.), California lilacs (*Ceanothus* spp.), toyon (*Heteromeles arbutifolia*), and several oaks (*Quercus* spp.) (Parker et al. 2016). Manzanita and California lilac are the two most important taxa with respect to species diversity and rarity, and both are sensitive to drought. Many manzanita and California lilac species have narrow distributions that require special management and conservation considerations. Found almost entirely in southern California, CSS occurs at low elevations (<1,000 feet) along the coast and inland areas and sporadically in the Coast, Transverse, and Peninsular mountain ranges. Common shrub taxa in CSS include California sage (*Artemisia californica*), sages (*Salvia* spp.), brittlebushes (*Encelia* spp.), and buckwheats (*Eriogonum* spp.). Both chaparral and CSS have species-rich herbaceous flora comprising perennial and annual species (e.g., Cleland et al. 2016, Parker et al. 2016).

The response of chaparral and CSS communities to drought is similar to their response during the dry summer months. Seedlings of nonsprouting plants often exhibit high rates of mortality during their first summer dry season (Frazer and Davis 1988, Thomas and Davis 1989), and mortality may increase during drought (Pratt et al. 2008). When drought becomes severe, the branches of some plants die back, and mortality of entire plants may be observed (Coates et al. 2015, Paddock et al. 2013, Valliere et al. 2017, Venturas et al. 2016). During the 2012–2016 drought in California, dieback and shrub mortality were widespread among many species (fig. 4.10). In addition to drought, chaparral and CSS communities can be stressed by wildfire, pathogens, invasive species, nitrogen deposition, and freezing temperatures. When drought occurs following wildfire, resprouting chaparral and CSS species may experience elevated mortality (Kimball et al. 2014, Pratt et al. 2014) or reduced ability to sprout (Pausas et al. 2016). Habitat fragmentation and land-use changes can amplify the effects of drought (Davis et al. 2005, Kimball et al. 2014, Pratt et al. 2014, Riordan and Rundel 2014, Valliere et al. 2017).

Woody species in chaparral communities have diverse responses to drought. Most chaparral shrubs are evergreen, retaining leaves during drought but with thinning of their canopies. Part of this thinning is the senescence of leaves, but leaves may also change shape

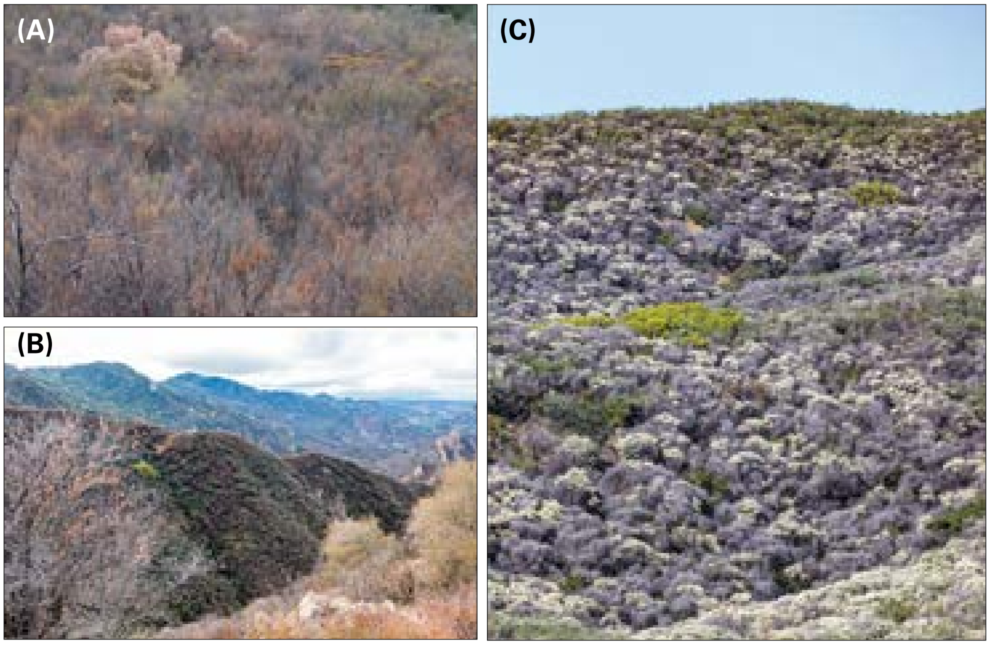

Figure 4.10—During a severe drought in 2014, chaparral shrublands experienced shoot dieback and plant mortality. (A) Shrub mortality reduced stand density by 63 percent, greatly modifying community structure (Venturas et al. 2016). (A, B) The red-orange leaves died relatively recently. Because these plants are evergreen, mortality of foliage generally indicates that branches are dead. (C) A stand photographed in 2016. Two years after the drought, many dead gray branches are still visible from plants that died in 2014. (Photos by A. Jacobsen, California State University-Bakersfield [A] and R. Pratt, California State University-Bakersfield [B, C])

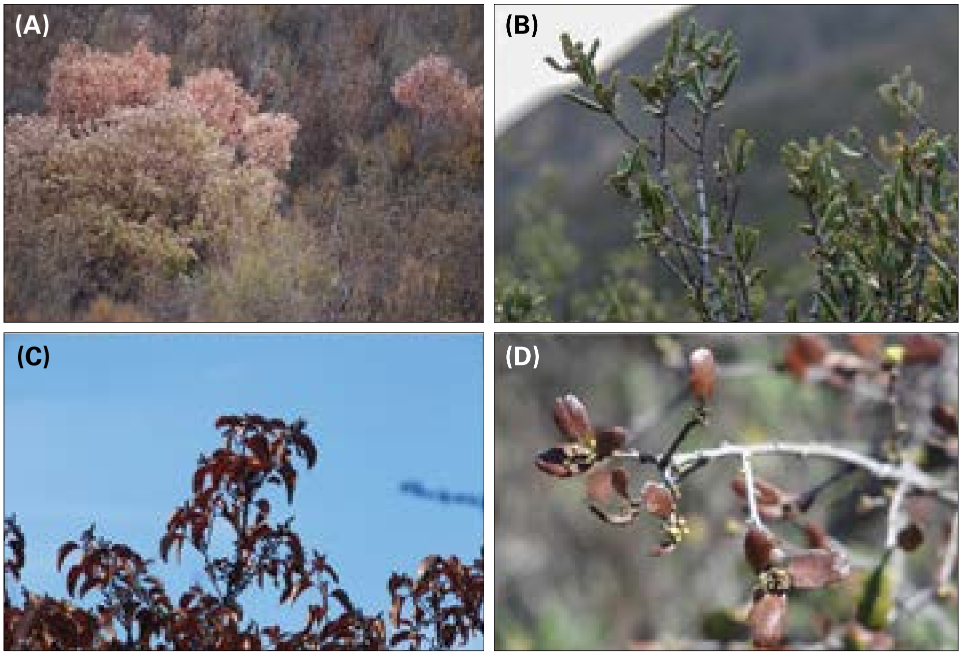

Figure 4.11—During drought, evergreen species often retain their leaves and show signs of extreme stress. Both (A) manzanita and (B) California lilac species show increased leaf angle, and California lilac may also have curled leaf margins. Increased or continued stress leads to branch or whole-plant dieback and death. Other species, such as *Rhus* and laurel sumac, fold their leaves into a “taco” shape, and (C) laurel sumac often reddens considerably during periods of stress. (D) Scrub oak can lose many or all of its leaves during drought and is considered a facultatively drought-deciduous species; small green living buds are visible on the branch of a plant that lost nearly all of its leaves during drought. (Photos by A. Jacobsen, California State University-Bakersfield [A, C, D] and R. Pratt, California State University-Bakersfield [B])

and orientation, including orienting vertically toward the sky, curling at the margins, or folding (fig. 4.11). Leaf yellowing and reddening during drought often signal extreme stress. If the drought is severe enough, leaves fall from the dead branches and gray stems are visible (fig. 4.10C). Growth and flowering of shrubs are generally suppressed by drought, but they are also affected by the timing of rainfall. Some species (e.g., manzanita, California lilac) produce flower buds in the year before they flower, and drought can suppress flowering even if the subsequent year has normal rainfall. Other species (e.g., chamise) produce buds and flower in the same year and are affected by current-year conditions.

Dominant CSS species respond differently to drought than chaparral species in some respects. Many drop a substantial portion of their leaves during the dry season, even during normal rainfall years (fig. 4.12). During drought, leaf drop may occur earlier, and suppression of growth can lead to stands appearing open and sparsely vegetated. Dieback of branches is common, and many CSS species produce tissues that are moderately woody (suffrutescent) and that do not live as long as chaparral species. The more open conditions in CSS stands have a higher risk to invasion by nonnative forbs and grasses (Cleland et al. 2016, Kimball et al. 2014, Jacobsen et al. 2009).

Rooting patterns affect the response of shrubs to drought; in general, species with shallow roots are most sensitive to droughts because they do not have access to water at lower depths in the soil profile. More deeply rooted species (e.g., scrub oak [*Quercus berberidifolia*], laurel sumac [*Malosma laurina*], sugar sumac [*Rhus ovata*], hollyleaf cherry [*Prunus ilicifolia*]) will be less visibly affected by droughts of mild or moderate intensity. In contrast, species with more restricted root systems (e.g., California lilacs, manzanitas, chamise) will be more affected, with substantial mortality of individuals observed (Coates et al. 2015, Paddock et al. 2013, Venturas et al. 2016). California (coastal) sage scrub species, in general, are shallow rooted.

Minimizing Drought Impacts

Effects of drought on chaparral and CSS are difficult to mitigate. However, minimizing other stressors and disturbances that create gaps in the plant community may help to deter nonnative species (especially grasses in the genera *Bromus* and *Avena*) that are flammable for much of the year (Brooks et al. 2004, Merriam et al. 2006) (table 4.2). Intact closed-canopy chaparral shrublands are quite resistant to invasion by nonnative annuals (Merriam et al. 2006), and flammability is moderate because their tissue moisture content remains relatively high during most of the year. Highly flammable fuels produced by annuals from late spring through autumn, in combination with increasingly frequent human-caused ignitions, are causing higher fire frequency in some chaparral systems than occurred historically. California (coastal) sage scrub is adapted to more frequent fires (Keeley et al. 2005, Zedler et al. 1983).

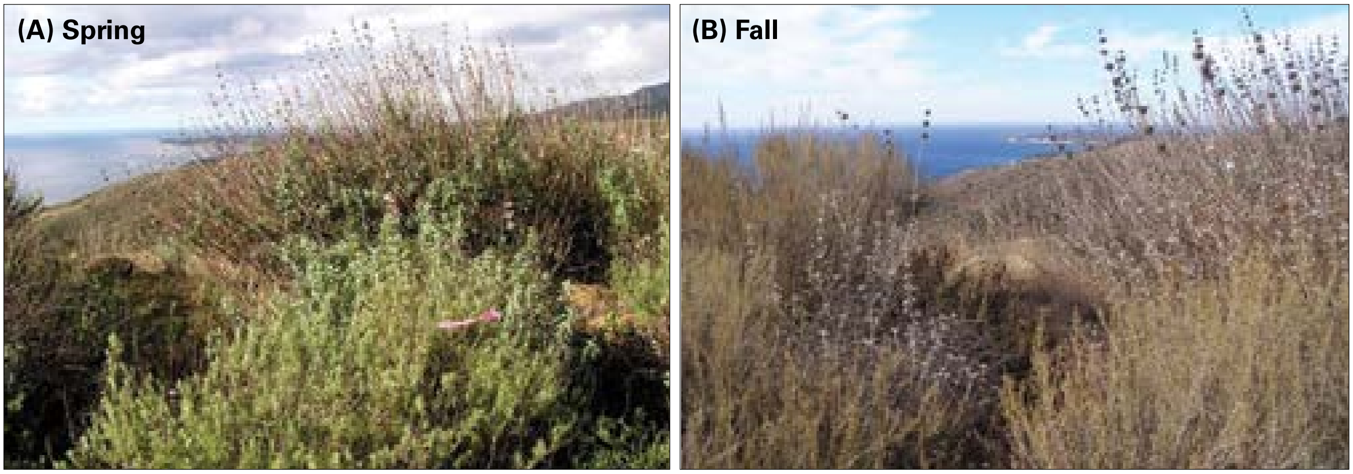

Figure 4.12—California (coastal) sage scrub (CSS) species show large seasonal changes in leaf type and abundance. (A) Many species have large green leaves during the winter wet season and early spring. (B) During water stress in summer-autumn, some species shed a large portion of their leaf area. Other CSS species have seasonally dimorphic leaves and grow a cohort of small, tough leaves as they head into the summer (e.g., *Salvia* spp.). California (coastal) sage scrub species respond to drought in the same manner as they respond to a typical dry season, by shedding leaf area. (Photos by A. Jacobsen, California State University-Bakersfield)

Although hazardous fuel reduction in some chaparral and CSS systems (e.g., wildland-urban interface) is desirable (Wilkin et al. 2017), fuel reduction treatments (mastication, fuel breaks, prescribed fire) can facilitate the spread of nonnative annuals (Brennan and Keeley 2015, Merriam et al. 2006, Wilkin et al. 2017). Therefore, feasible ways to minimize drought impacts involve proactive invasive plant management programs that focus on disturbed areas, including areas where fuel reduction treatments have been implemented (Cox and Allen 2008).

Facilitating Recovery

Widespread degradation of chaparral and CSS has increased interest in facilitating recovery of these ecosystems. Research on the efficacy of restoration efforts in degraded chaparral communities has been limited. Restoration efforts are better documented in CSS, in which management of nonnative annuals is a top priority (Cox and Allen 2008). In some cases, the most practical approach to facilitate recovery may be to focus limited resources on species that are rare and have limited ranges (many manzanitas and California lilacs) and those that are most affected by drought (table 4.2). However, drought may delay the ability of seeding plants to reach reproductive maturity and produce enough seeds to replenish soil seed banks (Zammit and Zedler 1993), decreasing the ability of stands to recover (Jacobsen et al. 2004).

GRASSLANDS

Two gradients influence grassland productivity in California. First, as climate becomes warmer and drier, productivity decreases from north to south. Second, the moderating effects of maritime fog decrease with distance from the Pacific Coast, and coastal prairies tend to be more productive than interior valley grasslands (Reever Morghan et al. 2007). California grasslands have experienced a near-complete conversion from native perennial bunchgrasses and annual forbs to nonnative annual grasses and forbs (D'Antonio et al. 2007, Jackson and Roy 1986) (fig. 4.13). The extent of this conversion typically increases with distance from the coast; hotter, drier interior grasslands contain more nonnative annual grasses and forbs, and coastal prairies contain more native perennial grasses (Clary 2008).

Direct effects of drought on grassland vegetation include decreased productivity and changes in plant composition, including species and functional groups (e.g., perennial to annual, native to nonnative, grass to forb). Effects of drought on grassland productivity are not uniform throughout the State. For example, during the height of the 2013–2014 drought in California, rangelands in northern California, where the drought was less severe, maintained >50 percent of their average annual forage production, whereas forage production in rangelands in southern California fell below 5 percent (Becchetti et al. 2016).

Unlike the effects of drought on forest ecosystems, drought conditions need not last for years to produce noticeable effects on grassland vegetation. Variability in rainfall during typically productive months (autumn through spring) can strongly affect grassland plant composition for the rest of the growing season. For example, when early autumn rains are followed by

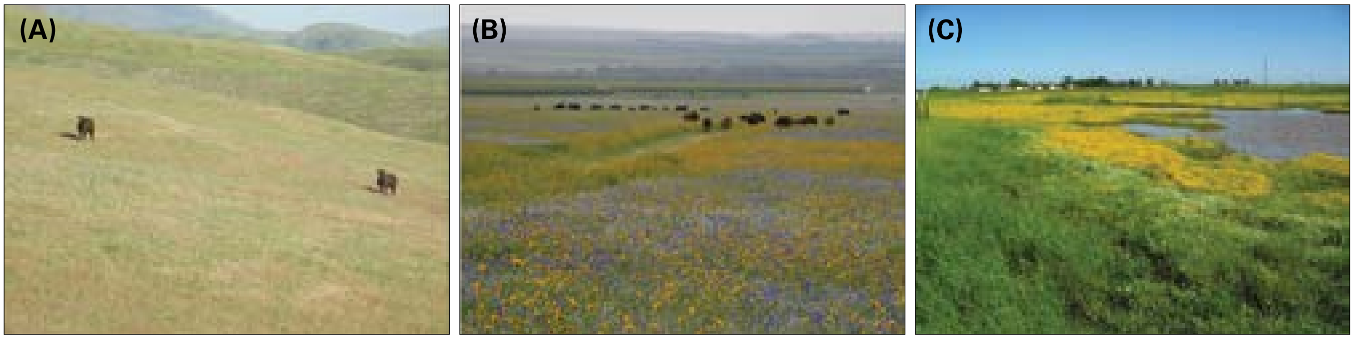

Figure 4.13—(A) Annual grassland at Tejon Ranch, Los Angeles County, provides forage for livestock. (B) Native forbs, including fiddleneck (*Amsinckia* spp.), lupine (*Lupinus* spp.), and California poppy (*Eschscholzia californica*) bloom among nonnative annual grasses at Tejon Ranch. (C) Native Fremont's goldfields (*Lasthenia fremontii*) bloom along the edge of a vernal pool in Grasslands Regional Park, Yolo County. Vernal pool complexes embedded within California grasslands provide habitat for many native, endemic, and special-status plant and animal species. (Photos by R. Wenk, University of California [A, B] and J. Balachowski, USDA California Climate Hub [C])

sustained rainfall, earlier germinating annual grasses typically dominate grassland vegetation that year. In contrast, if germination is followed by drought, the early annual grasses are more likely to die, leading to increased abundance of drought-hardy forbs (e.g., *Erodium* spp.) or later germinating forbs and legumes (Bartolome et al. 2007, Eviner 2016, Young and Evans 1989). These alternating patterns of "grass years" and "forb years" have long been recognized. Midwinter droughts, which are common in California (Reever Morghan et al. 2007), tend to favor perennials over annuals (Corbin et al. 2007).

Drought can also reduce plant diversity. A recent study found that 15 years of drought in a California grassland community reduced native annual wildflower diversity (Harrison et al. 2015). Because community-level diversity is associated with invasion resistance, such declines may favor establishment of nonnative species. The effects of drought may also be expressed through interactions with other stressors and management practices. Indeed, drought in combination with overgrazing by livestock is the most commonly cited cause of widespread conversion from native perennials to nonnative annuals (D'Antonio et al. 2007, Eviner 2016). Drought and warming can also lead to more wildfires, which can further favor replacement of native species with fire-tolerant nonnative species (Finch et al. 2016). Rapid establishment of cheatgrass (*Bromus tectorum*) increases the likelihood of more frequent, intense, and large fires, which in turn makes conditions even more favorable for cheatgrass (Balch et al. 2013).

Grasslands have high biodiversity, and the effects of drought extend beyond associated plant communities. For example, endangered kangaroo rats (*Dipodomys ingens*) and kit foxes (*Vulpes macrotis*) in the Carrizo Plain National Monument have declined because of loss of vegetation due to drought (CDFW 2016). In addition, across grasslands in North America, drought is generally associated with an increase in insect outbreaks (Finch et al. 2016), although the effects vary with biogeographic context (Barnett and Facey 2016).

Minimizing Drought Impacts

In grasslands managed for grazing, drought leads to decreased forage production, so managing livestock to reduce grazing pressure is critical (table 4.2). Proactive strategies commonly used by ranchers to minimize effects of drought include moderate stocking rates, supplemental feeding, resting pastures, and incorporating yearling cattle into an operation (Macon et al. 2016). Development of drought contingency plans and income diversification (on and off ranch) will help to minimize long-term risks (Brown et al. 2017, Macon et al. 2016, Roche 2016). Rangeland stock ponds offer a means to store water during wet years, which will become more important as precipitation becomes more variable (e.g., California Rangeland Conservation Coalition; see box 4.1). Stock ponds also provide essential habitat for endangered amphibians, such as the California red-legged frog (*Rana draytonii*) (USFWS 2006).

Prescribed fire is often used in western grasslands to control nonnative or undesirable species (e.g., annual grasses and woody encroachment; Breshears et al. 2016, Knapp et al. 2009), thus minimizing the effects of drought because perennial grasses are typically more drought- and fire-resilient than annuals (Knapp et al. 2009, but see Potts et al. 2012). Timing of prescribed burns is critical, and burns should generally be applied when annuals and other undesirable species are most vulnerable to mortality from fire (Gornish 2017).

Facilitating Recovery

Grassland restoration in California typically involves removal of nonnative species and replacing them with native bunchgrasses, rhizomatous grasses, and forbs. On rangelands, supplemental planting often occurs without large-scale removal of standing vegetation. Both practices depend on water availability during the growing season (Gornish 2017; Hardegree et al. 2011, 2016), so embarking on large-scale grassland restoration during droughts is generally not a sound investment. Success may be improved by deploying several smaller projects over multiple years, increasing the likelihood that 1 or more years will provide sufficient rainfall to establish plants (Gornish 2017).

Weed management efforts may benefit from more variable rainfall (Eviner 2016). Many native perennial grasses have similar growth and reproductive timing to later developing noxious weeds (e.g., barbed goatgrass [*Aegilops triuncialis*], medusahead [*Taeniatherum caput-medusae*]), which are a growing concern for grassland and rangeland managers. Once established, native species suppress noxious weed growth. Fluctuating rainfall provides beneficial conditions for establishment of these native species, which are better adapted to withstand short-term droughts and to take advantage of late-season rains (Reever Morghan et al. 2007).

Planting diverse combinations of drought-hardy species and genotypes can minimize the consequences of drought and facilitate recovery. Different guilds (e.g., Funk et al. 2015, Vaughn et al. 2011), species (e.g., Balachowski et al. 2016, Vaughn et al. 2011), and genotypes (e.g., Balachowski and Volaire 2018) can vary in both the traits they use to survive drought and thresholds of plant mortality during drought. Planting a diverse array of species and functional groups (e.g., grasses and forbs) can help buffer against drought and other disturbances by increasing the likelihood that some species will survive to maintain ecosystem function even if others fail (Broadhurst et al. 2008, McKay et al. 2005, Yachi and Loreau 1999). Resource guides (e.g., Gornish 2017), decision-support tools, and best practices are being developed and updated to help identify drought-appropriate species and seed sources (e.g., Seedlot Selection Tool, National Seed Strategy; see box 4.1).

CONCLUSIONS

Although droughts are common in California, the 2012–2016 drought is believed to be the most severe in the last 1,200 years (Griffin and Anchukaitis 2014). Similarly, a drought that occurred in the Southwestern United States in the early 2000s is believed to be the most severe in the last 1,000 years (Williams et al. 2013). Evidence from global climate modeling suggests that these events portend future droughts that will have widespread effects on forests and rangelands. We anticipate that severe droughts will become the norm by the middle of the 21st century (Griffin and Anchukaitis 2014, Williams et al. 2013), but even moderate droughts can have crucial and long-lasting effects on the structure and function of ecosystems. Specific management options for addressing drought impacts vary by ecosystem (table 4.2), and in general attempt to (1) shift systems back within the natural range of variation (including disturbance regimes) to the degree possible and (2) facilitate a transition to plant species better adapted to future droughts. In forests and woodlands, drought management focuses on the use of mechanical thinning and prescribed burning both to decrease stand densities and to promote the growth and vigor of desirable tree species. In chaparral, frequent disturbances are stressors, so soil disturbances need to be limited as much as possible to reduce the spread of nonnative annuals that promote wildfires. Invasive plants are also an important problem in grasslands, where they should be removed and replaced with native grasses and forbs. In grasslands, prescribed fire may be useful to manage nonnative species and increase perennial plant cover to make grasslands more drought-resilient. In rangelands, conservative stocking rates, supplemental feeding of livestock, and resting pastures should be considered during times of drought. Many of these management strategies will also help California to reach its objective of maintaining natural and working lands within the State as carbon sinks (i.e., net zero or negative greenhouse gas emissions) (CARB 2017, Forest Climate Action Team 2018).

For drought management strategies to be most effective, timely implementation is needed across large spatial scales. However, land managers and land management agencies require both political and fiscal support for this proactive approach to be realistic. As the frequency and magnitude of droughts increase, our ability to better quantify and predict impacts on ecological and human systems, and to develop and implement appropriate management actions, will become more critical. This is especially true in California, where a large human population, diverse natural resources, and large agricultural and forestry sectors are all potentially vulnerable.

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CHAPTER 5

Managing Effects of Drought in Hawai‘i and U.S.-Affiliated Pacific Islands

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INTRODUCTION: CONTEXT AND PROBLEM FRAMING

How Is Drought Expressed in Hawaiʻi and the U.S.-Affiliated Pacific Islands?

Drought is a significant climate feature in Hawaiʻi and the U.S.-Affiliated Pacific Islands (USAPI) (figs. 5.1, 5.2), at times causing severe impacts across multiple sectors. Below-average precipitation anomalies are often accompanied by higher-than-average temperatures and reduced cloud cover. The resulting higher insolation and evapotranspiration can exacerbate the effects of reduced rainfall. These altered meteorological conditions lead to less soil moisture. Depending on the persistence and severity of the conditions, drier soil can cause plant stress, affecting both agricultural and natural systems. Hydrological effects of drought include reductions in streamflow, groundwater recharge, and groundwater discharge to springs, streams, and near-shore environments.

The effects of drought on reduced water supply also have social and economic consequences. Therefore, drought has been defined from at least five different perspectives: (1) meteorological, (2) hydrological, (3) ecological, (4) agricultural, and (5) socioeconomic (see chapter 1). In this chapter, we explore how these drought perspectives are expressed in Hawaiʻi and the USAPI, and how resource managers address drought-related stressors to their systems.

Direct and Indirect Impacts

Meteorological drought—Droughts vary in duration, frequency, extent, and severity. A region with meteorological drought is characterized by severe episodic droughts, with little or no rainfall for months, even in areas that normally have no dry season. El Niño events (the warm phase of El Niño Southern Oscillation [ENSO]) fall into this category. These moderate-frequency events are typically responsible for shorter lived but intense drought events that affect large areas.

Drought can also be expressed as infrequent but long-duration events of moderate severity, or long-term rainfall decline, where the baseline condition appears to be changing when examined on longer time scales. From the perspective of a resource manager, understanding the duration, frequency, extent, and severity of drought is critical to understanding the duration, frequency, extent, and severity of the drought

BOX 5.1

Geographic Scope

This chapter covers the State of Hawaiʻi and the U.S.-Affiliated Pacific Islands (USAPI). Hawaiʻi comprises eight major islands: Niʻihau, Kauaʻi, Oʻahu, Molokaʻi, Lānaʻi, Maui, Kahoʻolawe, and Hawaiʻi. The main Hawaiian Islands are in the Pacific Ocean between 18.90°N and 22.24°N latitude, and 160.25°W and 154.80°W longitude (fig. 5.1). The climate of the Hawaiian Islands is extremely diverse, partly due to the large elevation range from 0 to 4205 m (13,796 feet), with mean annual rainfall from 200–10 270 mm (8–400 inches) (Giambelluca et al. 2013).

The USAPI comprise six jurisdictions in the Pacific Basin having special relations with the United States (see fig. 5.2). Two of these jurisdictions, American Samoa and Guam, are territories (as are the U.S. Virgin Islands), and one, the Commonwealth of the Northern Mariana Islands, is a commonwealth (as is Puerto Rico). The residents of these territories are U.S. citizens, except in American Samoa where the residents are U.S. nationals (U.S. State Department). Three other jurisdictions—the Republic of Palau, the Republic of the Marshall Islands (RMI), and the Federated States of Micronesia (FSM)—are now independent nations, but they were formerly districts of the United Nations' Trust Territories of the Pacific Islands, created after World War II and administered by the United States (U.S. State Department).

In combination, the islands in the USAPI occupy a wide range of latitude and longitude, spanning an aggregate east-west distance of over 2,700 miles (4345 km), from 20°30′N to 14°30′S and from 171°56′E to 131°07′E, which is greater than the width of the continental United States. All of these islands, except those of American Samoa, lie north of the equator in the broad region of Oceania known as Micronesia. As a result, these Micronesian islands have some general similarities in regard to their overall climate regimes and meteorological forcing mechanisms. The Samoan Islands, by contrast, lie south of the Equator, and as a result are subject to a somewhat different meteorological regime (Polhemus 2017).

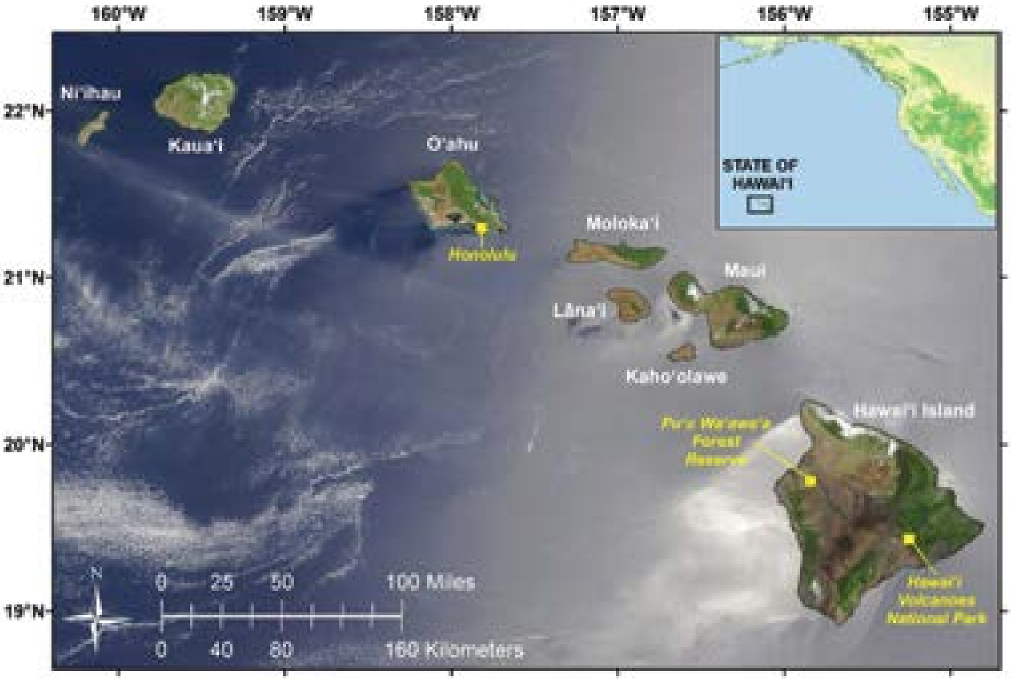

Figure 5.1—State of Hawai‘i with eight major islands labeled. Background imagery: MODIS Image of Hawai‘i, NASA Earth Observatory. Map: A. Frazier, U.S. Department of Agriculture, Forest Service.

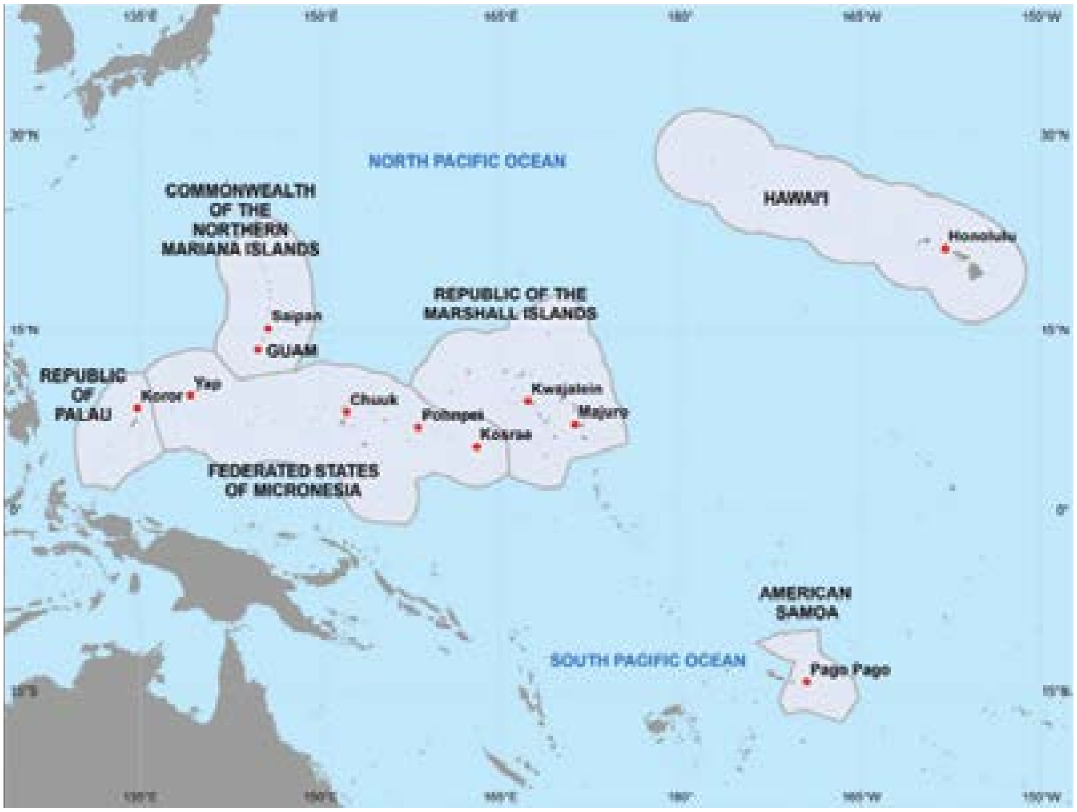

Figure 5.2—Map of the U.S.-Affiliated Pacific Islands, showing EEZ (exclusive economic zone) boundaries and locations of major islands, atolls, and cities. Map courtesy of L. Brewington, East-West Center.

response. For example, an agency’s response to El Niño events, with a focus on short-lived but large-scale emergency response campaigns, may differ from a response to baseline change or an increase in the frequency of extended dry periods, with a focus on longer lived institutional, infrastructure, and personnel responses.

A long-term network of climate stations is necessary to understand and characterize meteorological drought. Rainfall has been extensively monitored in Hawai‘i since the early 1900s, owing to the expansion of plantation agriculture (Giambelluca et al. 1986), while rainfall monitoring for most of the USAPI began in earnest in the 1940s, after World War II (Polhemus 2017). Because of prevailing winds, most land area in Hawai‘i is characterized by a wet season from November to April and a dry season from May to October. However, dynamic features affect climate systems of the Pacific. For example, because of their tropical location, rainfall patterns in both Hawai‘i and the USAPI are strongly controlled by large-scale modes of climate variability, including ENSO. El Niño events are typically associated with drier-than-average winter wet seasons and wetter dry seasons, whereas La Niña events often result in wetter-than-average wet seasons and drier dry seasons.

Many historical drought events have been attributed to El Niño events, which produce atmospheric conditions unfavorable for rainfall (Chu 1995). However, the relationship between El Niño events and drought is not simple: not all El Niño events result in drought, and effects differ depending on whether the El Niño is classified as Central Pacific (CP) or Eastern Pacific (EP) because the latter is characterized by more atmospheric water vapor over the eastern Pacific region (Bai 2017, Polhemus 2017). Furthermore, successive El Niño and La Niña events appear to be a dominant factor for long-duration drought events in Hawai‘i (e.g., dry winter from El Niño followed by dry summer with La Niña) (Frazier 2016).

Hydrological drought—Long periods of low rainfall can reduce surface water and groundwater availability (table 5.1), leading to hydrological drought. Reduced streamflow is the first indication of the onset of hydrological drought, as prolonged precipitation deficiencies begin to affect components of the hydrological cycle. Reduced streamflow leaves less

Table 5.1—Sectors affected by drought

TYPE OF EFFECT	SECTOR OR ASPECT AFFECTED	MECHANISM	EFFECTS
Direct	Streams	Less rainfall for sustaining streamflow	Less streamflow and groundwater recharge, more conflict over water use
Indirect	Stream habitat	Higher stream temperatures, less connectivity, threatened stream fauna	Higher management cost for species identified as threatened or endangered; potential loss of species
Indirect	Wildfire management	More wildfire activity	Spread of fire-adapted, often fire-promoting, invasive grasses and shrubs; forest degradation and species loss
Indirect	Invasive species management	Dry conditions favor invasive species that out-compete native species	Higher management cost for species identified as threatened or endangered; potential loss of species
Indirect	Pest and disease management	More pest and disease activity	Native plants vulnerable to infestation and mortality
Direct	Agriculture—farming	Less soil moisture	Crop-yield losses in rain-fed systems
Indirect	Agriculture—ranching	Reduced growth of vegetation (forage) needed by livestock	Lower livestock production, higher livestock prices
Direct	Drinking water	Less rainfall (supplying water to reservoirs, catchments, and groundwater recharge), higher water demand	Water shortages for water catchment users; voluntary water reductions
Indirect	Nearshore habitats	Wildfires expose soils to rain, increasing erosion and sediment delivery to nearshore areas	Sediment exacerbates other climate-driven stressors for nearshore reefs, e.g., warming that can cause coral bleaching and ocean acidification
Direct	Traditional cultural practices	Less rainfall and streamflow reduce available water (stream) for domestic uses and irrigation; less groundwater discharge to nearshore fishpond environment	Lower yields of traditional food sources (e.g., taro, breadfruit); lower aquaculture yields in native fishponds; negative impacts to other ceremonial and medicinal plant species
Direct	Threatened and endangered species	Lack of water	Death of endangered nēnē goslings (Hawaiian goose, *Branta sandvicensis*), and endangered plants (seedlings and adults)

water to replenish lakes and ponds, support wetland and wildlife habitats, restore reservoirs, and divert into ditch systems. As hydrological drought progresses to extreme hydrological drought, groundwater levels are reduced. Lower groundwater levels exacerbate the potential for saltwater intrusion and can negatively impact drinking water wells and nearshore and marine ecosystems that rely on the discharge of fresh groundwater.

The most important aquifers in the region consist of freshwater lenses floating on denser seawater, and the groundwater in these aquifers is sustained by deep percolation of rainfall (Giambelluca et al. 1991). Thick freshwater lenses (e.g., Pearl Harbor, O‘ahu) generally are less sensitive than thin lenses to periods of low rainfall. However, increased demand for agricultural and domestic water, resulting in higher pumping rates, can cause water levels to decline and salinity of pumped water to increase. For thin aquifers (e.g., Kona, Hawai‘i), the transition zone between fresh and saltwater is closer to the pump intakes. During droughts, small changes in lens thickness due to reduced recharge may increase salinity of water pumped from these aquifers (Giambelluca et al. 1991).

High islands, with their topographic complexity, larger aquifers, and perennial stream networks, have water resources that are more resilient to severe hydrological drought. Less resilient are low-lying atolls, characterized by less extensive groundwater bodies that are more vulnerable to saltwater intrusion and do not sustain perennial streams (Polhemus 2017). Low-lying islands rely heavily on rainwater catchment systems and thin freshwater lenses for water supply, making the consequences of below-average rainfall severe and immediate. Sea-level rise and increased storm activity, both manifestations of a changing climate, can cause saline contamination in these thin lenses due to marine overwash events, where saltwater percolates into soil and groundwater. Increased frequency of these saltwater inundations, and degradation of lenses themselves, interact to severely reduce recovery time for the lenses.

Freshwater ecosystems are particularly vulnerable to reduced streamflows (Gillson et al. 2012) because drought conditions reduce surface water runoff and groundwater discharge into streams (Strauch et al. 2015, 2017a). Drought may also cause increased concentrations of fecal bacteria, with higher loads immediately after rain events (Strauch et al. 2014). Reductions in streamflow limit the availability of freshwater habitat and reduce water quality (e.g., increase stream temperature, decrease dissolved oxygen), which negatively affect stream fauna (Strauch et al. 2017b). Reduced discharge of surface water and groundwater into estuaries and nearshore environments also may harm brackish and marine organisms.

Continued drought conditions force many populations—suppliers of municipal drinking water, domestic users, and agricultural irrigation systems—to rely on more expensive delivery from groundwater sources (see case study 5.1). Some traditional and customary practices of Native Hawaiian communities depend on surface water resources. These practices, including wetland cultivation of taro (*Colocasia esculenta*), gathering of aquatic and riparian species, and aquaculture, are also directly affected by drought conditions. Because Native Hawaiians and Pacific Islanders have persisted on islands for millennia, future research should evaluate historic drought management strategies that have allowed these cultures to thrive across innumerable drought events.

Ecological drought—As meteorological drought persists, soil water availability decreases, which can lead to many impacts on both natural and managed systems (table 5.1), expressed as ecological drought. In Hawai‘i and the USAPI, the most common expression of ecological drought is an increase in wildfire occurrence (Polhemus 2017, Trauernicht et al. 2015). Wildfires in Hawai‘i are most frequent and extensive in nonnative grasslands and shrublands, which cover approximately 25 percent of total land area in the State and account for 80 percent of annual area burned (Hawbaker et al. 2017). During more severe drought events, wildfire can also occur in native wet forests (see case study 5.2). In the USAPI, most wildfires occur in native-dominated savannas, which can be up to 10–20 percent of total land cover on many islands, and which probably developed from recurrent burning since human arrival (3,000–4,000 years BP) (Athens and Ward 2004, Dickinson and Athens 2007, Minton 2006).

In response to drought, the risk of wildfire in grasslands and savanna vegetation can increase rapidly, which then increases the vulnerability of adjacent forest. The capacity of native forests to recover after wildfire in the Hawaiian Islands and some areas in the USAPI can be significantly limited by the rapid establishment of nonnative species, many of which increase the probability of future fires (LaRosa et al. 2008, Smith and Tunison 1992).

Wildfire leads to other ecological consequences, causing higher rates of erosion from recently burned areas and increased sediment delivery to streams and nearshore areas (Minton 2006). Nutrients in post-fire ash can be mobilized and, along with soil, be transported into streams and eventually nearshore areas, with impacts to stream biota and reef communities. Wildfires also have direct effects on human communities, damaging valued resources and infrastructure. In the most severe cases, these events cause road closures and even evacuations.

El Niño events can increase wildfire danger because of reduced rainfall and increased fuels from drying vegetation. During summer months, El Niño events are typically associated with more tropical cyclone activity, with increased rainfall for the islands. These wetter summer/fall conditions increase plant productivity and biomass accumulation, including in fire-prone grasslands and savannas (Cheney and Sullivan 2008). During winter months, however, El Niño events are typically associated with drier than average conditions. Dry winter weather results in widespread senescence and curing of vegetation and reduced fuel moisture, increasing the potential for wildfire occurrence and rate of spread.

Aside from the effects of ecological drought on wildfire, understanding is limited about other effects of ecological drought on the region. Remote-sensing studies offer some evidence. Barbosa and Asner (2017) found that, although remotely sensed greenness indicators were affected by short-term drought, a significant amount of variation in greenness was explained by centennial-scale drought data. Other remote-sensing evidence shows clearly that dry forest regions "brown down" during drought events (Pau et al. 2010), and that El Niño-induced drought events can shift the position of the upper elevation forest line (Crausbay et al. 2014). Studies of species-specific animals and plants in Hawai'i have identified recent droughts as a contributing factor in the decline of endemic forest birds (e.g., the palila [*Loxioides bailleui*], a critically endangered species of Hawaiian honeycreeper) and high-elevation plant populations (e.g., the iconic Haleakalā silversword [*Argyroxiphium sandwicense* ssp. *macrocepahalum*]) (Banko et al. 2013, Krushelnycky et al. 2013, Lindsey et al. 1997). In dry forest systems, drought-pest interactions have led to tree mortality of native species (see case study 5.3). Ecophysiological studies are under way to better understand the vulnerability of native ecosystems to drought.

CASE STUDY 5.1

Drought effects on drinking water supply on Maui

Reduced rainfall from meteorological drought can have direct effects on social-ecological systems; the most obvious consequence is reduced runoff and streamflow. Streams provide important ecological services on tropical islands, including water for hydropower production, habitat for freshwater fauna, irrigation of agriculture, and potable water supply. On Maui Island, surface water is a critical source of potable water supply, supplying 26.7 percent of total water for the island. Some regions are more dependent on surface water supply than others. For example, surface water sources supply most of the water systems in upcountry Maui (84.6 percent) and west Maui (65.1 percent) (fig. 5.3). These streams are vulnerable to drought, leading to frequent declarations of stage 1 water shortages (voluntary reductions in water use), where anticipated water demand is projected to exceed available water supply by 1–15 percent. Reservoirs in these regions help buffer the water system against shifts in surface water availability. However, if drought conditions continue and water conservation measures do not limit short-term use, stage 2 or stage 3 water shortages may be declared, requiring mandatory reductions in water use.

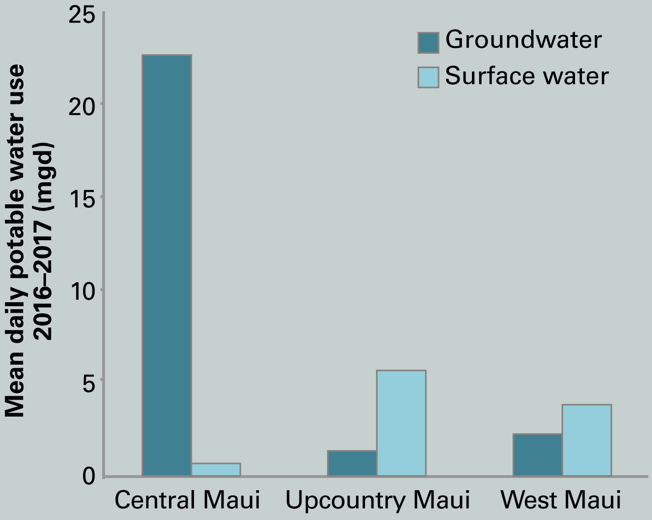

Figure 5.3—Maui County Department of Water Supply mean daily groundwater versus surface potable water use for central Maui, upcountry Maui, and west Maui regions, 2016–2017.

mgd = million gallons per day.

CASE STUDY 5.2
Drought and wildfire at Hawai'i Volcanoes National Park

During the 2002–2003 drought, relative humidity values dropped into the single digits, and wildfire spread into "safe areas" of Hawai'i Volcanoes National Park, including wet forests, with tree ferns (*Cibotium menziesii*) and uluhe ferns (*Dicranopteris linearis*) as the main carriers. Despite dozens of firefighters, miles of fuel breaks, and helicopter water drops, the fire spread into the East Rift Special Ecological Area, burning important habitat and damaging the ungulate-proof fence. Immediate action was required to replace the fence and prevent pig ingress to the area. This series of fires also impacted the lower elevation wet/mesic forest, with swordfern (*Nephrolepis multiflora*) as the main carrier. Post-fire restoration work included monitoring along with seeding and planting fire-tolerant native species. Years of lab and field trials (Loh et al. 2009) were conducted to determine which species are fire-tolerant and then to collect and bank seeds from those species (McDaniel et al. 2008). Future projects will re-survey the plots to examine longer term changes in community composition.

"The 2010 drought is the one that really changed the way I personally see the threat of drought. It was shocking to walk into the 'Ōla'a area of the park and see the forest floor dusty and the ferns crispy and dry. This is a place you usually don't venture to without rubber boots, rain gear, and Rite-in-the-Rain paper (see fig. 5.4). It made an impact on me to see how vulnerable the rare wet forest species are to extended dry periods. Some of these species are represented by only a handful of individuals, or in the case of the jewel orchid (*Anoectochilus sandvicensis*), a single patch. If their patch of forest suddenly cannot support them they could be extirpated—or if the park has the bulk of the individuals, extinct."—*Sierra McDaniel, Botanist, Hawai'i Volcanoes National Park*

Figure 5.4—'Ōla'a area of Hawai'i Volcanoes National Park during normal conditions. (Photo by S. McDaniel, National Park Service)

Predrought management:

- **Other stressors:** manage other stressors, e.g., remove ungulates, control invasive species (some nonnative species like strawberry guava [*Psidium cattleianum*] have higher transpiration rates), test rat control measures on a small scale
- **Fire:** establish and maintain fuel breaks, reduce fuels, bank fire-tolerant seeds, monitor fuel conditions
- **Monitoring:** establish monitoring plots for community change in subalpine and wet forest (Inventory & Monitoring [I&M]), map rare species
- **Rare species:** expand rare plant populations across ecological range, provide ex situ storage

Management during drought:

- Implement fire prevention including closures
- Supplement food/water for endangered bird species, e.g., nēnē (Hawaiian goose, *Branta sandvicensis*)
- Increase frequency of fence inspections because of added pressure on fences from animals seeking greener forage
- Adjust restoration activities (e.g., no planting)
- Continue invasive plant control (typically), but may need to suspend treatment of alien grasses if conditions are too dry and they are not photosynthetically active
- Increase predator trapping

Management after drought:

- If a fire occurred, conduct post-fire restoration with fire-tolerant native species (see fig. 5.5)
- Possibly replace rare species
- Use I&M data to evaluate long-term vegetation changes and formulate response

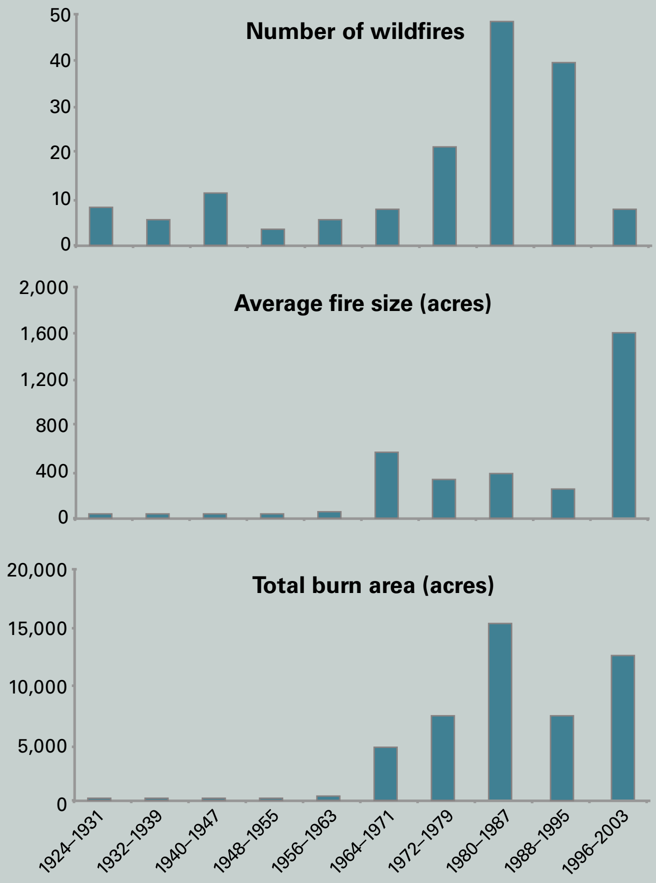

Figure 5.5—In Hawai‘i Volcanoes National Park, fires are increasing in frequency, size, and total area burned.

CASE STUDY 5.3

Coping with drought at Pu‘u Wa‘awa‘a Forest Reserve

2010 Drought

"The 2010 drought was particularly severe at Pu‘u Wa‘awa‘a Forest Reserve (PWW). Everything looked gray and brown without a hint of green in the kikuyu grass (*Pennisetum clandestinum*) anywhere. Dust was blowing in the wind, it was really hot and sunny almost every day without the usual afternoon cloud cover, and the forest looked parched. There wasn't a lot of vegetation on the Pu‘u Wa‘awa‘a cinder cone because most of it had died or was dormant, and there seemed to be stick forests everywhere (mostly dead māmane [*Sophora chrysophylla*], fig. 5.6). There were very few insects, and our vegetable garden (on irrigation of course) was very productive and did extremely well as compared to today where everything seems to get eaten by invertebrates. There were also no State staff around because everyone was fighting the large wildfire at Pōhakuloa Training Area up on Saddle Road."
— *Elliott Parsons, Coordinator of the Pu‘u Wa‘awa‘a Forest Reserve*

Figure 5.6—Dead māmane trees (*Sophora chrysophylla*) in a brown field of dead kikuyu grass (*Pennisetum clandestinum*), September 2010. (Photo by E. Parsons)

Management during drought:

- General: PWW was shut down for public access for at least 6 months to reduce wildfire threat, large public events such as the 2011 Run for the Dry Forest were canceled, and research access was curtailed as well.
- Cattle grazing to reduce fire fuel loads: The State Division of Forestry and Wildlife issued special use permits (1-year revocable permits) for cattle grazing to reduce fountain and kikuyu grass biomass outside of fenced restoration/protection areas. Some cattle in the area were unhealthy because of lack of forage, nutrients, and water, and many died. New high-elevation areas were opened up during the drought where cattle had previously been kept out to allow for forest recovery. In this area, dozens of native koa (*Acacia koa*) trees had grown, ranging from a few feet to 10–15 feet high. Cattle heavily browsed the smaller koa trees; today, only the trees that were at least 10 feet tall at the time are still standing.
- Endangered and vulnerable species:
  - Endangered A'e trees (*Zanthoxylum dipetalum* var. *tomentosum*) were individually fenced (the last 10 wild trees left are at PWW, see fig. 5.7). Some of the invasive plants around the base of the trees were removed, and ooze tubes were set up to water the trees over a period of a couple weeks. The ooze tubes were refilled every month from a water tank in the back of the work truck. Seeds were collected whenever they were found.
  - Supplemental food was provided for nēnē (Hawaiian goose, *Branta sandvicensis*) at the main nesting site because drought had largely eliminated forage (kikuyu grass).

Figure 5.7—Supplemental watering and fencing of A'e (*Zanthoxylum dipetalum* var. *tomentosum*), endemic to Hualālai area and highly endangered. (Photos by E. Parsons)

- Monitoring: New monitoring programs were started including:
  - Surveys for endangered plants.
  - Resurvey for all endangered plants in the proposed Kauila-Halapepe conservation unit.
  - A halapepe (*Chrysodracon hawaiiensis*) survey across the reserve, begun when the Forest Service found that the agricultural pest banana moth (*Opogona sacchari*) had infested these trees. The survey included identifying the banana moth and individually tagging a large number of halapepe to follow their fate over time.
  - A naio (false sandalwood, *Myoporum sandwicense*) monitoring study, to evaluate the impact of the newly invasive thrips (*Klambothrips myopori*) on tree health (see fig. 5.8).
  - A survey of invasive tree tobacco (*Nicotiana glauca*) use by the endemic and endangered Blackburn's sphinx moth (*Manduca blackburni*).
- Restoration work, including weed removal and outplanting of dryland forest species and mixed mesic species, required hand watering multiple times a month to keep them alive until rainfall arrived.

Figure 5.8—Invasive Myoporum thrips (*Klambothrips myopori*, inset) in Hawai'i infesting naio (*Myoporum sandwicense*, false sandalwood), resulting in galling, dieback, loss of foliage, and eventually tree death. (Photos by E. Parsons)

Management after drought:

- Public access was reopened in 2011 after some rainfall returned.
- Permitted cattle grazing is still occurring on a rotating basis to reduce fire fuel loads around existing fenced conservation units. This decision has consequences for grass biomass in some areas, but not all sensitive ecological areas have been fenced yet to exclude ungulates including cattle.
- A new $5.5 million capital improvement project was begun in 2017 to fix a large water catchment system, reline an upper elevation reservoir, and send water down to a lower elevation reservoir where fire threat is greater. This project will reduce wildfire threat during future droughts by adding a large amount of water for restoration, firefighting, and cattle grazing.
- Mapping all of the four-wheel-drive ranch roads was initiated to aid managers and fire fighters, and large fire fuel breaks have been created in several areas.
- The individual fencing for A‘e trees is being maintained and seeds are being collected, but the ooze tubes are no longer needed.
- Seeds of as many native species as possible were collected and deposited in the Hawai‘i Island Seed Bank for future restoration efforts and to guard against loss of genetic diversity from mortality due to drought and wildfire.
- The monitoring programs initiated during the drought are all ongoing. However, about 50 percent of the halapepe trees were lost since 2011. Signs of banana moth infestation were present during 2012–2013, but the massive tree die-off did not occur until 2013–2014, suggesting a possible lag between drought effects on native plants and mortality. Around 10–20 percent of the tagged naio trees were lost to thrips damage, and mortality was likely exacerbated by drought.
- Native plant survival during the drought was high, probably because of consistent supplemental watering. Some of the wild endangered plants that disappeared entirely during the drought have regenerated from the seed bank (e.g., *Hibiscus brackenridgei*) but are suffering from pests.

Lessons learned:

- There is a need to improve water infrastructure, create better mobile monitoring tools, survey all roads and threatened, endangered, and rare (TER)species, and have a better drought and fire plan in place before the next drought cycle.
- Cattle-grazing operations in forests with native plants are complicated during drought. Many regenerating koa trees were likely lost to cattle. Although cattle are used for fire-fuel reduction, they may create more problems through trampling, erosion, soil loss, and subsequent invasion by exotic plants during severe drought than they solve.
- Loss of the top vegetation layer from drought and ungulates (e.g., cattle, feral sheep, goats) led to erosion, loss of topsoil, and invasion by many weeds during and after the drought. Large thickets still remain of invasive apple of Sodom (*Solanum linnaeanum*) and tree tobacco that colonized large areas during the 2010 drought.
- Some TER plants that disappear during drought may come back if there is a seed bank and plants are protected by fencing (e.g., *Hibiscus brackenridgei*).
- Native trees were probably weakened during drought, leading to infestation by different pests. A lag may occur between when trees become stressed and infested and when they die.
- Many weed issues that were not a problem during drought became problematic afterwards. For example, Tinaroo glycine (*Glycine wightii*) was not a problem during drought but is now a huge problem in the dryland fenced areas.
- Monitoring of certain species and resources is easier during drought because foot surveys are easier when surveyors are less impeded by dense vegetation. Roads can be seen clearly on satellite imagery during drought but not as easily afterwards. Drought is the time to find roads, look for native trees, and do anything that requires moving easily over the landscape.
- More information is needed on which species can be recovered after drought or fire using seed-scattering methods.
- Finally, restoration is possible during drought. There is less weedy plant biomass to remove and far fewer pests that harm outplants. Therefore, if irrigation or hand watering is possible, at least some dryland forest plants can do well.

Agricultural drought—In an agricultural setting, irrigated systems are less vulnerable to short-term agricultural drought, but they become susceptible when water supplies decline or become too costly to buy or transport. By comparison, rain-fed fields, orchards, and pastures are the most vulnerable to agricultural drought, experiencing reduced crop yields, ground cover, and pasture productivity. For pastoral systems, these reductions can in turn affect livestock operations, often causing managers to reduce herd sizes as forage production declines.

In Hawaiʻi, drought impacts are most severe on non-irrigated agriculture and pasture lands supporting livestock. In 1953, a severe drought across the islands reduced pineapple production on Molokaʻi by 30 percent and resulted in substantial loss of cattle. The drought of 1980–1981 was declared a disaster, causing at least $1.4 million in cattle and agricultural losses. Drought emergencies in 1996, 1998–1999, and 2000–2002 caused heavy damage to agriculture and especially the cattle industry, with losses estimated at $6.5–9.4 million (CWRM 2005). The high-value vegetable-growing regions of Kamuela (Hawaiʻi Island) and upcountry Maui, which rely on aging ditch systems to divert stream water, are especially vulnerable to droughts. The drought of 1983–1985, for example, reduced crop production in Kamuela by 80 percent.

Droughts in the USAPI occur less frequently than in Hawaiʻi, but recent research indicates an increase in frequency and severity of El Niño-driven drought events (McGree et al. 2016, Polhemus 2017). The drought of 1983 was especially severe, causing 80- to 95-percent losses to taro and cassava (*Manihot esculenta*) in Palau. The El Niño drought of 1997–1998 significantly reduced harvests of important subsistence crops across the Federated States of Micronesia (FSM), including taro, coconut (*Cocos nucifera*), breadfruit (*Artocarpus altilis*), banana (*Musa acuminata*), yam (*Dioscorea alata*), and sweet potato (*Ipomea batatas*). Coconut production declined by 20 percent and did not recover to predrought production levels for 5 years. In the Republic of the Marshall Islands (RMI), the 1982–1983 and 1997–1998 droughts severely impacted agriculture, decimating nearly 50 percent of food crops across the central, southern, and western atolls. The 1997–1998 drought cut coconut production by more than 80 percent; as in the FSM, production took almost 5 years to rebound. More recently, drought conditions that began in 2012 across the northern Marshall Islands culminated in a declaration of a state of disaster in the Marshalls in 2013, persisting through 2016 (Polhemus 2017). The recent droughts in the Marshalls have severely impacted breadfruit production.

Non-irrigated pasture land devoted to the livestock industry in Hawaiʻi covers 761,420 acres, equivalent to approximately 83 percent of Hawaiʻi's active agricultural land area. Pasture lands in low rainfall areas (<30–50 inches per year) are already marginal for forage production and so are more vulnerable to droughts than in higher rainfall areas. A substantial portion of Hawaiʻi's pasture land is found in these drought-vulnerable regions: on Hawaiʻi Island, pastures in low rainfall areas occupying 291,100 acres (51 percent of Hawaiʻi pasture lands); 42,370 acres on Maui (57 percent of Maui pasture lands); and 23,353 acres on Kauaʻi (39 percent of Kauaʻi pasture lands) (Fukumoto et al. 2015, 2016a, 2016b). Within the agricultural sector, the livestock industry is often the first and most severely impacted because most ranch lands are non-irrigated and occur in low-rainfall zones that are immediately affected by lack of rainfall.

The high-value vegetable production areas of upcountry Maui (Olinda and Kula) and Hawaiʻi Island (Waimea) are also vulnerable to drought because the irrigation systems servicing both areas cannot provide adequate water during frequent dry periods. In the USAPI, where the vast majority of agriculture is rain-fed, droughts have severe impacts on food production and local food security. The impacts are most severe on atolls where freshwater resources are already limited and in low-lying agricultural systems; for example, taro and swamp taro (*Cyrtosperma chamissonis*) are vulnerable to salinization (Taylor et al. 2016).

Socioeconomic drought—The complete range of social and economic impacts of drought depends on the aggregate physical characteristics of drought and the characteristics of the resources and social systems exposed to drought. Low reservoir levels, thinning freshwater lenses, and saltwater intrusion can lead to water shortages. These are most often managed through water restrictions, typically voluntary but in some cases mandatory, and are applied to both residential and agricultural sectors. Water shortages can result in millions of dollars of lost revenue in the agricultural sector as well as millions of dollars in costs of relief assistance during water shortage emergencies (CWRM 2017, Polhemus 2017).

Other human dimensions of drought, such as physical and mental health problems, interpersonal conflict, loss of educational opportunities, and loss of cultural traditions are more difficult to quantify (Finucane and Peterson 2010). Cultural impacts that continue after an acute or prolonged drought include stress on agriculture (subsistence or economically important) and soils, changes in nearshore fisheries, change in accessibility of important freshwater heritage sites (springs and seeps), lack of key plant and animal species used in cultural practices, and even forced migration (Sproat 2016, Taylor et al. 2016). Human communities, and the ecosystem services on which they rely, regularly recover from the impacts of drought (Weir et al. 2017), although the speed and ability with which they recover depends on the geography of the island, specific resources, governance system, the general socioeconomic status of the area, and other stresses (Adger et al. 2013).

For communities that rely on subsistence agriculture and fishing, recovery can be particularly difficult (Taylor et al. 2016). Within subsistence communities, atoll residents who depend on shallow groundwater aquifers for their irrigation and potable freshwater may suffer harsh consequences. For example, if wells in shallow aquifers are over-pumped and infiltrated with saltwater during or after drought, they may remain brackish or never recover enough to be a potable supply (van der Brug 1986). A reduced freshwater supply could affect both the ability of a community to remain in that location and its ability to irrigate agricultural crops. Coastal fisheries and reefs that are integral for both subsistence and the social structure of a community can be set back long after drought events because droughts can shift estuarine and coastal fish species composition (Gillson et al. 2012), slow flushing times and increase the chance of algal blooms (Alber and Sheldon 1999), and alter coastal vegetation communities for years afterward (White and Alber 2009). In Hawai‘i, traditional loko i‘a (fishpond) aquaculture helps to cultivate fish and supports the intergenerational teaching of local fishing practices. Shifts in freshwater inputs, sediment and pollutant fluxes, salinity, and water quality after a drought can impact the function and species composition of these culturally significant systems (table 5.1).

The aftereffects of drought have significant consequences for varied sectors of the economy throughout Hawai‘i and the USAPI, including tourism, agriculture, and associated commercial development. In 2011, tourism in Hawai‘i comprised about 20 percent of the total adjusted gross domestic product, with estimates for agriculture ranging from 3 to 6 percent (Keener et al. 2012, Leung and Loke 2002). Both tourism and agriculture will suffer where drought intensifies saltwater intrusion and accelerates salinization of the water supply. Saltwater intrusion negatively impacts agricultural practices that rely on groundwater, but both irrigated and non-irrigated crops show lower yields during and after a drought (CWRM 2017). Drought also affects visitor industries because of the high dependency on supplies of clean freshwater. Islands that rely on ecotourism operations are further affected because of drought-related consequences to the ecosystems that are the focus of the tourist experience. For example, after the 2015–2016 El Niño drought event in the Pacific, the Republic of Palau experienced a large spike in the mortality of moon jellyfish (*Aurelia aurita*) and golden jellyfish (*Mastigias papua etpisoni*) in Jellyfish Lake, a major tourist attraction. Mortality was attributed to reduced freshwater flows and other potential interacting ecological impacts (PEAC Center 2016a).

On isolated atolls, cascading impacts from natural disasters, such as severe drought followed by storms or saltwater intrusion, can produce mounting negative effects across different measures of socioeconomic well-being, such as public health, education, and food security (Hernández-Delgado 2015). In the 1982–1983 drought event in the Republic of the Marshall Islands (see case study 5.4), daily freshwater rationing was reduced to 1 gallon per day per person (van der Brug 1986); subsequent drought events have been associated with gastrointestinal illness and conjunctivitis (WHO 2015). Drought can lead to lower incomes at the individual and community level, where agriculture both provides subsistence and supplements household income and commercial sales (Bell and Taylor 2015, Friday et al. 2017). In American Samoa, where the tuna cannery traditionally employed over 1,500 workers, drought conditions required importing freshwater at high cost to support continued cannery operations (Dworsky and Crawley 1999).

CASE STUDY 5.4

Drought and ENSO predictions in the Marshall Islands

The Republic of the Marshall Islands (RMI) lies north of the equator in the western North Pacific Ocean (fig. 5.2) and consists of 29 atolls with over 1,100 individual islands and islets. The tropical Pacific location of RMI makes it sensitive to variations caused by the El Niño-Southern Oscillation (ENSO), affecting rainfall, sea level, and tropical cyclone activity. El Niño is a strong predictor of meteorological drought in this region and allows skillful predictions of drought events, with lead times up to 9 months. The low-lying nature of these atolls and their dependence on rainwater catchment systems for drinking water make them highly vulnerable to prolonged periods of below-average rainfall (Holding et al. 2016, Polhemus 2017). The major RMI population centers, on Majuro and Kwajalein Atolls, are both served by international airports whose runways also serve as rainfall catchments that feed centralized water delivery systems (Polhemus 2017). During periods of low rainfall, these systems must be supplemented by water from reverse osmosis units and wells. Wells often rapidly become brackish from overuse.

During the drought of 1982–1983, the water supplies on Majuro became extremely depleted, and water service from the central delivery system was restricted to 2 hours each morning and evening; in February 1983, it was then cut back even further, to 1 hour every third day. By May 1983, this system was so depleted that water deliveries were primarily reserved for use at the hospital, with the populace relying largely on shallow wells hastily developed by the government. On the other more remote atolls, which rely on small catchments and shallow wells, the water supply situation became acute, with daily rations reduced to 1 gallon per day per person (van der Brug 1986). During the drought, rainfall at both Kwajalein and Majuro from January through May was only 13 percent of the long-term averages for each location.

In 1994, after recognizing the strong relationship between climate variability and drought in the USAPI, the NOAA National Weather Service (NWS), along with the University of Hawaiʻi and other partners, established the Pacific ENSO Applications Center

Figure 5.9—Public Works in Majuro, Marshall Islands, established freshwater "filling stations" around the atoll to help people access water during the extended drought of 2015–2016. Majuro Atoll Local Government is delivering reverse osmosis-produced drinking water from the College of the Marshall Islands to these filling stations April 9, 2016. (Photos courtesy of the Marshall Islands Journal)

Figure 5.10—Dying pandanus trees (*Pandanus tectorius*) during drought on Mejit Atoll, Marshall Islands, May 2013. (Photo courtesy of Moana Marine, http://moanamarine.com/projects/)

(PEAC) (Schroeder et al. 2012); the name was changed to Pacific ENSO Applications Climate (PEAC) Center in 2007. The mission of the PEAC Center is to monitor ENSO conditions, provide tailored products for planning and management including advisories and outlooks, prepare a 3-month outlook every month, and make skillful long-lead, ENSO-based rainfall and sea-level forecasts. The PEAC Center also provides periodic education and event warning outreach.

During the El Niño of 1997–1998, which resulted in severe water rationing in Majuro and other Pacific Islands, the PEAC Center proactively worked to help people by providing preemptive information about the impact of El Niño. By April 1997, the PEAC Center had successfully predicted dry conditions for early 1998, and by July the predictions indicated that this event would be comparable to the 1982–1983 event. The PEAC Center scheduled in-person outreach visits with each island and assisted in the development of drought response plans. The PEAC Center also contacted the Federal Emergency Management Agency (FEMA), which assisted RMI in developing and submitting presidential declaration requests (Schroeder et al. 2012).

Drought continues to plague the Marshall Islands (figs. 5.9 and 5.10), with acute socioeconomic drought effects seen again in 2015–2016, when a state of drought disaster was declared for the northern atolls of the RMI (Polhemus 2017). Total rainfall at Majuro from October 2015 to July 2016 was the driest 10-month period in the 62-year historical record at that station (PEAC Center 2016b). The PEAC Center and local NWS offices are critical partners in helping local government officials to prepare for drought events and have worked to lessen the socioeconomic drought impacts across the region.

Identifying and Quantifying Future Drought Risk in Hawai‘i and USAPI

Limitations—Hawai‘i and the USAPI have small land areas (~500 km wide in Hawai‘i) that are poorly captured in general circulation models (GCMs) because these models typically use 100-km horizontal grid spacing or greater for simulations. Tall islands, including the main Hawaiian Islands, have complex topography and extremely spatially diverse climate patterns that vary greatly over short distances. However, a GCM may represent all major Hawaiian Islands in only a few grid cells (Lauer et al. 2013), which is too coarse to accurately simulate these complex climate patterns (Elison Timm et al. 2015). To overcome this issue, a technique known as “downscaling” is needed to derive local- and regional-scale information (<3-km horizontal grid spacing) from larger scale models. Downscaling uses two main approaches: dynamical downscaling (DDS) and statistical downscaling (SDS). Dynamical downscaling uses regional climate models, while SDS develops statistical relationships between large-scale atmospheric variables and local/regional climate variables (empirical data), then applies the relationships to predictors from global models (IPCC 2013).

Downscaling accuracy varies with location, season, parameter, and boundary conditions. Uncertainty can arise from many areas: resolution, model complexity, method chosen, observational uncertainty in evaluation data and parameterizations, choice of model domain, and boundary data (driving data). For Hawai‘i, both DDS and SDS products are available to predict future temperature and rainfall (Elison Timm 2017, Elison Timm et al. 2015, Zhang et al. 2016), but other climate variables are available only from DDS (Lauer et al. 2013, Zhang et al. 2016). For the USAPI, only DDS products are being developed, and only for some islands (Polhemus 2017).

Future projections—Future temperatures in Hawai‘i are expected to increase (Elison Timm 2017, Lauer et al. 2013, Zhang et al. 2016), and the trade wind inversion is projected to become more frequent, resulting in drying, particularly at high elevations (Longman et al. 2015, Zhang et al. 2016). If atmospheric moisture increases, windward areas are expected to show slight increases or no changes in precipitation, while leeward areas are projected to experience significant drying (Elison Timm et al. 2015, Zhang et al. 2016). Even if rainfall does not change in the future, temperatures will continue to rise, and drought severity and frequency in the future will increase because of greater evaporative demand. However, with the

BOX 5.2
Measures of drought

In Hawai‘i, the U.S. Drought Monitor (USDM) (Svoboda et al. 2002) is a widely used drought resource. The USDM is a weekly product with contributions from local authors who synthesize empirical data, drought indices, and drought impact reports from local informants to develop a map depicting drought conditions across Hawai‘i. U.S. Drought Monitor maps show drought intensities ranging from D0 (Abnormally Dry) to D4 (Exceptional Drought) as well as associated impacts.

Other indices such as the Standardized Precipitation Index (SPI) and the Keetch-Byram Drought Index (KBDI) are available for Hawai‘i, but are limited in their spatial and temporal coverage. The KBDI, for example, is publicly available for only one station in the State, at the Honolulu Airport (although KBDI is calculated by individual agencies like the National Park Service using data from nearby stations). For example, the National Park Service uses KBDI as part of the National Fire Danger Rating System (NFDRS) through data collected at Remote Automated Weather Stations (RAWS) at Kalaupapa, Haleakalā, and Hawai‘i Volcanoes National Park. Keetch-Byram Drought Index values are calculated through the Wildland Information Management System (WIMS) program. At this time, indices like the Palmer Drought Severity Index (PDSI) cannot be calculated because of insufficient data on soil moisture and evapotranspiration in Hawai‘i.

The USDM was made available for the USAPI in April 2019. Before this product was released, however, a widely used source of drought information for Pacific Islands is the Pacific ENSO Applications Climate (PEAC) Center. The PEAC Center, developed in 1994, is a partnership among multiple institutions, including the National Oceanic and Atmospheric Administration (NOAA) National Weather Service (NWS), the University of Hawai‘i–School of Ocean and Earth Science and Technology, and the University of Guam–Water and Environmental Research Institute (Schroeder et al. 2012). The mission of the PEAC Center is to “conduct research and develop information products specific to the USAPI on the ENSO climate cycle, its historical impacts, and latest long-term forecasts of ENSO conditions, in support of planning and management activities in such climate-sensitive sectors as water resource management, fisheries, agriculture, civil defense, public utilities, coastal zone management, and other economic and environmental sectors of importance to the communities of the USAPI” (https://www.weather.gov/peac/). See case study 5.4 for more information about the PEAC Center and its role in drought preparedness and management in the USAPI.

already-dry, drought-prone leeward areas projected to become drier, these leeward areas are expected to be at high risk for drought in the future. In addition to the regional projections from downscaled models, the strong link between ENSO and drought in this region allows us to use global ENSO projections to infer potential changes to drought in Hawai‘i and the USAPI. The frequency of extreme El Niño events is projected to increase (Cai et al. 2014, Wang et al. 2017), which will likely result in more extreme drought in the region.

PREDROUGHT MANAGEMENT

Water Infrastructure

Predrought management practices can improve resilience to drought and mitigate the impacts of drought if they are implemented before the onset of drought. The Hawai‘i Drought Plan (CWRM 2017) recommends seven broad categories or mitigation actions that could reduce the impacts of drought:

- Statewide and island-wide water resources monitoring, drought forecasting, and impact assessments
- Development of water sources
- Increasing freshwater security
- Public education awareness and outreach
- Watershed protection partnerships
- Legislation
- Land-use planning

This section will cover water infrastructure for agriculture, drinking water, and forest/wildland fire suppression. Management options for water infrastructure before drought focus on increasing water capture and storage capacity, improving delivery efficiencies, securing backup/alternative water sources, improving end-user efficiencies, and providing education and outreach. Regardless of sector, other predrought management options also include drought response plans that outline actions to take once a drought event occurs (table 5.2).

Agriculture—Reservoirs are the most important infrastructure solution to buffer agricultural and municipal systems from drought. However, the capacity of current infrastructure to effectively buffer this sector from prolonged drought is limited by small reservoir sizes and losses due to seepage and evaporation. The collapse of large-scale plantation agriculture during the 1980s and 1990s greatly reduced reservoir maintenance and management. As a result, many reservoirs throughout the State of Hawai'i are no longer in compliance with State code and have been taken out of service.

Hawai'i's sugar plantation legacy left many operational surface water irrigation systems across the State. These systems are supplied by water diverted from streams. Most systems are privately owned and continue to serve agricultural needs, and a few also serve drinking water needs. However, many systems are nearly a century old and need continual maintenance and repair. Some systems traverse lands with different owners, which adds complexity to maintaining these systems.

Drinking water—Much of Hawai'i's population relies on 135 regulated public water systems to deliver potable water to their homes and businesses. Over 90 percent of these systems are supplied by surface water, and the rest are supplied by groundwater wells (see case study 5.1). Drought affects utilities supplied by surface water faster (weeks to months) than utilities supplied by wells because most aquifers in Hawai'i have large storage capacities and may respond slowly to changes in rainfall (months to years). Further, throughout Hawai'i and the USAPI, many especially rural households depend on catchment water (CWRM 2017, Polhemus 2017). People can depend on these self-supplied systems directly for drinking water, particularly in USAPI, and they are also important water resources for other domestic uses.

Forest/wildland fire—Water for wildland fire suppression usually comes from nearby freshwater sources such as reservoirs, lakes, and other open water sources. However, many fires occur in dry areas with limited access to these water sources. Portable dip tanks supported by water-hauling tenders/tankers are a key resource for fire suppression in areas without available surface water or municipal water. In some areas, helicopter dip tanks are constructed near reservoirs or fire hydrants to facilitate water pick-ups. Hawai'i Volcanoes National Park constructed dip tanks in multiple locations, with one tank near sensitive park

Table 5.2—Predrought management options for improving water infrastructure and conservation

OBJECTIVE/SECTOR	AGRICULTURE	DRINKING WATER	FOREST/WILDLAND FIRE
Increase water capture and storage capacity	Expand and add reservoirs; increase supply from stream diversions and wells; line reservoirs	Add new wells or increase pumping capacity; expand/add reservoirs	Expand/add reservoirs; establish new dip tank sites; pre-position equipment in high-risk areas
Improve delivery efficiencies	Enclose or line open-ditch systems; detect and repair leaks; establish ditch cleaning and maintenance programs	Conduct water audits; detect and repair leaks; create main line replacement programs; manage pressure	Establish dip tanks and helicopter landing pads near critical areas
Secure backup and alternative sources	Construct wells; secure agreements for recycled water where feasible; explore storm-water capture	Construct backup wells; maintain replacement pumps/parts locally; use desalination	Secure agreements with landowners to use water sources
Improve end-use efficiencies	Use efficient irrigation methods (drip irrigation); seasonally adjust irrigation schedules; mulch; use conservation tillage	Implement customer water conservation programs (e.g., incentives, conservation rates, give-away and direct replacement programs)	Develop maps of critical infrastructure (e.g., fire roads, water sources, locked gates, equipment)
Outreach/education	Workshops for conservation practices; university extension service programs	Media advertising; water conservation contests; Fix-a-Leak Week[a]	Pre-fire season stakeholder planning meeting;[b] fire prevention campaign; Wildfire LOOKOUT![c]

[a] U.S. Environmental Protection Agency annual awareness campaign, which can be used by local water utilities.

[b] Although this does not directly improve end-use efficiency of water, this planning meeting can help firefighters coordinate response and equipment between organizations and make more efficient use of equipment, personnel, and water resources.

[c] Annual pre-fire season campaign headed by Department of Land and Natural Resources and Hawai'i Wildfire Management Organization (http://www.hawaiiwildfire.org/lookout/).

resources. These tanks are filled by rainfall catchment and supplemented by water hauling. In the summer of 2017, they were used successfully to suppress a rapidly spreading wildfire within the park.

Closing of sugar plantations and recent Hawaiʻi State dam safety regulations pose a challenge to keeping and maintaining reservoirs operational and filled for agriculture and firefighting uses. Saltwater from the ocean is not typically used for firefighting because it kills plants and can render the soil toxic for existing or recovering plants.

Wildfire

Strong drought events are closely linked with large fire years across the USAPI, when large percentages of total land area have burned on Palau, Guam, and the drier islands of the FSM. Drought and fire are also linked in Hawaiʻi, but they interact differently across Hawaiian landscapes. The Hawaiian Islands are more climatically diverse than any other USAPI, with a much stronger presence of nonnative, fire-prone vegetation (Trauernicht et al. 2015). Regardless of how drought affects fire danger, preparing for wildfire before a drought is critical to mitigate its impacts (table 5.3). Preparation includes (1) building up or maintaining fire suppression and emergency responder capacity and readiness and (2) preparedness at the level of individuals, households, communities, and large landowners and land managers.

BOX 5.3
Historical and recent drought in Hawaiʻi

In Hawaiʻi, the 2010 drought was one of the worst on record. According to the U.S. Drought Monitor, at least 40 percent of Hawaiʻi experienced severe drought (category D2) or worse for 35 consecutive weeks in 2010. For about half the State, severe drought or worse occurred from July 2008 through January 2014. This drought was associated with a Central Pacific (CP) El Niño event in 2009/10, and caused the U.S. Department of Agriculture to designate all four counties in Hawaiʻi as Primary Natural Disaster Areas. Drought consequences included lost crop and livestock production, encroachment of feral ungulates into agricultural areas, and wildfire occurrences on every island (Pierce and Pickett 2014), even in wet forest areas, as well as post-fire rain events that caused significant erosion and sediment delivery to nearshore areas.

Response—The capacity for firefighters to respond quickly to wildfires is essential to minimize suppression costs and fire damage (Lee et al. 2013). Municipal fire departments are typically first to respond to wildfires in the Pacific region, but they are primarily trained and equipped to fight structural fires. Many forestry agency staff are trained and equipped for wildland firefighting, but they must be called away from regular duties to fight a fire, which can lengthen response times. The National Park Service and U.S. Fish and Wildlife Service use continental U.S. firefighting resources on extended-duration incidents through a Master Cooperative Wildland Fire Management and Stafford Act Response Agreement. For other organizations, firefighters have identified two top priorities to maintain readiness and build cooperative relationships among agencies: (1) provide wildland-specific equipment (e.g., engines and water tenders with off-road capabilities) and (2) create training opportunities, especially those involving cross-agency participation (Gollin and Trauernicht, in press). Regardless of fire danger level or wildfire incident size, resources for fire suppression equipment and supplies are limited, and any equipment coming into Hawaiʻi to support fighting of fires needs to be shipped long distances. Mutual Aid Agreements and shared jurisdictions can facilitate joint responses by multiple agencies on fires, especially on larger, multi-day incidents.

Preparation—Planning for wildfire incidents by homeowners, landowners, and land managers involves (1) identifying hazards, valued resources, and mitigation opportunities; (2) developing evacuation procedures, especially for large landholdings; and (3) creating maps and other documents to communicate this information with fire responders.

Most fires on islands are caused by human activities, but there are also occasional lightning-strike fires and, on Hawaiʻi Island, lava-caused ignitions (e.g., fig. 5.11). The dry conditions that accompany drought are a primary cause of fires, but wildfire hazards also include high wind, low relative humidity, high ignition frequency, and unmanaged vegetation. Of these, ignitions and vegetation can be actively managed. Ignition risk can be mitigated somewhat by restricting access to high-risk or high-priority areas and restricting high-risk activities (e.g., operating machinery, welding) during drought (see

Figure 5.11—Aerial view of lava-ignited fire in June 2007 at Hawai‘i Volcanoes National Park. (Photo courtesy of National Park Service)

Invasive Species below). Another way to reduce ignition risk is to properly inform the public, the source of mostly accidental but also intentional ignitions.

Reducing vegetation-based fuels is another action that landowners and managers can take to mitigate drought effects on wildfire risk. Fuel loads and fuel continuity can be reduced by lowering hazardous fuels through restoration (invasive species removals and the planting of native species), establishing fuel breaks, targeted livestock grazing, and prescribed burning. All of these steps can reduce the size of wildfires and the intensity and speed at which they burn and spread (e.g., Oliveira et al. 2016, Prichard et al. 2017, Taylor 2006). However, higher intensity animal grazing can expose more soil, increasing the incidence of erosion when rains resume as well as causing impacts to remnant native vegetation. Fuel breaks are most effective at stopping fires when they provide access and defensible space for firefighters (Syphard et al. 2011). Adaptations in the built environment are also important (Penman et al. 2014), especially when extreme fire weather (e.g., very high winds and low relative humidity) reduce the effectiveness of fire breaks and strain suppression capacity (Arienti et al. 2006, Cheney and Sullivan 2008). Other ways to reduce fire impacts and facilitate fire response include increasing water availability; fireproofing homes and buildings; and improving roads, access, and signage.

Outreach—Science communication and outreach efforts are essential to increase the adoption of best practices for pre-fire planning and fuels management, and these are being implemented in three main ways. First, forestry agencies throughout the region have worked to various extents on public education about wildfire safety. More recently, the Hawai‘i Wildfire Management Organization (HWMO) and the Wildland Fire Program with University of Hawai‘i (UH) Cooperative Extension have increased the technical support and resources available on fire planning for the public and land managers throughout the region.

The HWMO has expanded the number of Community Wildfire Protection Plans and Firewise-certified communities throughout Hawai‘i State and on Guam. HWMO also partners with UH Cooperative Extension and the U.S. Department of Agriculture (USDA) Forest Service Institute of Pacific Island Forestry (IPIF) on the Pacific Fire Exchange (PFX), a regional partnership for the exchange of fire science knowledge funded by the Joint Fire Science Program. The HWMO and PFX have co-developed fire preparedness technical guides and workshops that promote landscape-scale, cross-boundary planning and resource sharing to maximize the effectiveness of pre-fire mitigation efforts. Finally, IPIF and USDA Forest Service Region 5 Fire and Aviation Management also have been funding multifaceted research and management projects in fire-prone areas of Hawai‘i, and in Guam, Palau, and the FSM, including fire history mapping, landscape restoration, shaded fuel break establishment, and fire prevention through education and outreach.

Invasive Species

Invasive nonnative (alien) species encompass an increasingly wide range and diversity of organisms, from microbial organisms (e.g., fungal and bacterial pathogens) to plants (e.g., small fire-prone grasses, large nitrogen-fixing canopy dominants) to animals (e.g., plant-eating insects, omnivorous foraging rodents, forest-modifying ungulates). Not surprisingly, invasive alien species can have wide-ranging impacts on ecosystem composition, structure, function, and dynamics. Across biome types, efforts to build ecological and social resilience to drought by managing invasive alien species are complicated by variations in (1) invasive species encountered, (2) the types of effects that invasive species can exert on watersheds and water supply, and (3) the individual and interactive responses of these organisms to changing environmental conditions. Conversely, the many co-benefits to drought-focused management of invasive alien species include enhanced native biodiversity, often improved health and increased human safety (in the case of fire), and other biocultural benefits, such as continued access to cultural and economic goods and services provided by native species.

Predrought management of invasive species (table 5.3) is most effective with a clear understanding of the hydrological benefits of invasive species management, whether by increasing water supply in previously invaded wet systems or by reducing erosional threats in previously fire-prone drier systems. For example, in wet systems that are heavily invaded by or have the potential to be invaded by strawberry guava (*Psidium cattleianum*), management of this alien invader can support ecological, botanical, and hydrological objectives (Balzotti and Asner 2017, Strauch et al. 2017a). To this end, Povak et al. (2017) used distributed hydrological modeling (after Strauch et al. 2017a) within a decision-support framework to build a tool to support efficient watershed stewardship on Hawai'i Island's windward wet forests, with a focus on invasive alien plant species removal.

This modeling tool identified those 250-acre hydrological units that, if either treated for strawberry guava or protected from invasion by strawberry guava, would provide the largest hydrological benefits to managers. The tool also considered other factors in constructing restoration or protection priorities. For example, each unit was scored with respect to the kind of conservation protection the land parcel received, how easy the parcel is to access, and any conservation co-benefits of restoration protection. In this case, drought was addressed indirectly by first considering the implications of reduced water supply, then maximizing opportunities for targeting management to those areas most likely to positively affect water supply (wet forests of Hawai'i Island).

Water-demanding invasive plant species can be targeted, with physical and chemical methods for removal of incipient populations or with biocontrol agents for extensive populations. Because drought management is fundamentally landscape management, drought-relevant management of invasive species ideally also considers and operates at landscape scales.

Agriculture

Well-managed pastures in good condition (i.e., high plant diversity with a range of growing seasons and rooting depths) are better adapted to withstanding the negative effects of drought (table 5.3). Pasture management entails regulating the intensity, frequency, and timing of grazing (Howery 1999). Moderate grazing intensity, carefully spaced over time, ensures that a pasture does not suffer from overgrazing. Overgrazing, including reduced root biomass and growth, prevents the ability of plants to extract soil resources and ultimately reduces aboveground growth and forage production. Moderate grazing, in contrast, maintains adequate root growth, enabling plants to extract soil moisture even during drought. More forage biodiversity in the pasture ensures a range of forages with varying tolerance to drought and a range of rooting depths, both of which promote vegetative coverage of the soil. Maintaining soil cover, even during drought, improves recovery once rains return by increasing infiltration and percolation, reducing evaporation, and preventing erosion.

In irrigated row-cropping systems, one strategy to counter the negative effects of reduced rainfall is to build and maintain soil organic matter. Soil organic matter increases soil water retention and increases plant-available water in the soil. Another way to reduce evaporative water loss from the soil surface is to use natural (wood chips) and synthetic (plastic cover) mulches. Although building and maintaining soil organic matter is a cornerstone of soil health and resiliency, this alone cannot overcome the destructive effects of drought on crop productivity. On the other hand, biodiverse agroforest-cropping systems developed in the islands of the USAPI are much better able to withstand and recover from drought because these systems are characterized by high plant diversity, with many varieties having more tolerance to drought and salinity.

MANAGEMENT OPTIONS DURING AND AFTER DROUGHT

To address the impacts of drought in an island system, diverse responses are needed to meet specific ownership, partnership, and county or larger State needs. The nature of these responses must recognize that municipality needs might conflict with agricultural needs, and both of these may conflict with the needs of native species in diverse ecosystems, including streams, forests, shrublands, and grasslands.

The duration, extent, frequency, and severity of a drought will affect how recovery proceeds. For areas that rarely experience drought, recovery from a severe drought of long duration will be different from areas that experience frequent droughts of short duration and moderate severity (see Barbosa and Asner 2017 for an ecological example). Once a drought event is over and rainfall returns to normal patterns, sectors will recover differently both spatially and temporally. Sustaining or reestablishing ecosystem services while recovering from drought depends on many factors, including type of harm done to an ecosystem, its accessibility for recovery efforts, resources available, and postdrought weather conditions. Postdrought reports, which can inform both drought recovery and drought preparedness actions, should document impacts, response actions, and effectiveness of preparation and response.

Water Resources

Stream fauna—Once streamflow returns, native stream fauna rapidly (within 1–12 months) recolonize stream habitats that connect to the ocean. As examples, after the 2014 restoration of ridge-to-reef streamflow in Wailuku River on Maui, native snails (hihiwai, *Neretina granosa*) were observed returning upstream from the ocean. Within 1 month of restored streamflow on Honomanu Stream, Maui, in 2016, both hihiwai and oopu nopili (*Sicyopterus stimpsoni*) were observed recruiting upstream (Skippy Hau, pers. comm.[1]). However, the control of nonnative species is critical for restoring native stream ecosystems. For example, during drought, nonnative Tahitian prawn (*Macrobrachium lar*) will populate pool environments, consuming detritus and preying on native species. Restoring streamflow using water diverted from other streams might also transport nonnative species, spreading their distribution and increasing the transmission of diseases they carry.

Infrastructure—During recovery from drought, managers and landowners can focus on restoring water infrastructure to predrought capacity, but this requires several considerations. Water-use restrictions should be lifted with caution to ensure that system capacity can effectively meet postdrought high water demand. Lowered flows during drought may have caused sedimentation and water quality issues in surface water ditch systems and reservoirs. Unused portions of irrigation systems may become desiccated from lack of water. Low reservoir levels may expose portions of these reservoirs to plant growth or erosion, which need to be addressed before filling. Guidelines for many drought recovery actions for infrastructure are like those for predrought management (tables 5.3, 5.4).

During drought, system managers and operators can carefully monitor both the water resources supplying their systems and customer consumption, quantifying streamflow and diverted water amounts along with water quality metrics. Groundwater resources should also be carefully monitored. Metrics include water withdrawn, water levels, freshwater thickness, salt-brackish-freshwater transition zone depth, pumping amounts, and chloride concentration of water pumped by wells.

Alternative water sources—Hawaiʻi's human population is growing, and along with it is the demand for water. This trend, together with higher awareness of environmental needs and cultural rights, has increased competition for limited natural supplies. In a future warmer climate with many land-use changes and increased pressures, use of alternative resources will increasingly become a key component in sustainable resource management for nonpotable needs. Alternative water sources available in Hawaiʻi include recycled water, gray water, storm water, and desalinated seawater.

Wildfire Prevention and Suppression

Tracking climate and weather is critical to monitoring and predicting the threat of wildfire (table 5.4). In Hawaiʻi, several efforts modeled off the National Fire Danger Rating System have been put forward, but strong climate gradients and insufficient information on local fuel types (Pierce and Pickett 2014) have limited the adoption of a statewide system (Burgan et al. 1974, Fujioka et al. 2000, Weise et al. 2010). The National Weather Service posts Red Flag warnings for Hawaiʻi and Guam when drought and weather conditions meet specific criteria (e.g., in Hawaiʻi: Keetch/Byram Drought Index [KBDI] >600, relative humidity [RH] <45 percent, sustained winds >20 miles per hour).

For the goal of wildfire suppression, fire danger warnings are effective only if agencies have the capacity to increase resources available for fire response. Ideally, increases in fire-related staffing are commensurate with fire danger. For example, Federal wildland firefighters with the U.S. Army Garrison will increase personnel during times of high fire danger. The National Park Service conducts fire training for most field-going personnel and equips qualified personnel with

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[1] Personal communication. 2016. S. Hau, Aquatic Biologist, Hawaiʻi Department of Land and Natural Resources (DLNR) Division of Aquatic Resources (DAR), 101 Māʻalaea Boat Harbor Road, Wailuku, HI 96793.

Table 5.3—Predrought management options by sector

SECTOR	MANAGEMENT OPTIONS
Water resources	• Increase water capture and storage capacity. • Improve delivery efficiencies. • Secure backup/alternative water sources. • Improve end-user efficiencies. • Increase education and outreach. • Make drought response plans outlining actions to be taken once a drought event occurs.

Wildfire	• Build up or maintain fire suppression and emergency responder capacity and readiness.
	• Improve preparedness at the level of individuals, households, communities, and large landowners/land managers:
	  • Identify hazards, valued resources, and mitigation opportunities.
	  • Develop evacuation procedures.
	  • Create maps and other documents to communicate this information with fire responders.
	• Reduce vegetation-based fuels through restoration (invasive species removals with planting of native species), fuel breaks, targeted livestock grazing, and prescribed burning.
	• Establish and maintain physical (roads) or biological (green stripes) fuel breaks to help reduce the spread of wildland fires and provide access and defensible space for firefighters.
	• Increase water availability, fireproof homes and buildings, and improve roads, access, and signage.
	• Increase science communication and outreach efforts to promote adoption of best practices for pre-fire planning, fuels management, and reducing ignition risk.
	• Ensure adequate water availability for fire suppression (nearby reservoirs, lakes, and other open freshwater sources). In areas without available surface water or municipal water:
	  • Provide where possible portable dip tanks supported by water hauling tenders/tankers—a key resource for fire suppression.
	  • Consider constructing helicopter dip tanks near reservoirs or fire hydrants to facilitate water pick-ups.

Invasive/TER species	• Target water-demanding invasive plant species with physical and chemical methods for removal of incipient populations, or with biocontrol agents for extensive populations. • Reduce the number of nonnative ungulates through culling or exclusion by fencing.
Agriculture	• Ensure that pastures are well-managed and in good condition (high plant diversity with a range of growing seasons and rooting depths). Manage intensity, frequency, and timing of grazing. • Maintain soil cover, even during drought, to improve recovery once rains return to increase infiltration and percolation, reduce evaporation, and prevent erosion. • Build and maintain soil organic matter in irrigated row-cropping systems. • Use natural (wood chips) and synthetic (plastic cover) mulches to reduce evaporative water loss from the soil surface. • Use biodiverse agroforest cropping systems (i.e., with high plant diversity and with many varieties having greater tolerance to drought and salinity). • Ensure adequate reservoirs to buffer agricultural and municipal systems from drought.

TER = Threatened, endangered, and rare.

Table 5.4—Drought and postdrought management options by sector

SECTOR	MANAGEMENT OPTIONS
Water resources	• Restore water infrastructure to predrought capacity. • Assess water quality in surface water ditch systems and reservoirs. • Control nonnative species to restore native stream ecosystems. • Lift water-use restrictions cautiously to ensure that system capacity can effectively meet high water demand. • Carefully monitor groundwater resources, including water withdrawn, water levels, freshwater thickness, salt-brackish-freshwater transition zone depth, pumping amounts, and chloride concentration of water pumped by wells. • To inform drought recovery and future drought preparedness, write a postdrought report to document drought impacts, describe drought response actions taken, and evaluate effectiveness of drought preparation and response. • Consider use of alternative water resources for sustainable resource management for nonpotable needs (recycled water, gray water, storm water, desalinated seawater).
Wildfire	• Restrict access to high-risk or high-priority areas, or restrict high-risk activities (operating machinery, welding) during drought to mitigate ignition risk. • Track climate and weather to monitor and predict the threat of wildfire. • Ensure that agencies have the capacity to increase resources available for fire response. • Consider using fire danger rating systems to support prevention efforts by (1) informing the public about hazardous conditions and (2) justifying to agencies and landowners the need to restrict access and activities to reduce the chance of ignitions. • Scale up wildfire-prevention messaging in response to drought, a relatively low-cost, potentially high-impact mitigation strategy. • Use signage and media including radio for wildfire prevention campaigns, especially when El Niño development allows longer range forecasting of drought conditions.

Invasive/TER species	• Protect TER species:
	  • Enhance fire prevention (reduce fuel conditions and number of ignitions).
	  • When ignitions cannot be prevented, increase investment in fire suppression.
	  • Reduce the number of nonnative ungulates through culling or exclusion by fencing.
	  • Target fencing of individuals or groups of individuals of nonnative ungulates.
	  • For TER species of greatest concern, provide supplemental water through irrigation systems or even hand watering (see case studies 2, 3).
	• Plant TER species back into the wild, taking future droughts/climate into consideration as to where, when, and how TER enrichment planting and restoration are done.
	  • Select genotypes that are more resistant to drought for outplanting, better able to cast shade, or more competitive with aggressive nonnatives.
	  • Strategically locate plantings within or adjacent to areas that already are managed for other objectives.

Agriculture	• Ranchers may move or cull herds, slaughter cattle, or wean calves early. • Farmers may harvest early, plant less thirsty crops, prioritize irrigation, apply mulch, and pump more groundwater. • Use traditional knowledge to inform response actions. • Monitor reservoir, stream, and well levels more often. • Seek authorization to convert and use nearby wells for emergency water, facilitating use for private reservoirs; coordinate installation and use of standpipes for ranchers for livestock drinking water; use military surplus equipment to transport equipment and/or water to drought-stricken areas. • Coordinate and facilitate access to Federal assistance programs, low-interest State loans, and Federal crop loss programs and agriculture loans.

TER = Threatened, endangered, and rare.

firefighting gear during periods of elevated fire danger. Other agencies, however, especially in the USAPI, often lack additional personnel or equipment to increase suppression readiness during times of high fire danger.

Another way to support prevention efforts is with fire danger rating systems. These not only inform the public about hazardous conditions, but they also reduce the chance of ignitions by justifying to agencies and landowners the need to restrict access and activities.

In the USAPI, scaling up messaging on wildfire prevention in response to drought is a relatively low-cost, potentially high-impact mitigation strategy (table 5.4). Nearly all wildland fires on Pacific Islands are human-caused (Trauernicht et al. 2015). Preventable wildfires cause losses that vastly exceed the cost of prevention education (Prestemon et al. 2010). Wildfire prevention campaigns using signage, the media, and radio occur across the USAPI, especially when El Niño development allows longer range forecasting of drought conditions.

In Hawaiʻi, the 2015–2016 El Niño event provides an example of using science communication to spur agency response to a climatic event in the context of wildfire prevention. In November 2015, the Pacific Fire Exchange produced a fact sheet outlining the link between El Niño and increased fire activity (Trauernicht 2015). Many agencies—the University of Hawaiʻi Cooperative Extension, Hawaiʻi Wildfire Management Organization, and the National Weather Service—used this fact sheet to approach local wildfire-coordinating groups. The outcome was the development of the statewide Wildfire LOOKOUT! campaign, spearheaded by the Hawaiʻi Department of Land and Natural Resources and endorsed by over 20 Federal, State, and county agencies. In addition to an annual kick-off media event coinciding with the nationally recognized Community Wildfire Preparedness Week (the first week of May), the campaign has a web page (www.hawaiiwildfire.org/lookout) with fact sheets covering homeowner safety and fire occurrence in Hawaiʻi. To encourage media coverage of wildfire in Hawaiʻi, the campaign organizers also created a web page with ready-made press briefs highlighting fire mitigation projects around the State.

Endangered Species

Managing threatened, endangered, and rare (TER) species during a drought should address not only the basic water-supply needs of the species, but also elevated threats that other stressors may impose (table 5.4). Drought stressors include elevated fire danger conditions, increases in browse pressure by nonnative feral ungulates, and increases in rodent damage (e.g., bark stripping by rats). The interacting effects of multiple stressors can also increase susceptibility to disease or insect pests.

Because many TER plant species in Hawaiʻi occur in dry to mesic biome types (Ostertag et al. 2014) that are susceptible to drought and drought-related impacts, managing for the direct and indirect effects of drought are fundamentally a biodiversity concern. Managers are therefore tasked with reducing stress to or preventing death of TER species and are often required to manage the whole ecosystem. Managers can enhance fire prevention (reduce fuel conditions and number of ignitions), increase investment in fire suppression when ignitions cannot be prevented, reduce the number of nonnative ungulates (either by culling or exclusion by fencing), target fencing of individuals or groups of individuals, and, for the TER species of greatest concern, provide supplemental water through irrigation systems or even hand watering (see case studies 5.2, 5.3).

Although not a method that has been used by managers of the Pacific Islands, planting of TER species back into the wild probably needs to be done in a way that considers future droughts in deciding where, when, and how TER enrichment planting and restoration are done. For example, depending on genetic variation in remaining wild populations, managers could select genotypes for outplanting that are more resistant to drought, cast more shade, or are more competitive with aggressive nonnatives (table 5.4). Plantings could be located strategically based on historical and future climate trends (e.g., at the wetter end of the range limit if there has been a drying trend), and within or adjacent to areas that already are managed for other objectives. Such areas include those that are ungulate-free, receive regular fuel reduction treatments, have fire awareness and prevention promoted in adjacent communities, and have supplemental watering.

Agriculture

Farmers and ranchers respond to drought in a number of ways (table 5.4). Farmers may harvest early, plant less thirsty crops, prioritize irrigation, apply mulch, and pump more groundwater. Ranchers may move or cull herds, slaughter cattle, and wean calves early.

Both farmers and ranchers may need to pay for water deliveries and supplemental feed.

Some response actions are informed by Native Hawaiian traditional knowledge. For example, the following management strategy refers to the observations of limu (seaweed):

> *When a certain kind of limu begins to appear it's a solid sign of a drought because (it reflects) the changing water temperatures of the ocean. And so (when) these different kinds of limu began appearing they said, "Now is the time to start getting your fields ready for sweet potato." And you know these were observations of a great amount because sweet potato can stand a drought. (Finucane and Peterson 2010)*

The Hawai'i Department of Agriculture has a responsibility to manage drought and may implement a number of response actions (CWRM 2017):

- Implement more frequent monitoring of reservoir, stream, and well levels.
- Continue to notify system users regarding storage and supply conditions.
- Implement voluntary and/or mandatory water restrictions for system users.
- Seek authorization and available funding to mobilize contractors to truck water to ranches without source.
- Seek authorization to convert and utilize nearby wells for emergency water use.
- Seek authorization for use of private reservoir sources and coordinate installation and use of standpipes for ranchers for livestock drinking water.
- Advise farmers and ranchers regarding required documentation and data collection for Federal assistance and disaster relief programs.
- Coordinate and facilitate access to Federal assistance programs, low-interest State loans, Federal crop loss programs, and agriculture loans.
- Seek authorization for use of military surplus equipment to transport equipment and/or water to drought-stricken areas.

CONCLUSIONS

Hawai'i and especially the USAPI have not seen a comprehensively designed research strategy focused on identifying and developing solutions for drought-related thresholds and their interactions with other threats. Clearly, resource management can alleviate drought-related social and biophysical factors that push natural and human systems across these thresholds (Barnett and Adger 2003). Management efforts need to be expanded to engage multiple interacting stressors: invasive species, altered fire and climate regimes, pests, and pathogens. The many areas of applied drought-focused research include:

- Silvicultural management of nonnative species for watershed function
- Restoration practices that increase resilience of native ecosystems to drought and fire, including appropriate genotypes and species
- Spatial and temporal variation in the effects of drought on fire behavior, including fuel loads and the potential of management to reduce fuels
- The human dimensions of drought, wildfire, and their interactions
- Groundwater resiliency to drought and saltwater intrusion
- The genetic drought adaptation potential for TER species
- Drought-pathogen-pest interactions and spatial and temporal variation in the effects of pathogens and pests on native plants and animals
- The design of agricultural and pastoral systems that allow for more rapid accommodation of drought events while reducing sensitivity to financial loss

Many communities in Hawai'i and the USAPI have features that may make them more resilient to drought compared to some of the other regions covered by this report. Pacific Island host cultures rely on traditional knowledge developed over thousands of years and on the resulting community-based approaches, practices, tools, and institutions that have supported communities during drought periods from the distant past into the present. Traditional knowledge-based communities also are more resilient to drought because close connections exist between landowners, resource managers, and decision makers, allowing for more timely and targeted support (Barnett 2001, Mimura et al. 2007). Although crossing certain drought-related thresholds cannot be prevented, the effects may be mitigated more easily and cost effectively in the region because of these attributes.

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CHAPTER 6

Managing Effects of Drought in the Interior West

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BIOGEOGRAPHIC AND CLIMATIC CONTEXT

The biogeography of the Interior West region (Idaho, Montana, Wyoming, Nevada, Utah, Colorado, Arizona, New Mexico) is diverse, with terrestrial ecosystems varying greatly both from north to south and from high elevation to low elevation. Subalpine forests are dominated by species adapted to cold, snowy environments at high elevation: subalpine fir (*Abies lasiocarpa*), Engelmann spruce (*Picea engelmannii*), Rocky Mountain bristlecone pine (*Pinus aristata*), limber pine (*Pinus flexilis*), and whitebark pine (*Pinus albicaulis*). Mixed-conifer forests are the most common forest vegetation throughout the region, in which Douglas-fir (*Pseudotsuga menziesii*) and ponderosa pine (*Pinus ponderosa*) are often the dominant overstory species, with variable species composition and density in the understory. Ponderosa pine is found in nearly pure stands in many low-elevation, dry sites.

Woodlands dominated by various species of juniper (*Juniperus* spp.), pinyon pine (*Pinus edulis*, *P. monophylla*), and Gambel oak (*Quercus gambelii*) are common in drier portions of the southern half of the region, typically at lower elevations than mixed-conifer or ponderosa pine forests. A diversity of shrublands is found below woodlands and mixed-conifer forest in most of the region; several sagebrush species (*Artemisia* spp.) are dominant, along with mountain mahogany (*Cercocarpus* spp.) and antelope bitterbrush (*Purshia tridentata*). Perennial grasslands, often including nonnative annual grasses, are widespread at the lowest elevations in dry locations, intergrading with shrublands and woodlands. Riparian systems comprise a small but important component in all vegetation types and are often hotspots of biodiversity in arid to semiarid environments.

The topography and climate of the Interior West are highly varied; the region is home to some of the driest, hottest, and coldest locations in the conterminous United States. The Interior West is characterized by numerous mountain ranges, high-elevation basins and valleys, and low-elevation mesas and canyons, and climate is influenced by this complex terrain. Moisture comes predominantly from the Pacific Ocean, resulting in orographic precipitation in the mountains. Central Idaho and the Greater Yellowstone Area are some of the coldest portions of the region, and climate in these areas is strongly influenced by mountains and interactions among topography, elevation, and aspect. The southern portion of the region is the hottest and driest in the United States.

Drought is a familiar phenomenon throughout the Interior West, as evidenced by significant periods of drought in the 1930s to early 1940s (Dust Bowl), 1950s, mid-1960s, late 1970s, and 1990s (Weiss et al. 2009). Drought was also widespread in 2002–2007 and 2012–2015. Severity is generally greater in the southern portion of the region, for which arid climate is normal. The paleo record indicates that droughts in earlier centuries were more frequent and longer, in some cases lasting for multiple decades (Allen et al. 2013, Cook et al. 2014, DeRose et al. 2015, Meko et al. 1995).

Average annual temperatures in the region have risen by 1.6 °F (Vose et al. 2017) since the beginning of the 20th century. In most areas, warming has been greatest and most widespread in winter. In some cases, temperature increase has accelerated during recent centuries; for example, average annual temperatures in Colorado have increased 2 °F since 1977 (Lukas et al. 2014). Across the United States, the rate of increase in average annual temperature has been greater over the last several decades, and several of the warmest years on record have occurred since 2010 (Vose et al. 2017). Precipitation trends have been highly variable across the region, with some areas increasing and some decreasing (at both annual and seasonal time scales).

Global climate models project increases in mean annual temperature of 2–6 °F by mid-century (2036–2065) and 4–10 °F by late century (2070–2099) compared to 1976–2005 (Mote et al. 2014, Wuebbles et al. 2017). Warming is expected to occur during all seasons. Most models project the largest temperature increases in summer, ranging from 3.4 °F to 9.4 °F (under the Representative Concentration Pathway 8.5 scenario). All models suggest that heat extremes will increase.

Changes in precipitation are more uncertain. Annual average precipitation is projected to increase by about 3 percent, with general climate model (GCM) projections ranging from -4.7 percent to +13.5 percent (Mote et al. 2014, Wuebbles et al. 2017). Most models project decreases in summer precipitation, but model projections for precipitation vary for the other seasons, with some models projecting increases and others decreases. However, GCMs agree that extreme precipitation events will likely increase in the future.

Warming temperatures, regardless of precipitation changes, will affect hydrological processes in the Interior West, including the amount, timing, and type

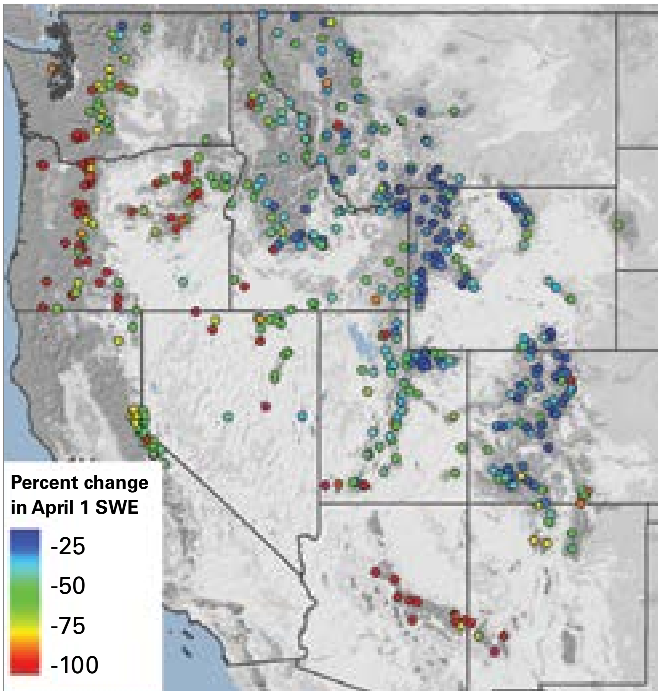


Figure 6.1—Estimated April 1 snow-water equivalent (SWE) sensitivity (percentage change) for a 5.5 °F increase in winter average temperature at each snowpack telemetry station. From Muir et al. (2018), modified from Luce et al. (2014a).

of precipitation, as well as timing and rate of snowmelt (Luce et al. 2012, 2013; Mote et al. 2018; Safeeq et al. 2013), which will affect snowpack volumes (Hamlet et al. 2005), streamflows (Hidalgo et al. 2009), and stream temperatures (Isaak et al. 2012, Luce et al. 2014b). In response to warming, shifts are already occurring from snowmelt-dominant to mixed rain-and-snow watersheds, and from mixed rain-and-snow to rain-dominant watersheds (Mote et al. 2018). These shifts are resulting in earlier and reduced spring peak flow, increased winter flow, and reduced late-summer flow (Raymondi et al. 2014). With future increases in temperature and altered hydrological dynamics, evapotranspiration is likely to increase, and soil moisture availability is likely to decrease during the summer, leading to more frequent, more intense, and longer droughts (Gershunov et al. 2013) (fig. 6.1).

SOCIAL AND REGULATORY CONTEXT

Water has enormous social, economic, and biological importance in the Interior West because most of the region is semiarid, and even under "average" weather conditions water is in short supply for much of the year. Surface water and groundwater contribute to municipal water supplies for major metropolitan areas, hydropower, habitat for fish and other aquatic species, and recreation (Warziniack et al. 2018a, 2018b). In some parts of the region, water (typically supplied from snowmelt and groundwater) is used for irrigation of a wide range of perennial (e.g., tree fruits) and annual (e.g., potatoes, hay) crops. Water supply in the southern part of the region is a concern in years when precipitation is average and becomes more acute during drought years. Water for agriculture and municipal use during drought periods is often supplemented by additional pumping of groundwater, in some cases depleting sources that are already declining.

Streams and riparian areas contribute greatly to aquatic and terrestrial biodiversity, especially in semiarid to arid landscapes. Water provides critical habitat for salmon and trout species throughout the northern and central portions of the region, and for fragmented fish populations (often threatened or endangered) associated with ephemeral aquatic habitat in desert ecosystems. Several salmon stocks are listed as threatened or endangered, and nearly all populations are much lower than they were prior to 1900; dams are a major impediment to recovery of many populations, especially on the Columbia and Snake Rivers and their tributaries. High temperatures and drought reduce habitat quality for cold-water fish species across all spatial and temporal scales, facilitating expansion of nonnative fish species that tolerate higher water temperature (Isaak et al. 2012). Declines in native fish and other traditional food sources will have detrimental effects on economic and cultural values for Native Americans and other rural residents in the region.

Grazing by domestic livestock is an important enterprise in rangelands in the Interior West (Reeves et al. 2018). These rangelands also provide habitat for elk (*Cervus elaphus*), mule deer (*Odocoileus hemionus*), pronghorn (*Antilocapra americana*), and many other animal species. Grazing occurs on both public and private lands, requiring frequent (and sometimes contentious) interactions between public land managers and ranchers focused on sustainable management of rangelands, especially during drought (Hawkes et al. 2018). Management of greater sage-grouse (*Centrocercus urophasianus*) habitat is a major conservation issue in sagebrush-steppe throughout the Interior West, further complicating these interactions in terms of public policy, grazing access on public lands, and local decision making.

Although timber production is still an important component of some local economies in the Interior

West, it has declined significantly since the 1990s (Halofsky et al. 2017). Changing social perspectives on resource management priorities, accompanied by a shift in timber production to locations that are more productive and have lower labor costs (e.g., the Southern United States), resulted in the closure of many timber mills. In response to social demands, most forest management in the Interior West now focuses on restoring native vegetation, creating mature forest structure, and improving wildlife habitat and various aspects of biological diversity.

Recreationists participate in a wide range of outdoor activities throughout the Interior West, including hiking, camping, sightseeing, skiing, hunting, fishing, and water-based activities. These recreational activities generate far more economic activity than traditional resource sectors such as timber, representing the New West in which human values and experiences represent an area of increasing demand (Halofsky et al. 2017). However, recreational activities can also generate significant demands for access to infrastructure and facilities, which in some cases can damage resources. Most recreation activities are affected in some way by a warmer climate and drought, some positively and some negatively (Hand and Lawson 2018, Hand et al. 2018).

Natural resources, social issues, human values, and ecosystem services are interwoven with the economy, lifeways, and culture of Native Americans. This has always been true for salmon and other "first foods" that have been used by Native Americans for millennia, and Federal land managers are becoming more aware of the need to involve Tribal partners in developing conservation plans. As a result, Tribes are increasingly influential in decision making and planning on lands where their interests may be affected. Including Tribes as partners when developing conservation plans and projects is now a common element of Federal land management.

Water availability is expected to decrease in the future because of shortages arising from decreased water supplies and increased water demand. Ninety percent of water consumption in the Western United States is used for irrigated agriculture, so competition with usage by municipalities, industry, and natural resources (e.g., fish habitat) can become intense during droughts (Warziniack et al. 2018a, 2018b). As a result, it will be necessary to minimize vulnerability of water-related infrastructure and water-dependent resources on public lands and to maximize efficiency of water uses where possible (Furniss et al. 2018). An integrated perspective on physical, biological, social, and economic processes and values will be necessary to ensure long-term sustainability of water and other resources.

ASSESSING THE EFFECTS OF DROUGHT

As noted above and in chapter 2, GCMs project that temperature will increase significantly in future decades, and the magnitude of temperature changes will likely decrease summer water availability, regardless of precipitation trends. Although we have considerable confidence in long-term projections (decades) of decreasing water availability and increasing frequency and magnitude of droughts, the actual occurrence of drought will be difficult to forecast at short time scales (months to years).

Water Resources and Aquatic Systems

Water is the most widely valued resource provided by public lands. 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. Drought affects not only the quantity of water available but also water quality (higher temperature, turbidity) (Goode et al. 2012). Along with limited water availability, higher water temperature 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). Droughts that cause low summer streamflows and high water temperature can have multiple consequences to cold-water fish populations, including significant mortality (Matthews and Marsh-Matthews 2003).

Surficial geology and soils determine both drainage properties and the severity of drought effects across mountainous landscapes in the Interior West. For example, in areas with highly permeable subsurface rocks and well-drained soils, water rapidly infiltrates down hundreds of feet, reducing both water storage for human uses and water availability for vegetation (Konrad 2006). Projected declines in snowpack and earlier snowmelt (chapter 2) will reduce the magnitude and duration of both surface and subsurface water (Luce 2018, Muir et al. 2018) (fig. 6.2), especially during years with low snowpack. Warmer winters will lead to earlier peak flows and lower, warmer base flows (Kormos et al. 2016, Mote et al. 2018), as well as very low summer flows in some streams (Luce 2018) (fig. 6.3).

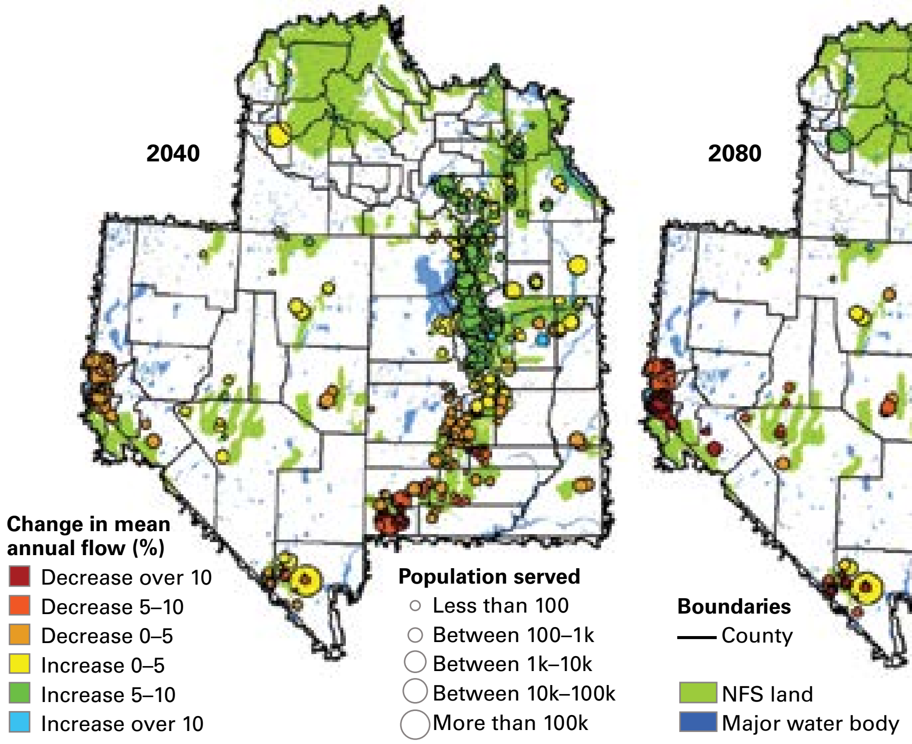


Figure 6.2—Projected changes in mean annual flow for municipal water systems in Nevada, Utah, and southern Idaho. Projections are based on streamflows generated from the Variable Infiltration Capacity (VIC) model (Liang et al. 1994) using an ensemble of Coupled Model Intercomparison Project Phase 3 models under the A1B emission scenario (similar to the RCP 6.0 emission scenario) (see Muir et al. [2018] for details on methods). The center of each circle is the central location of each drinking water system relative to intake locations. Mean summer flow (compared to historical flow) across this geographic area is -21 percent for 2040 and -26 percent for 2080. From Warziniack et al. (2018a).

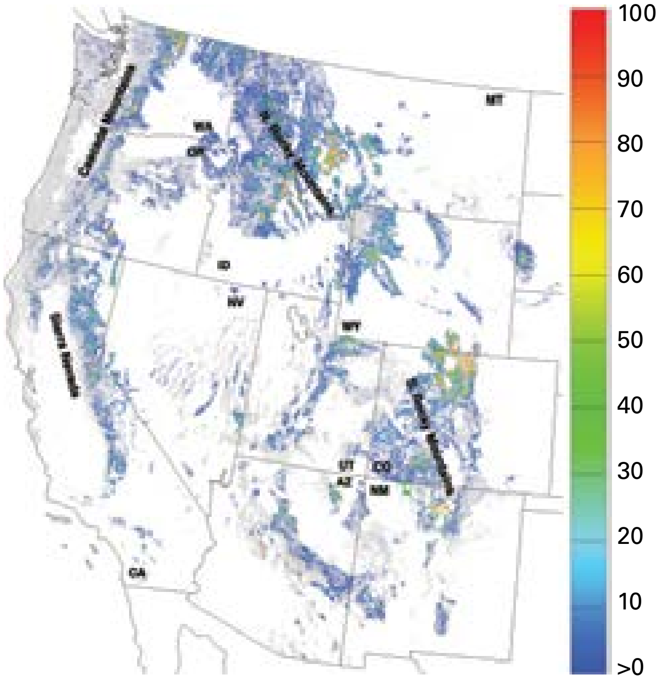
Figure 6.3—Percentage change in mean summer flow projections for drainage areas in Nevada, Utah, and southern Idaho between a historical period (1970–1999) and the 2040s. Projected streamflows were generated from the Variable Infiltration Capacity (VIC) model (Liang et al. 1994) using an ensemble of Coupled Model Intercomparison Project Phase 3 models under the A1B emission scenario (similar to the RCP 6.0 emission scenario) for the 2040s, following the methods of Wenger et al. (2010).

Forest Ecosystems and Disturbances

Drought-related water limitations will likely decrease growth in most tree species in most locations in the Interior West, especially in low- to mid-elevation coniferous forests. Species such as Douglas-fir and ponderosa pine, which are important ecologically and economically, are expected to have lower growth throughout the region (Behrens et al. 2018, Keane et al. 2018, Restaino et al. 2016), even though they are considered relatively drought-tolerant. Some species in high-elevation coniferous forests may have higher growth during drought years because less snowpack means a longer growing season in areas where water limitations are uncommon (Peterson and Peterson 2001).

Drought-related tree mortality has been rare at large spatial scales in the Interior West, with the exception of two-needle pinyon (*Pinus edulis*), which experienced significant mortality at low-elevation locations in northern New Mexico after a 10-year drought in the early 2000s (Breshears et al. 2005). More tree mortality can be expected, especially in dense stands at the lower elevations where drought exacerbates water deficit. Dry soils and topographic positions that do not retain soil moisture are vulnerable, especially where they affect the establishment of seedlings which are near the ground and have small root mass (Joslin et al. 2000). Carbon storage in vegetation and soils will become more difficult to manage as wood growth decreases and disturbances increase, and early-seral forest structure may become more prevalent across the landscape (Kashian et al. 2006).

Dense forests are particularly susceptible to bark beetle attack. Although beetles typically focus on weak trees, they can also spread to nearby vigorous trees when beetle populations are high (Fettig et al. 2007, Lieutier 2004). Lodgepole pine (*Pinus contorta* var. *latifolia*) in particular has experienced significant mortality from mountain pine beetles (*Dendroctonus 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) (fig. 6.4). Drought frequency and duration also affect the extent and severity of wildfires because drought causes both fine surface fuels and live fuels to dry earlier and stay dry longer, increasing fire hazard and likely the duration of the fire season (McKenzie et al. 2004, Peterson et al. 2011).



Bark beetles: area of killed trees

Figure 6.4—Tree mortality caused by bark beetles, 1997–2012, indicating the pervasiveness of bark beetle damage throughout the Interior West. Colors show area and percentage of tree mortality. From Hicke et al. (2016).

Rangelands

Drought reduces growth in rangelands during the growing season, especially if large numbers of invasive annual grasses are present (Fehmi and Kong 2012, Finch et al. 2016, Hanberry et al. this volume, Runyon et al. 2012). Drought conditions favor the spread of annual grasses (especially cheatgrass [*Bromus tectorum*]) (Kindschy 1994, Tausch et al. 1994), which further limits the extent and productivity of native plant species (fig. 6.5). Excessive grazing by livestock and native ungulates during drought decreases aboveground and belowground biomass, creating growing space for invasive plant species (Biondini et al. 1998, Fuhlendorf et al. 2001). Although grazing typically occurs on perennial grasses, shrubs are also vulnerable to browsing when grasses are unproductive or dormant. In the summer, when conditions are hottest and grasses in the adjoining uplands are dormant, livestock are more likely to graze riparian areas (Padgett et al. 2018).

As drought intensity increases, rangeland productivity decreases (Hanberry et al. this volume, Padgett et al. 2018, Reeves et al. 2018), although the extent

Figure 6.5—Cheatgrass is common in grasslands throughout the Interior West. (Photo by Cassondra Skinner, USDA Natural Resources Conservation Service PLANTS Database)

of decrease depends on dominant vegetation (e.g., sagebrush versus mountain meadows) and soils. In semiarid locations, annual grasses tend to increase fire frequency and spread (Balch et al. 2013), favoring further spread of annual grasses and less cover of native shrubs, grasses, and forbs (Link 2006, Melgoza and Nowak 1991). Although the quantity of fuel controls fire intensity, drought can extend the duration of conditions under which fuels will readily burn (Brown et al. 2005).

Socioeconomic Effects

More frequent, more intense, and longer drought will reduce surface water supply more often, leading to significant impacts on social and economic sectors that demand continuous, reliable water (Vose et al. 2016; Warziniack et al. 2018a, 2018b). In some cases, 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 sectors (e.g., among agriculture, hydroelectric power generation, and fish habitat). Recent projections of the effects of a warmer climate indicate that municipal watersheds will increasingly face water shortages in future decades (Warziniack et al. 2018a, 2018b), with periodic drought accentuating those shortages. Water supply in mountainous regions is often limited by reservoir capacity, and this can be depleted during years when snowpack is low and water demands are high (Harpold et al. 2017).

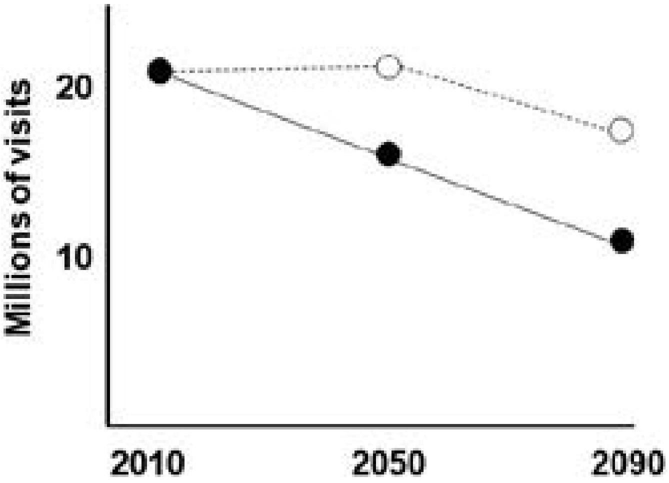


Figure 6.6—Projected effects of climate-altered snowpack on downhill skiing visits. The Rocky Mountain portion of the Interior West currently has by far the highest number of skiers of any region. By the end of the 21st century, visits are expected to decline by 50 percent for a constant population (closed circles), but only by 17 percent if the population increases according to recent demographic projections (open circles). From Wobus et al. (2017).

Any given drought period can affect multiple resource sectors (Halofsky et al. 2017). As noted, low water supply can cause stress and economic losses in agriculture and rural communities. "Snow droughts" can lead to low flows in rivers and streams (Harpold et al. 2017), reducing recreational opportunities for rafting and fishing (Hand and Lawson 2018, Hunt et al. 2016) and in some cases causing fish mortality. Snow droughts also affect winter recreation, with potential financial losses for downhill skiing operations and associated support businesses (Hand et al. 2018, Wobus et al. 2017) (fig. 6.6). Following widespread drought in 2017, wildfires burned 4.4 million acres in the eight Interior West States, incurring over $1 billion in suppression costs (National Interagency Fire Center data: https://www.nifc.gov), causing economic damage in many communities, reducing access to public lands, reducing forage for grazing, and in some locations, degrading air quality for several weeks.

MANAGING FOR DROUGHT, EXTREME EVENTS, AND DISTURBANCES

The 2016 Federal Action Plan of the National Drought Resilience Partnership (White House 2016) 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. Drought-related guidance (in the form of guidebooks and manuals) (e.g., Hawkes et al. 2018) is rare in the Forest Service, U.S. Department of Agriculture (USFS) and other Federal agencies, although some USFS Regions have issued guidance to national forests during severe drought periods. The Bureau of Land Management (BLM) has used instruction memoranda to issue guidance on drought response.

Existing frameworks and tools used by the USFS and BLM can be used to address drought 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 program activities such as water use, aquatic ecosystems, rangelands, 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 USFS Watershed Condition Framework (Potyondy and Geier 2011) and regional aquatic restoration strategies guide forest watershed and aquatic restoration programs, and restoration activities can help increase ecosystem resilience to drought. Incorporating drought in restoration planning could help to further improve drought resilience in the future. For example, two strategies to help decrease future drought-related mortality are to plant drought-tolerant vegetation in restoration treatments and reduce forest stand density (Sohn et al. 2016).

All national forests in the USFS Northern and Intermountain Regions have completed climate change vulnerability assessments, including adaptation options (Halofsky et al. 2018a, 2018b). These assessments cover a significant portion of the Interior West. They incorporate potential effects of increased temperatures on water resources, fish and aquatic systems, vegetation, wildlife, recreation, infrastructure, cultural resources, and ecosystem services, thus providing insight on potential effects of drought. Climate change adaptation options in the assessments similarly provide information that will help facilitate drought planning and prioritize responses. Disaster management tools and systems are in place in Federal agencies (e.g., Incident Command System, Burned Area Emergency Response), and these could be applied to drought response and used as a template for drought planning.

Management Options for Responding to Drought

Lower snowpack and increased drought severity in a warmer climate will lead to lower streamflows and reduced soil moisture, especially in arid to semiarid landscapes in the Interior West (Luce et al. 2012, 2013; Mote et al. 2018; Safeeq et al. 2013). Inevitably, water supplies for agriculture, cities and towns, aquatic systems, and other uses will decrease during periods of drought (Prestemon et al. 2016; Warziniack et al. 2018a, 2018b). At a series of workshops during 2016–2017, resource managers throughout the Interior West discussed the potential effects of drought on natural resources and developed options to build resilience in ecosystems and organizations, thus reducing vulnerability to drought. Management options discussed below (tables 6.1–6.4) are drawn from the output of these workshops (USDA FS 2017a, 2017b, 2017c, 2017d).

Water resources—Water conservation practices will help sustain water supplies, especially during the summer when water availability is already low. Water systems will be more resilient to drought if they use water-smart technology and anticipate future storage needs (Luce 2018) (table 6.1). In some cases, water diversion structures may need to be improved to minimize impacts on groundwater-dependent ecosystems. Reconnecting floodplains and side channels will help restore hydrological function, retain water for longer periods (including recharging groundwater), and restore functional riparian systems (fig. 6.7).

Riparian and wetland restoration can be prioritized for both hydrological and ecological values, assisted by geospatial analysis to identify where restoration will be feasible and have maximum benefit. Two ways to improve functionality of riparian systems are to (1) reduce gullying and (2) reconnect channels and facilitate maintenance and establishment of American beaver (*Castor canadensis*) populations to increase water storage (Pollock et al. 2014). In addition, stand density management and hazardous fuel reduction in dry forests will help reduce the severity of future wildfires (Luce et al. 2012).

Federal land management agencies currently have limited capacity to respond to frequent, severe droughts. This limitation can be improved by incorporating drought in all relevant aspects of planning and management (see Conclusions chapter in this volume). Doing so includes specific actions, such as increasing instream flows through altered water rights and incentives, and developing or revising standards and practices to protect stream corridors and other water features. Education on drought awareness can be institutionalized both

Table 6.1—Drought vulnerabilities and management options for water resources in the Interior West

WATER RESOURCES	
VULNERABILITY TO DROUGHT	**DROUGHT MANAGEMENT OPTIONS**
Drought will reduce the availability of water for a variety of uses during the summer.	• Increase water conservation; prioritize maintenance and reconstruction. • Make water systems more resilient to drought (e.g., use water-smart technology) and prepare for future storage needs. • Improve existing water diversion structures or design new structures to divert only the water needed while retaining water in groundwater-dependent ecosystems. • Reconnect floodplains and side channels, and maintain and restore functioning riparian corridors (e.g., reestablish riparian vegetation). • Recharge groundwater by using restoration techniques for rewetting floodplains (e.g., reconnect channels with floodplains).
Drought will reduce the functionality of hydrological systems and associated riparian systems.	• Prioritize and target riparian and wetland restoration to provide shade over water and reduce quick flow from roads; use geospatial tools to identify restoration priorities. • Continue to manage landscapes to reduce fire severity and promote fire-adapted native vegetation. • Control water pollution. • Manage American beaver activity to increase water storage. • Identify a target for a healthy riparian system and start managing for that target. • Reduce gullying and reconnect channels to maintain functionality of riparian areas.
Federal land management agencies have limited capacity to respond to frequent, severe droughts.	• Incorporate drought planning in management considerations, decisions, and analyses. • Increase instream flows through change in water rights and incentives (e.g., reduce water allotments when water supply is low, and provide rewards to users for reducing consumption). • Develop or improve standards/guidelines, mitigation measures, and best management practices to protect stream corridors and more isolated water features. • Increase drought awareness with agency leadership and the public. • Build and maintain constructive relationships with State agencies and other organizations, and engage in collective problem solving to manage a wide range of hydrological conditions.

Figure 6.7—Riparian restoration on Susie Creek, NV, has greatly increased retention of water during summer, improving habitat for both vegetation and wildlife. (Photo courtesy of USDI Bureau of Land Management)

internally and externally, while collaborating with other agencies and organizations to address water resource issues of common interest.

Fish and aquatic systems—Drought years are typically associated with low snowpack, often resulting in high winter streamflows and low summer streamflows, creating stress for a wide range of fish species and other aquatic organisms. Most options for improving resilience in aquatic systems focus on retaining adequate amounts of cool water and riparian vegetation (Isaak et al. 2018, Young et al. 2018) (table 6.2). For example, reconnecting floodplains and side channels helps maintain and restore functional riparian corridors. Connectivity among fish habitats will be critical, aided by modifying infrastructure (e.g., aquatic organism passages) and removing barriers to fish movement. Stream temperature models (e.g., NorWeST stream temperature database, https://www.fs.fed.us/rm/boise/AWAE/projects/NorWeST.html) will be especially helpful to guide future management actions so that refugia for cold-water fish can be identified (Isaak et al. 2015). In arid locations, identifying refugia will be especially critical for desert fish species, whose habitat is often highly dispersed (Carveth et al. 2006).

Increased drought frequency will reduce water retention in high-elevation and riparian systems. Therefore, to increase resilience across large landscapes in the long term, it will be necessary to restore and maintain healthy stream, riparian, and aquatic ecosystems. Restoration will be especially important in places that are likely to be refugia during future droughts (e.g., high-elevation streams and locations with cold-water upwelling), accompanied by restoration of native species in viable habitats (Isaak et al. 2015). As noted earlier, populations of American beavers will help increase water storage, including cool water. Drought is expected to increase the occurrence of wildfire, especially crown fires in areas with high fuel loadings. Fuel reduction treatments,

Table 6.2—Drought vulnerabilities and management options for fish and aquatic habitat in the Interior West

FISH AND AQUATIC HABITAT	
VULNERABILITY TO DROUGHT	**DROUGHT MANAGEMENT OPTIONS**
During drought years, winter streamflows will generally increase and summer streamflows will decrease, creating stress for fish and other aquatic organisms.	• Reconnect floodplains and side channels, and maintain and restore functioning riparian corridors (e.g., reestablish riparian vegetation). • Increase fish habitat connectivity by modifying infrastructure (e.g., aquatic organism passages). • Use stream temperature models (e.g., NorWeST stream temperature database) to guide future management actions. • Remove barriers to fish movement where appropriate and for bull trout (*Salvelinus confluentus*) in particular (e.g., modify infrastructure to increase habitat connectivity). • Create refugia habitats (e.g., hatcheries and ponds) during fire or drought evacuations to hold high-value species.
Increased frequency and magnitude of droughts will reduce water retention in high-elevation and riparian systems, especially when accompanied by wildfire, thus reducing habit quality for many organisms.	• Restore and maintain healthy stream, riparian, and aquatic ecosystems that will be more resilient to drought cycles. • Conduct riparian and stream restoration in places that are likely to be refugia during future droughts (e.g., high-elevation streams and locations with cold-water upwelling). • Prioritize native species restoration in habitats that will persist through drought periods. • Reintroduce American beaver where appropriate to increase water storage. • Use prescribed burning in dry forests in order to reduce high-intensity wildfire.
Drought will make it more difficult to maintain the functionality of riparian systems and infrastructure.	• Use land management plan revisions as opportunities to encourage riparian vegetation treatments across the landscape to restore desired functions and processes. • Maintain the function of the transportation system without damaging riparian and aquatic ecosystems (e.g., develop engineered solutions for high-priority roads in floodplains). • Develop partnerships with departments of transportation, counties, and other organizations to mitigate negative impacts of the transportation system on water resources. • Coordinate with range managers to better manage riparian areas, focusing on how cattle move across the landscape.

including prescribed burning in dry forests, can reduce the likelihood of high-intensity wildfires (Luce et al. 2012).

Drought will make it more difficult to maintain the functionality of riparian systems and infrastructure, such as roads. Federal land managers can use land management plan revisions as opportunities to encourage riparian vegetation treatments across the landscape to restore desired functions and processes. It is especially important to maintain the function of transportation systems without damaging riparian and aquatic ecosystems (e.g., develop engineered solutions for high-priority roads in floodplains). Partnerships with other agencies and organizations will help mitigate negative impacts of roads on water resources, while facilitating access to public lands.

Forest ecosystems—If drought becomes more frequent or of longer duration, tree regeneration may decrease or be more variable in drier locations. Strategic planting can ensure adequate tree establishment, especially where large-scale mortality has occurred and natural regeneration is low (table 6.3). Where site conditions and management objectives allow, forest managers can diversify planting with drought-tolerant species and genotypes (Kilkenny et al. 2013). This will require managing seed inventories to maintain genetic diversity, as well as producing sufficient nursery stock to meet demands. In some cases, planting densities can be increased to compensate for potential seedling mortality.

Drought will cause a general loss of tree vigor, growth, and productivity in most locations. In some cases, these stresses will lead to more tree mortality, both directly and because of increased frequency of disturbances. Drought-stressed trees may also have weaker defenses to bark beetle attack, and drought can increase the likelihood that attacks by different beetle species will erupt simultaneously (Raffa et al. 2005). To reduce

Table 6.3—Drought vulnerabilities and management options for forest vegetation in the Interior West

FOREST VEGETATION	
VULNERABILITY TO DROUGHT	**DROUGHT MANAGEMENT OPTIONS**
Tree regeneration may be lower or more variable if drought is frequent or protracted.	• Use planting to ensure adequate tree establishment. Focus on areas of large-scale mortality that are not regenerating naturally. Plant seedlings in suitable microsites and provide artificial shading. • Diversify stands and landscapes where site conditions and management objectives allow; focus on drought-tolerant species and genotypes. • Manage seed inventories to maintain genetic diversity; update and maintain seed procurement inventories to increase genetic diversity. Collect seeds from multiple trees of the same species in seed transfer zones. Increase planting densities to compensate for potentially higher seedling mortality.
Drought will cause tree vigor to decrease and tree mortality to increase, both directly and because of more frequent disturbances.	• Promote tree size and age diversity within stands and across landscapes to increase resilience to drought, insect outbreaks, and fire. • Use thinning and prescribed fire in dry forests to reduce stand densities by removing smaller trees. Prioritize thinning in fire-prone areas within the wildland-urban interface where feasible. • Use prescribed burning and managed wildfire to reduce surface fuels and manage for diversity of ages, structure, and species.
Local survival of viable populations of some tree species may be threatened by increasing frequency and duration of drought.	• Identify sites where special species can be protected; designate refugia where appropriate. • Increase resilience of sensitive species, such as whitebark pine, by protecting them from high-severity fire (e.g., through prescribed fire and removal of competing species such as subalpine fir and Engelmann spruce). • Enhance opportunities for self-migration (e.g., establish seedlings in sites more resistant to drought); favor seed production and dispersal in current habitat and receptive seedbeds in nearby habitats.
Drought will create additional stress for management organizations, requiring new approaches and greater flexibility.	• Increase resources to implement landscape treatments; look for cost-sharing opportunities with other agencies and organizations. • Create a regional rapid-response fire and vegetation management team by formalizing multi-agency cooperation and sharing resources and responsibilities.

stand densities, thinning and prescribed fire can be implemented in dry forests, thereby removing smaller trees, promoting diversity of tree size and age and increasing vigor of residual trees within stands and across landscapes (Clark et al. 2016, Sohn et al. 2016) (fig. 6.8). Prescribed burning and managed wildfire can further reduce surface fuels and create diversity in stand ages, structure, and species (Johnson et al. 2007, Keeley et al. 2009, Peterson et al. 2011). Although silvicultural manipulations may increase the defensive capacity of a tree by ameliorating the effects of drought, they may be ineffective at reducing large-scale mortality in association with drought and bark beetle outbreaks (Fettig et al. 2007).

Viable populations of some tree species may be threatened by increasing frequency and duration of drought. Thus, it will be critical to identify sites where special species can be protected, maintaining habitat connectivity if possible. To ensure resilience, sensitive species (e.g., whitebark pine) may need to be protected from high-severity fire (e.g., through prescribed fire and removal of competing species) (Keane et al. 2017). Habitat connectivity will facilitate self-migration by favoring seed production and dispersal in current sites as well as suitable nearby regeneration sites. All responses to drought will benefit from collaboration and increased flexibility among management organizations to encourage treatments across large landscapes.

Rangelands—Drought will decrease vegetation productivity in many arid to semiarid locations, necessitating altered grazing practices for domestic livestock (Finch et al. 2016). One commonly used option to deal with drought is to alternate periods of disturbance (grazing) and rest (table 6.4). Monitoring tools, such as the Evaporative Demand Drought Index (EDDI) and U.S. Drought Portal (National Integrated Drought Information System) (USDA FS 2017b), can help inform decisions about grazing. Grazing management tools, such as PastureMap (PastureMap n.d.), The Grazing Manager (Ishmael 2013), and Grazekeeper (Ellis 2015), can inform specific decisions about herd composition, stocking rate, and timing. Grazing can also be targeted to control cheatgrass infestations (e.g., by grazing in early spring or late autumn) (Foster et al. 2015).

The long-term effects of drought on water availability can be addressed by reintroducing American beavers into areas where they are not presently thriving in order to retain more water in meadows and riparian areas (Pollock et al. 2014). Integrated pest management and early detection/rapid response strategies can be used to control invasive species, along with educating the public and agency personnel about invasive species. Resilience of vegetative cover to drought can be improved by managing the amount, timing, and distribution of ungulate (native animals plus livestock)

Figure 6.8—Reducing stem density (from left to right), shown here in a ponderosa pine stand in the Colorado Front Range, reduces both competition among trees and the propagation of wildfires into the canopy, thus increasing the resilience of dry conifer forests to drought. (Photo courtesy of U.S. Air Force)

Table 6.4—Drought vulnerabilities and management options for rangelands in the Interior West

RANGELANDS	
VULNERABILITY TO DROUGHT	**DROUGHT MANAGEMENT OPTIONS**
Drought will decrease vegetation productivity, thus affecting grazing practices.	• Use grazing methods that alternate periods of stress (grazing) and rest (reduced grazing). • Use drought-monitoring tools (e.g., Evaporative Demand Drought Index, U.S. Drought Portal) to provide information that will inform decisions about herd composition and numbers so that stocking rates match forage production. • Implement targeted grazing methods (e.g., use livestock to eat weeds) after disturbance events such as fire to restore vegetation cover.
Drought reduces water availability during the summer, which affects vegetation composition and productivity and favors invasive species.	• Increase watershed health and function by reintroducing American beavers into areas where they are not presently thriving as a way to retain more water in meadows and riparian areas. • Increase efforts to control invasive species through integrated pest management, targeted livestock grazing, and early detection/rapid response strategies. • Educate the public and agency personnel about invasive species, and co-monitor and manage with permittees to encourage collaborative learning. • Increase or maintain vegetative cover to be more resilient to drought by managing the amount, timing, and distribution of ungulate herbivory. Implement woody plant management to promote herbaceous groundcover.
Drought affects the ability of Federal land managers to manage rangelands in a sustainable manner.	• Establish an integrated monitoring plan that includes livestock management, drought, and climate. • Design permits based on future drought considerations rather than historical ranch production. • Consolidate monitoring data into a geospatial database across resources to help preserve knowledge and to aid resource managers in multiple disciplines.
Drought causes stress in the organizations and social systems that administer access to public rangelands.	• Maintain collaboration with private landowners; include partners and stakeholders in decision making. • Use conservation easements to avoid loss of open space if forage production on Federal lands cannot support livestock grazing. Create community-scale social networks to pool resources and exchange technology, labor, equipment, forage, and ideas. • Develop Coordinated Resource Management Plans with the USDA Natural Resources Conservation Service across all Federal, State, and private lands.

herbivory, and by promoting herbaceous groundcover through removal of encroaching woody plants (Hanberry et al. this volume).

In anticipation of future droughts and a warmer climate, it will be beneficial to establish monitoring plans that include livestock management, drought, and climate. Grazing permits can be based on drought considerations rather than just historical ranch production. Strong collaboration with private landowners and shared ownership of drought impacts across stakeholders will help to facilitate effective options for managing rangelands (e.g., Coordinated Resource Management Plans with the U.S. Department of Agriculture (USDA) Natural Resources Conservation Service). Conservation easements can be used to avoid loss of open space if forage production on Federal lands cannot support livestock grazing (USDA FS 2017c). Pooling resources and sharing technology, labor, and equipment will maximize favorable outcomes for all parties. Finch et al. (2016) discussed additional options to adapt to drought in rangelands.

CONCLUSIONS

High temperatures, low snowpack, and low water availability in summer will affect both people and ecosystems in the Interior West more frequently in the future. Planning for and adapting to the likelihood of increasing frequency and duration of droughts are needed to minimize negative effects on species, ecosystems, and ecosystem services, and to facilitate a transition to different climatic conditions in the future. The diversity of the Interior West's climate, biogeography, and socioeconomics means that drought occurrence and effects will vary greatly from north to south and from year to year. Drought management options discussed here (tables 6.1–6.4) are a sample of potential responses and will need to be implemented in the context of local physical, biological, and social environments.

Generally, the first, best, and often least costly means of increasing resilience to drought are to reduce existing stressors and improve the current condition ("health") of ecosystems (Halofsky et al. 2017). Pre-emptive actions that create benefits for multiple resources are valuable, especially actions that increase the quantity and duration of water availability (Halofsky 2018). For example, reconnecting floodplains with side channels and restoring populations of American beaver both contribute to retaining water during the summer. This benefits water supply for agriculture and municipal watersheds, maintains productivity of riparian areas, and maintains high-quality fish habitat. In dry forests, the effects of past fire exclusion can be addressed by reducing stand densities and hazardous fuels to increase resilience to both drought and fire (Peterson et al. 2011). In rangelands, management responses to altered fire regimes, overgrazing, and invasive species will help maintain productivity and benefit livestock grazing, native ungulates, and many other species (Padgett et al. 2018, Reeves et al. 2018).

The organizational capacity of Federal agencies to respond effectively and quickly is the key to successful management of current and future drought conditions. Best management practices for water and climate change vulnerability assessments provide scientific information as the basis for decision making, as well as potential options to implement. Optimal responses can be developed by integrating existing policies and practices with new information and by timely reporting of current conditions. Coordination by Federal agencies with other agencies and stakeholders is needed for effective management of drought effects across large landscapes. If drought-informed thinking is institutionalized as part of agency operations, then planning and management will be more effective, and crisis management in response to drought can be avoided.

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CHAPTER 7

Managing Effects of Drought in the Great Plains

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INTRODUCTION

The Great Plains region of the United States is semiarid and frequently has water deficits that result in changes in natural resources, economic losses, and reduced ability of people to maintain their livelihoods. Drought occurs due to periods of low precipitation or extended elevated temperatures, or a combination of these weather conditions. Drought can directly affect soil characteristics, land use and land cover, productivity, abundance and composition of plants, animals, and soil organisms. Drought also affects social-ecological systems, particularly management of livestock, which is an important economic sector across the Great Plains.

In general, economic, social, and ecological systems in the Great Plains (box 7.1) are resistant and resilient to drought within the normal range of variability (Kopp et al. 2014). Drought occurred 43 percent of the time in the Southwestern United States and 27 percent in the northern Great Plains during 1944–1984 (Holechek et al. 1989), and tree-ring records have shown that 20th-century droughts were shorter in duration than past Great Plains megadroughts (during 1000–1300; Cook et al. 2007). The 2012 drought and associated dust storms revived interest in the Dust Bowl era. Although dust storms during drought were not new, the consequences of an inadequate management response to extended severe drought were demonstrated in the Great Plains during the 1930s. Farming arid land, plowing native grass, overgrazing, and lack of vegetation resulted in topsoil erosion that still persists in some locations (Hornbeck 2012). Instead of changes in agricultural land use, adjustment occurred through land abandonment and migration of drought “refugees.” Communities and local governments destabilized due to population collapse and debt, without drought relief programs. Management changes were slow, despite recommendations by Federal and State agencies, including agricultural experiment stations and extension services (Hornbeck 2012).

Although past events have had significant impacts, recent drought events yield insight on what can be expected in the future (box 7.2). These include the 2002 and 2012 droughts, and more recently the 2017 drought in the northern Great Plains. Recent droughts have led to severe and transformative ecosystem impacts (Breshears et al. 2016). For example, high temperature and severe droughts during 2002 and 2012 have caused a decline in several perennial grassland species, particularly blue grama (*Bouteloua gracilis*), in the eastern plains of Colorado (Rondeau et al. 2018). This opportunity allowed less valued forage species to proliferate, thereby reducing the quality of rangeland grasses, which has implications for livestock grazing and use by wildlife (Rondeau et al. 2018). Extreme drought may cause aboveground net primary productivity to decrease to historically low levels, primarily due to decreases in dominant forbs; however, C4 grasses may compensate for reduced productivity by recovering quickly after drought (Hoover et al. 2014).

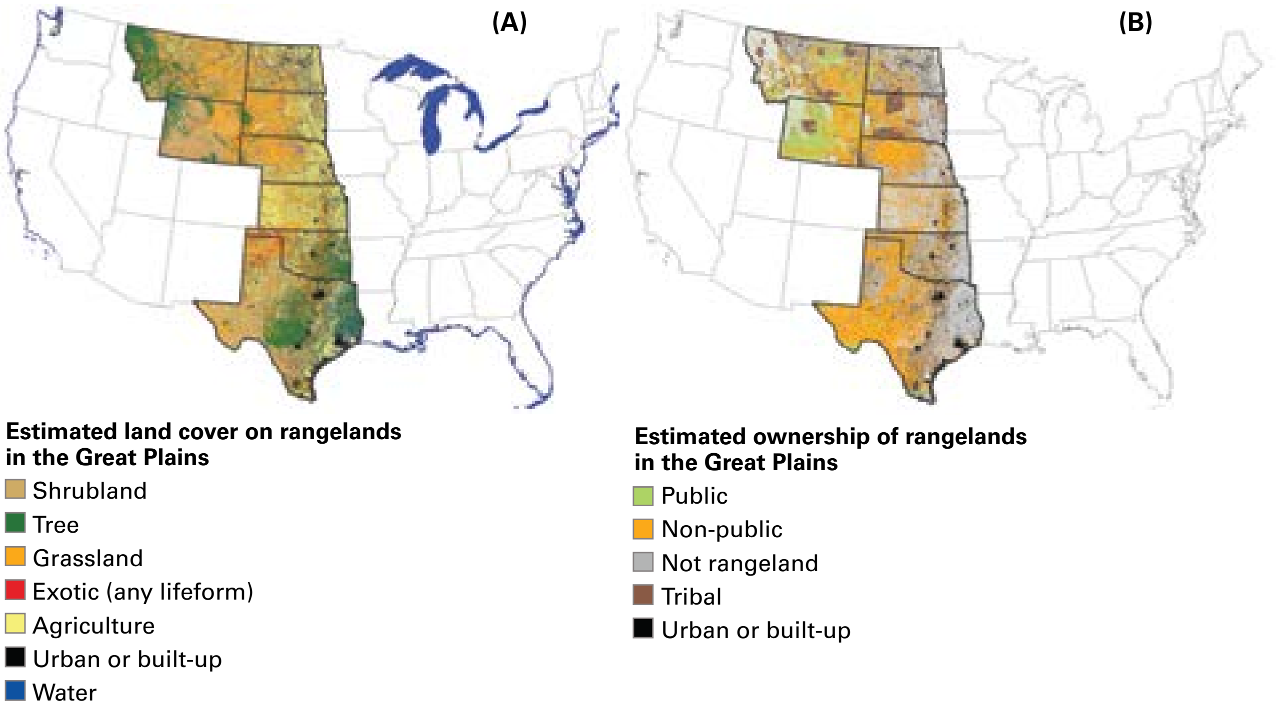
Approximately 75 percent of cattle were in an area of drought during 2012 in the United States (USDA NASS 2018). Drought during the previous year had already caused producers to reduce livestock inventories in Texas and Oklahoma (Rippey 2015). Drought-motivated increases in slaughter depressed cattle prices during 2012, although cattle and retail beef prices remained at or near-record high levels (USDA ERS 2018). Corn prices were also high, so removing lighter weight cattle from pastures and placing them in feedlots was not profitable (USDA ERS 2018). During 2017 in Montana and the Dakotas, drought caused ranchers to cull herds (USDA ERS 2018). Wildfire burned an area of 1.2 million acres, much of which was targeted for livestock grazing, exacerbating loss of forage in Montana.

Insights from both climate models and observations suggest increases in variability during recent decades and into the 21st century, resulting in relatively quick transitions (e.g., seasonal timescales) from anomalously wet to dry conditions (Collins et al. 2013, Heim 2017). Recent literature characterizes these events as “flash droughts,” a rapid intensification to drier conditions over a period of weeks to months (Otkin et al. 2018). During the 2015 growing season, the Wind River Indian Reservation in west-central Wyoming experienced near-record high precipitation in May. However, the anomalous wet conditions in the early part of the summer quickly dissipated by the latter half of the growing season, causing severe drought conditions by September. Evaporative Demand Drought Index (EDDI), one measure of water stress, was the lowest 1-month EDDI (i.e., low water stress) on record (since 1979), whereas September 2015 experienced the highest EDDI value (i.e., high water stress) (McNeeley et al. 2017).

The Great Plains are particularly prone to flash droughts from episodic precipitation deficits (Mo and Lettenmaier 2015, 2016). One example occurred in the northern Great Plains during the summer of 2017 when a severe flash drought developed because of near-record low precipitation in late spring and early

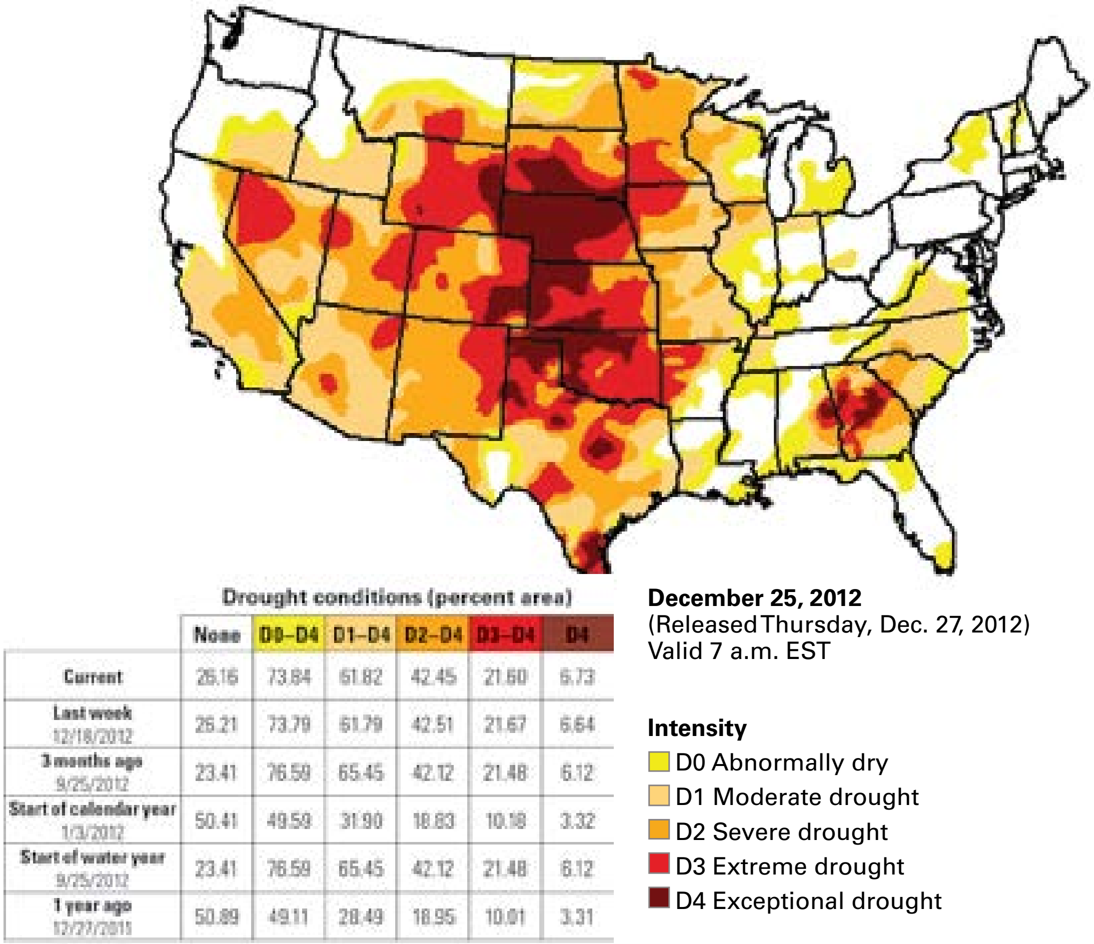
BOX 7.1
Geographic Scope and Climate

As defined by the National Climate Assessment, the Great Plains region comprises eight States: Kansas, Montana, Nebraska, North Dakota, Oklahoma, South Dakota, Texas, and Wyoming ([Shafer et al. 2014] estimated land cover from the LANDFIRE project, https://www.landfire.gov [panel A] and ownership from the Protected Areas Database of the United States [PAD-US], U.S. Geological Survey version 1.4 [panel B]). The climate of the Great Plains is diverse due in part to the large latitudinal range from the Canadian to the Mexican borders. Statewide mean annual temperatures range from 40.5 °F to 64.8 °F in North Dakota and Texas, respectively. Statewide annual precipitation ranges from 12.9 to 36.5 inches, generally following a west to east gradient. The region is also marked with extreme intra-annual temperature differences, in some cases exceeding 100 °F.



BOX 7.2
Drought Displayed at the U.S. Drought Monitor

Widespread drought in the Great Plains is shown here for the year 2012, although drought varies in extent and location. Many drought indices exist, including the SPEI, SPI, PDSI, Self-calibrated PDSI, and the newer EDDI. The U.S. Drought Monitor is a widely used drought resource (https://droughtmonitor.unl.edu), jointly produced by the National Drought Mitigation Center at the University of Nebraska, the U.S. Department of Agriculture, and the National Oceanic and Atmospheric Administration. The U.S. Drought Monitor is used to trigger disaster relief payments which total billions every year. U.S. Drought Monitor maps show drought intensities ranging from D0 (abnormally dry) to D4 (exceptional drought), as well as associated impacts.



Drought conditions (percent area)

	None	D0–D4	D1–D4	D2–D4	D3–D4	D4
Current	26.16	73.84	61.82	42.45	21.60	6.73
Last week 12/18/2012	26.21	73.79	61.79	42.51	21.67	6.64
3 months ago 9/25/2012	23.41	76.59	65.45	42.12	21.48	6.12
Start of calendar year 1/3/2012	50.41	49.59	31.90	18.83	10.18	3.32
Start of water year 9/25/2012	23.41	76.59	65.45	42.12	21.48	6.12
1 year ago 12/27/2011	50.89	49.11	28.49	18.95	10.01	3.31

December 25, 2012
(Released Thursday, Dec. 27, 2012)
Valid 7 a.m. EST

Intensity
- 🟨 D0 Abnormally dry
- 🟧 D1 Moderate drought
- 🟧 D2 Severe drought
- 🟥 D3 Extreme drought
- 🟫 D4 Exceptional drought

(Richard Heim, NCEI/NOAA)

SPEI = Standardized Precipitation-Evapotranspiration Index
SPI = Standardized Precipitation Index
PDSI = Palmer Drought Severity Index
EDDI = Evaporative Demand Drought Index.

summer when the region normally receives a large share of its precipitation. This drought, which caused widespread impacts to agriculture and ecosystems, emerged at the end of the wettest decade (2007–2016) on record for the region (Hoell and Rangwala 2018). Climate change is expected to increase the occurrence of flash droughts during the 21st century (Trenberth et al. 2014).

Water availability is expected to decrease in the future because of shortages arising from decreased water supplies and/or increased water demand. In the Western United States, 90 percent of water consumption is for irrigated agriculture (USDA ERS 2019). Depletion of aquifers and aboveground water bodies will reduce these water supplements. Well depths may no longer be adequate on public and private lands, resulting in inadequate water infrastructure to meet demand. Land parcels with extensive infrastructure including pipelines and pumping stations for water supply have high exposure to drought risk. In addition, with increased drought and demand for water from other resource sectors, transfer of water rights may occur from agriculture to urban centers or for multiple objectives, such as maintenance of minimum stream flows for protection of aquatic species, recreation, better water quality, and riparian and wetland restoration.

New management practices to minimize vulnerability and maximize water efficiencies will be necessary to maintain resilience of rangelands under long-term and spatially extensive drought. Social and ecological resilience to drought depends on adaptive capacity and strategies at many spatial scales (Joyce et al. 2013, McNeeley et al. 2016). That is, even robust agricultural technologies and data-driven management strategies may be ineffective in the absence of social capital. Social capital is a way to understand the benefits of relationship networks, reciprocity, trust, and cooperation for individuals, communities, and organizations who make natural resource decisions (Adger 2003). Trust, mutual respect, and proactive communication set the stage for learning and teamwork across fence lines and regions (Adger 2003, Muro and Jeffrey 2008, Rasmussen and Brunson 1996). These processes in turn enable managers to act in ways that lead to more resilient ecological outcomes. Processes linking social capital and natural capital, such as soil development, nutrient and water cycling, vegetation production, and land use, are key to understanding how drought affects the socio-ecological system in this region (fig. 7.1).

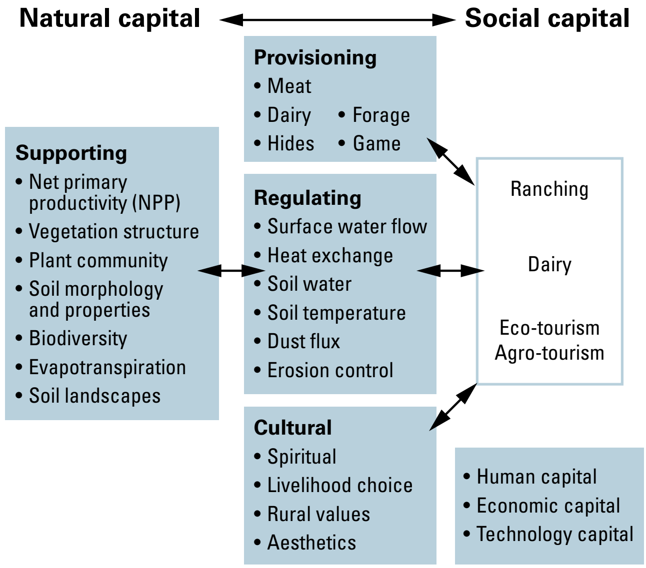


Figure 7.1—Understanding processes linking social capital and natural capital, such as land use, nutrient cycling, water cycling, vegetation production, and soil development, is key to understanding how drought affects different representations of the social-ecological system. These factors include forage production (vegetation productivity) and forage quality (e.g., nitrogen content) and are affected by land use and climatic factors such as precipitation and temperature. Drought has a profound impact on livestock numbers, with major reductions during periods of prolonged episodes of low precipitation. In addition, socio-economic trends affect livestock numbers due to market pressures and cultural value changes.

Here, we describe the need to track drought conditions, the prospect of future drought, and drought effects on rangeland resources. We provide drought-wise best management practices (BMPs), including both U.S. Department of Agriculture, Forest Service (USFS) and U.S. Department of the Interior, Bureau of Land Management (BLM) guidelines, to manage rangelands for increased drought resilience. We emphasize planning and collaboration that will help incorporate drought into management of natural resource systems. Although our focus is the Great Plains region, which is variously defined, concepts and management techniques are applicable to rangelands in general, where agriculture and livestock sectors are the dominant land uses.

CHARACTERIZING DROUGHT AND CLIMATE

Defining Drought

Following the preceding science synthesis of drought (Luce et al. 2016), drought is lack of water or precipitation levels lower than the annual average resulting from various factors including warmer temperatures and reduced precipitation (see chapter 1).

Drought metrics for the 20th century are a subset of the historical range of variability. Long-term reconstructions indicate more severe and longer lasting droughts over previous centuries (Cook et al. 2007, Finch et al. 2016, Luce et al. 2016).

Drought Monitoring

In recent years, there has been an upsurge in the availability of high-resolution (<0.6–6 miles) and near real-time weather information, which includes a better assessment of ecological water stress (i.e., anomalies in evaporative stress, evapotranspiration, soil moisture, and snow; see chapter 2) and higher confidence in near-term (1–2 weeks) weather forecasts. Weather involves shorter intervals than climate, which typically consists of 30-year averages. This information identifies regions with high risk for a drought emergence or intensification. Appropriate understanding and use of this information is often lacking among managers and can be greatly enhanced to inform their short-term preparedness (4–6 months). Beyond the short term, managers can develop a risk-based planning approach to prepare for a seasonal drought or longer term timeframe. Managers are encouraged to use a variety of drought monitoring and assessment tools, including those found at the U.S. Drought Portal (https://drought.gov), the National Drought Mitigation Center (https://drought.unl.edu), and the U.S. Drought Monitor (https://droughtmonitor.unl.edu) (box 7.2). Additional information may be found at the National Oceanic and Atmospheric Administration (NOAA) climate portal (https://www.climate.gov) and NOAA National Weather Service website (https://www.weather.gov).

Future Projections

Climate change is expected to increase the frequency and severity of drought episodes in the Great Plains because of increases in evaporative demand (Trenberth et al. 2014), greater proportion of precipitation occurring in high-intensity events, increases in number of dry days, and reduced snowpack (Easterling et al. 2017, Wuebbles et al. 2014). Future scenarios for the region generally project that elevated temperatures drive greater decreases in soil moisture, particularly in the latter half of the growing season, because of greater increases in evapotranspiration relative to precipitation (Hoell et al. 2018). Climate change is expected to intensify the hydrological cycle so the likelihood for both more severe droughts and flooding will increase; that is, more intense spring flooding may occur in the same year with more intense summer and autumn droughts. Larger and more extreme events will result in greater interannual and intra-annual variability in precipitation. In general, climate change during the 21st century will broaden the summer season with more extreme hot days than previously experienced; conversely, the winter season will shrink with fewer extreme cold days (Hansen et al. 2012, Meehl et al. 2009). Rangeland health may be particularly sensitive to the changing patterns of climate, especially a longer growing season, late growing season soil moisture deficits, and more water stress between rains.

For the Central and Western United States, there is a considerable range in global climate model projections for both temperature and precipitation during the 21st century. For example, by mid-21st century, this region may warm 3 to 8 °F (fig. 7.2), and precipitation change may vary anywhere from -20 to +20 percent (fig. 7.3). Severity and specificity (i.e., exact nature of ecological response) of climate change-induced effects on rangeland ecosystems will vary accordingly. Despite recent advances in climate modeling, uncertainty in regional projections remains high (Knutti and Sedláček 2013). As a result, innovative methods to incorporate uncertainty in planning are needed to ensure a foundation for decision making (Maier et al. 2016, Rowland et al. 2014, Sofaer et al. 2016).

In general, projections suggest increases in precipitation in the northern Great Plains and decreases in the southern Great Plains. The physical mechanisms driving this pattern are generally well understood, but the degree of change is largely controlled by variability of the climate system. The northern Great Plains has experienced a 12-percent increase in cold-season (October–March) precipitation during 1975–2014 compared to 1895–1974 (Livneh et al. 2016). Model projections also indicate a greater proportion of future moisture supply will occur via intense precipitation events (Easterling et al. 2017). These trends are being observed across much of the continental United States, including the Great Plains, in recent decades (Easterling et al. 2017, Livneh et al. 2016). Extreme precipitation will result in increased surface runoff and erosion potential, and comparatively less infiltration of water to deeper soil layers.

Soil moisture and vegetation will be affected significantly by altered snowpack, including total area under snow, depth, and duration of snow-covered ground. More precipitation will fall as rain rather than snow because of a warmer atmosphere. Warming will lead to earlier evapotranspiration and an earlier growing

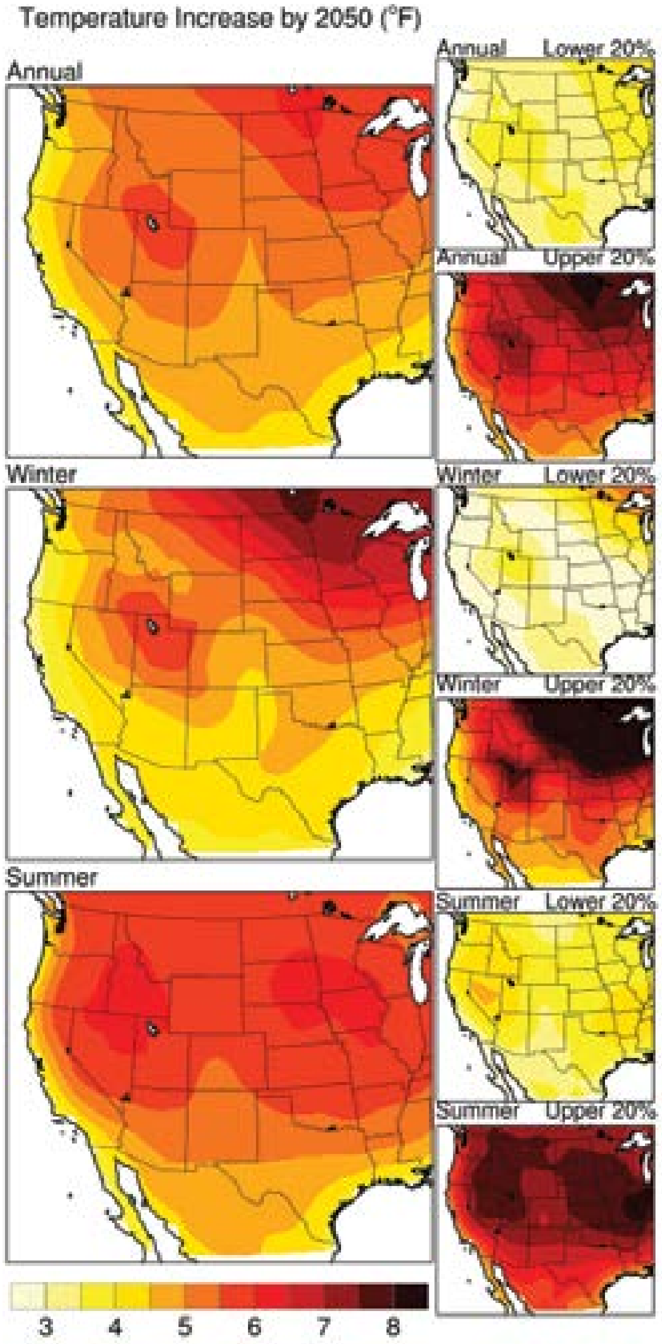


Figure 7.2—Projected changes in annual, winter (DJF), and summer (JJA) temperature by 2050 (2035–2064 relative to 1971–2000) over the Western United States from an ensemble of 34 climate models under Relative Concentration Pathway (RCP) 8.5. The large maps show the average change for all models; the small maps show the average changes of the highest 20 percent and lowest 20 percent of the models rank-based on change for the Great Plains. (Data source: CMIP5 projections re-gridded to 1-degree grid [Reclamation 2013; https://gdo-dcp.ucllnl.org]).

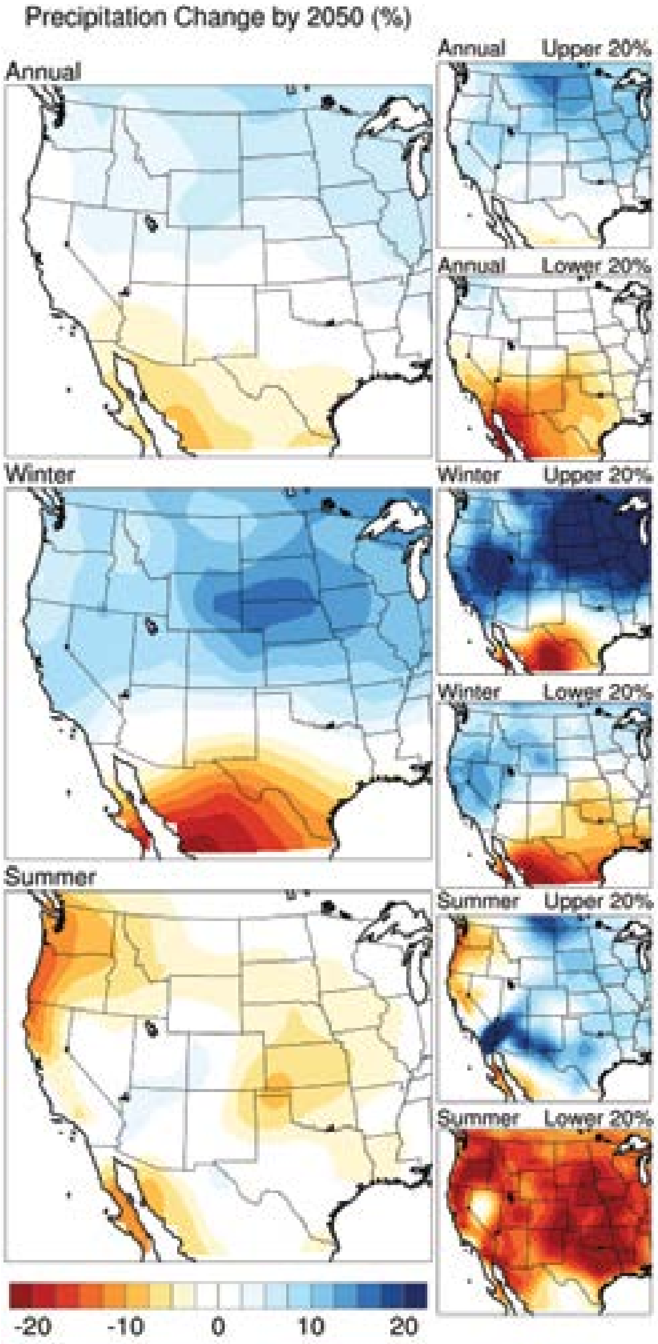


Figure 7.3—Projected changes in annual, winter (DJF), and summer (JJA) precipitation by 2050 (2035–2064 relative to 1971–2000) over the Western United States from an ensemble of 34 climate models under RCP 8.5. The large maps show the average change for all of the models; the small maps show the average changes of the wettest 20 percent and driest 20 percent of the models rank-based on the change for the Great Plains. (Data source: CMIP5 projections re-gridded to 1-degree grid [Reclamation 2013; https://gdo-dcp.ucllnl.org]).

season, as a result of shallow snow depth, rain-on-snow events, and earlier snowmelt. Warming and longer duration of evapotranspiration will also cause longer duration of depleted soil moisture, in some cases driving aridification in the American West (Cook et al. 2015, Mankin et al. 2017).

Climate models suggest that one of earliest signals of warming will be a reduced ratio of snowfall to rainfall (Pierce and Cayan 2013), a phenomenon that may already be occurring in the American West (Harpold et al. 2017, McNeeley et al. 2017).

For much of the Great Plains, climate models project increasing deficits in near-surface and deeper layer soil moisture during the latter half of the growing season (fig. 7.4). The anticipated decrease in soil moisture is due to continued climate warming during the 21st century (Cook et al. 2015, Walsh et al. 2014, Wehner et al. 2017), although such a risk appears to be greater for the southern plains as compared to the northern plains (Reeves et al. 2017), where most models project higher annual precipitation (Easterling et al. 2017, Walsh et al. 2014) (figs. 7.2, 7.4). However, there are many environmental factors that govern soil moisture loss through evapotranspiration, and there is uncertainty in our understanding of model accuracy (Ainsworth and Rogers 2007, Mankin et al. 2017). These factors include (1) increased water-use efficiency by plants because of elevated CO_2 levels, (2) increased transpiration rates from higher leaf area index (greening), and (3) evapotranspiration in response to increased leaf temperature and altered vapor pressure deficit. Warming may favor warm-season C4 grasses, whereas increased CO_2 may favor cool-season C3 plants. Combined warming and CO_2 enrichment may favor C4 grasses when soil moisture limits plant productivity (Morgan et al. 2011).

EFFECTS OF DROUGHT ON RANGELAND SYSTEMS

Soil Moisture

Soil moisture depends on the influences of precipitation, temperature, and wind on evaporation and transpiration by plants. Soil attributes such as infiltration, porosity, texture, and depth also affect available water capacity. Soil organic matter binds soil particles together into stable aggregates, improving water infiltration and porosity. Greater infiltration and pore space allow retention of more soil moisture during rain and prevent evaporation,

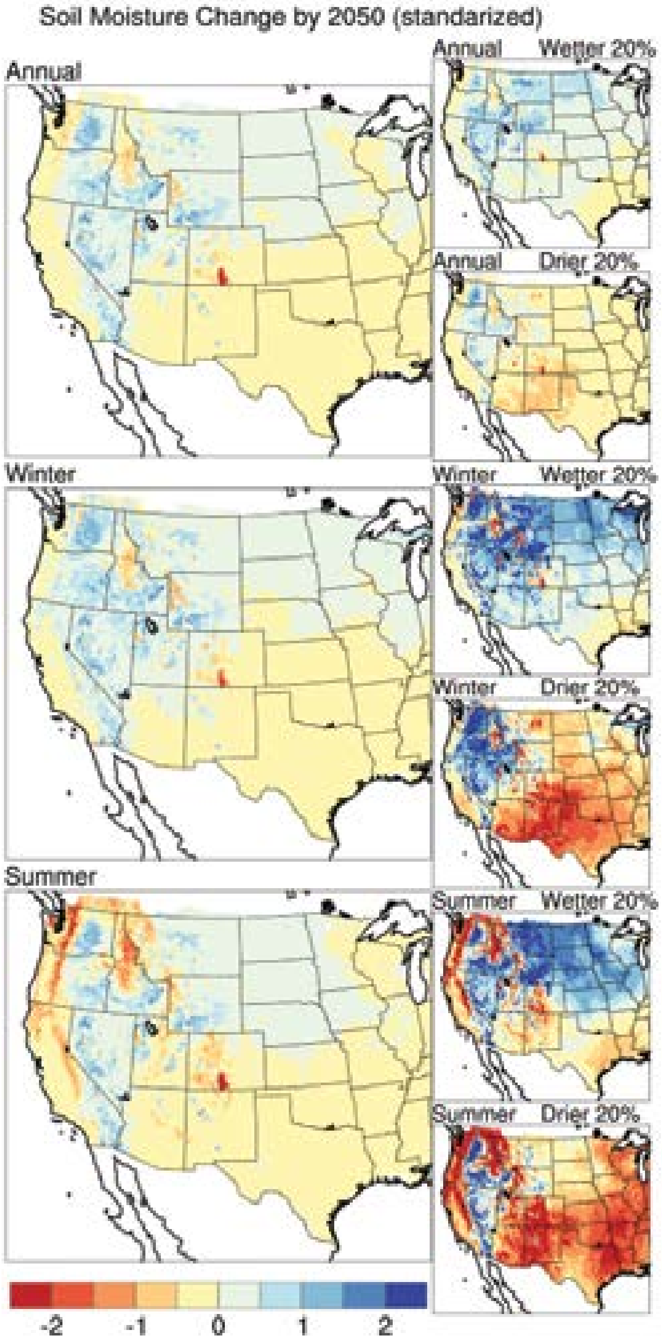


Figure 7.4—Projected changes in annual, winter (DJF), and summer (JJA) soil moisture by 2050 (2035–2064 relative to 1971–2000) over the Western United States from an ensemble of 29 climate models (all models that projected soil moisture) under RCP 8.5. The large maps show the average change for all of the models; the small maps show the average changes of the wettest 20 percent and driest 20 percent of the models rank-based on the change for the Great Plains. (Data source: 1/8th degree Variable Infiltration Capacity hydrological projections based on bias-corrected CMIP5 data [Reclamation 2014; https://gdo-dcp.ucllnl.org]).

reducing drought impacts and increasing productivity. A 1-percent increase in organic matter can triple water-holding capacity, equivalent to an additional 25,000 gallons of available water per acre and the equivalent of 3 inches of rain (Steiner et al. 2015). In addition, a 1-percent increase in organic matter adds up to $700 worth of additional nutrients per acre (Steiner et al. 2015).

Soil attributes can be mismanaged, particularly the amount of soil organic matter that controls infiltration and porosity. Land use may result in insufficient vegetative cover to protect soil from wind and water erosion. Typical erosion rates may be up to 0.04 inches per year, whereas topsoil replenishes at a rate of less than 0.004 inches per year (Thurow and Taylor 1999). Reduced productivity can result in reduced production of organic matter. Because most annual production occurs below the soil surface, roots are a primary contributor of organic matter in grasslands.

Vegetation

Water deficits limit vegetation growth, reproduction, and survival, indicated by reduced aboveground height and root length, limited seed development, dormancy during the growing season, and senescence. Deficits in water availability during the growing season will affect plants more than when plants are dormant. Vegetation cover, which may already be sparse due to aridity and use, will be reduced during drought, increasing soil vulnerability to wind and water erosion. Reduced vegetation cover also reduces water infiltration into soil, further exacerbating water loss to runoff and soil erosion. In addition, vegetation loss contributes to decreased soil organic matter critical to maintaining water holding capacity.

Each plant species has a different response to timing of rain events, drought, and drought combined with grazing and/or fire. After drought ends, loss of aboveground vegetation increases light and reduces competition. Therefore, plants may grow to above-average height and reproduce prolifically. Moran et al. (2014) showed that aboveground net primary production of Great Plains grasslands was correlated with total annual precipitation and aboveground net primary production of the previous year, even under chronic drought. Dominant vegetation assemblages have the capacity to physiologically adjust to climatic variability and may shift in composition, ensuring regenerative capacity following disturbance (Moran et al. 2014).

Invasive Species

Drought and changing seasonality of precipitation may be an inciting factor that facilitates invasion of plant species during dormancy of native plants. Alternatively, invasive species may be less drought resistant and establish during wetter winters; annual grasses in particular may not have deep roots. Invasive nonnative species remove or displace native species, which have been exposed to Great Plains conditions for thousands of years. Invasive grasses include species such as smooth bromegrass (*Bromus inermis*), Kentucky bluegrass (*Poa pratensis*), Timothy-grass (*Phleum pratense*), and crested wheatgrass (*Agropyron cristatum*) that are planted for forage, as well as cheatgrass (*B. tectorum*), red brome (*B. madritensis*), and medusahead (*Taeniatherum caput-medusae*) that spread aggressively on their own. Annual bromes and cheatgrass are present on about 30 percent and 22 percent, respectively, of pasturelands in the northern plains (includes Colorado and excludes Oklahoma and Texas) (USDA NRCS 2016). One species in particular that is changing ecological conditions in the eastern regions of the Great Plains is eastern redcedar (*Juniperus virginiana*), a tree species native to the Eastern United States. Drought and excessive grazing can influence the extent and magnitude of all of the species mentioned above, and must be considered in management plans (Davies et al. 2011).

The presence of invasive species affects ecosystem health by decreasing native forb and grass species diversity (Cully et al. 2003, DeKeyser et al. 2009, Miles and Knops 2009, Pritekel et al. 2006), affecting quality and abundance of forage, and disrupting nitrogen and soil organic carbon dynamics (Hendrickson et al. 2001; Wedin and Pastor 1993; Wedin and Tilman 1990, 1996). Therefore, invasive species can alter water infiltration into soils (Harivandi 1984, Hurto et al. 1980, Taylor and Blake 1982) and natural disturbance regimes, especially for wildfire. Shallow-rooted annual species may not produce as much organic matter as native vegetation (Rau et al. 2011), particularly during drought. Though crested wheatgrass is frequently seeded following wildfires, and both crested wheatgrass and Kentucky bluegrass reduce soil erosion, tolerate grazing, establish well, and are resistant to drought and cold (Hansen and Wilson 2006, Monsen et al. 2004), crested wheatgrass and Kentucky bluegrass hinder native plant recruitment and growth and are difficult to remove (Henderson and Naeth 2005, Marlette and Anderson 1986).

Wildfire

Wildfire requires vegetation as a fuel source and dry conditions for ignition. Seasonal rain provides moisture for vegetation growth followed by summers that dry vegetation and decrease humidity. Drought increases the length of time when humidity is low and vegetation is dry and susceptible to fire. Other factors increase fire frequency, such as presence of nonnative species (especially cheatgrass in Montana and Wyoming) that contain less moisture early in the summer compared to native species. Conversely, drought combined with overgrazing of vegetation will reduce availability of fuels for fire. Minimal fine fuels, active fire suppression, and fragmentation of vegetation may decrease fire frequency and allow an increase in woody vegetation.

Grasslands are typically fire-dependent ecosystems, and frequent fire is needed to maintain ecosystem structure and function (Limb et al. 2016). Without fire, woody vegetation will replace herbaceous vegetation. Trees and shrubs may establish during wetter conditions and spread in the absence of control by fire, in some cases becoming dense enough to shade out herbaceous vegetation. For example, without fire, eastern redcedar is spreading north through the Great Plains. Currently, eastern redcedar is sold commercially, including by USFS nurseries, and planted for windbreaks. Within 35–40 years, tree densities can be high enough to replace rangelands (Limb et al. 2014).

Drier rangelands, where both fire and woody vegetation are limited by aridity, are less dependent on fire. Although fire suppression may allow invasion by species with low fire tolerance, nonnative annual grasses tend to increase fire frequency, subsequently spreading post-fire while reducing habitat suitability for native species (Havill et al. 2015). Cheatgrass influences fire regimes through positive feedbacks in drier grasslands where fire is less frequent (e.g., Wyoming and Montana). Annual grasses have greater flammability than native perennial grasses due in part to low moisture content (Neibergs et al. 2018). Native grasses retain moisture in plant tissue into August, even when no longer actively growing (Neibergs et al. 2018). Where invasive annuals dominate, dry fuels may be available in June, lengthening the duration of flammable conditions (Neibergs et al. 2018). Cheatgrass life history varies from year to year. As a winter annual, its abundance is driven primarily by available moisture during autumn when it germinates, and during spring when seedlings initiate growth prior to native or naturalized perennial grasses (Knapp 1998). This is consistent with other findings that showed that above-average precipitation in autumn and winter before fire season (analysis for 1977–2003) was better correlated with larger and more numerous wildfires than were common drought measures such as low precipitation or high temperature (Littell et al. 2009).

DROUGHT MANAGEMENT OPTIONS IN RANGELANDS

Soil Moisture

Management strategies that are likely to increase soil organic matter will also increase soil moisture. Strategies include promotion of (1) dense herbaceous vegetation cover, (2) deeply rooted, perennial herbaceous plants rather than shallow-rooted annuals, (3) drought-tolerant herbaceous plants, and (4) diverse native plants (Rau et al. 2011). Control of nonnative annual species that produce less soil organic matter is also needed. Plant diversity will ensure plant cover and activity under a variety of conditions throughout the year. Monitoring of grazing levels to ensure continuous vegetative cover under drought conditions, at least during most years at most locations, may be necessary. Careful consideration of cover thresholds and risk assessment is needed for allotment management plans. This is important because soil compaction from intensive grazing during drought may reduce water infiltration and increase surface erosion, which may lead to reduced vegetation growth and cover.

Vegetation and Restoration

Because vegetation protects soil and contributes to soil organic matter, proactive management strategies are the same for both soil and vegetation, namely promotion of (1) dense herbaceous vegetation cover, (2) deeply rooted, perennial herbaceous plants rather than shallow-rooted annuals, (3) drought-tolerant herbaceous plants, and (4) diverse native plants. A diversity of plants will possess different traits, such as drought tolerance strategies, root-to-shoot ratios, growth rates, rooting depths, and different growing seasons, allowing some species to be more successful under varying soil moisture regimes. Establishment of plants during drought is not likely to be as successful as during wetter conditions. Surviving aboveground plant shoots may have reduced crude protein and digestibility. Therefore, not only is there less vegetation, the available vegetation provides less nutritional value. Reduced nutritional value, in turn, may require adjustments in grazing regimes.

Ecological restoration aims to restore degraded landscapes to healthy ecosystems that are resilient to disturbances such as drought, fire, and flooding and provide various ecosystem functions such as water supply, flood control, and pollination. Part of the restoration process aimed at increasing resilience to drought may also include restoring critical ecological processes such as appropriate fire regimes and grazing strategies. More resilient landscapes tend to have more diverse communities (Peterson et al. 1998), so building and maintaining ecosystems that are resilient to drought help restore landscapes with a diversity of native plant species. Restoration in grasslands is more successful when plant material is diverse (Barr et al. 2016, Serajchi et al. 2017).

Successful restoration is challenging, and an integrated approach suited for specific sites and management goals is essential. Restoration during a drought is even more challenging with extended periods of little to no rain resulting in reduced soil moisture and vegetation growth, increased fire risk, and accelerated invasion of some invasive species (Finch et al. 2016). Using climate information (e.g., the National Weather Service Climate Prediction Center's 3-month outlook) to determine anticipated precipitation levels in upcoming months will help restoration planning relative to site preparation, invasive species control, seeding, and planting (Kimball et al. 2015). A decision-support tree has been developed to help guide restoration efforts in a cost-effective manner (Kimball et al. 2015).

With ample precipitation, efforts should focus on restoring diverse, native plant communities because seeding and planting in wet conditions improve restoration success and effectiveness (Bakker et al. 2003, Kimball et al. 2015), although continued control and removal of invasive species is still necessary. Seeding and planting during a drought are possible, although not optimal, but a variety of techniques are needed to improve plant establishment and survival such as seed pillows, seed coatings, irrigation, and transplanting seedlings (Finch et al. 2016). Seeding with mixes that contain multiple species and applying these mixes at high rates enhance restoration success, and increasing seed-mix diversity contributes to grassland restoration success (Barr et al. 2016). Incremental shifts in planting times should occur to coincide with precipitation. Dormant seeding may result in more successful germination. Examining and updating planting techniques to include climate information (Printz and Hendrickson 2015) will improve restoration success.

Seed transfer guidelines have been developed to help guide land managers in obtaining native seed that is adapted to specific environments (Johnson et al. 2004), although modified guidelines may be needed in a warmer climate. Provisional seed zones delineate areas of similar climate focusing on variables important to plant survival and growth: winter minimum temperature (cold hardiness) and aridity (the ratio of mean annual temperature and mean annual precipitation; Bower et al. 2014). Empirical seed zones have been developed for a number of species and delineate areas based on climatic variables and genetic information for wild populations (Erickson et al. 2004, Johnson et al. 2013). The genetic information is gathered in common garden experiments, focusing on plant traits that are important to survival and reproduction. The use of provisional or empirical seed zones may help to guide land managers on where to source plant material for restoration so that material is adapted to the local environment. This information, along with local expertise and projections of future climate and drought conditions, will aid in matching specific seeds with specific sites.

Restoration using native plant material is a directive or strongly encouraged in Federal agencies, but obstacles exist in using native plant material, such as expense of seed and lack of sufficient quantities. The National Seed Strategy for Rehabilitation and Restoration 2015–2020 was developed to encourage use of native plant materials in restoring plant communities and supporting healthy ecosystems. This strategy is generating a network of resource managers and restoration ecologists who have experience in selecting the right seed in the right place at the right time. In addition, the strategy is enhancing the capacity of native seed collectors, agricultural producers, nurseries, and seed storage facilities to provide adequate amounts of economical native plant material. The national Native Seed Network (http://nativeseednetwork.org) has an online database of native seed vendors throughout the United States.

A review of grazing studies on shrub-steppe rangeland concluded that bunchgrasses are more sensitive to defoliation during the growing season than to grazing after seed shatter and the cessation of active growth (Burkhardt and Sanders 2012). The authors recommended that native bunchgrasses, particularly jointed grasses, be allowed to produce seed approximately every other year. This can be accomplished by deferring all grazing in a given year until after plants have produced seed or by allowing a relatively short period of early spring grazing followed by rest until after seed shatter.

Invasive Species

A variety of treatments, alone or in combination, may be evaluated to reduce invasive species and restore native plant communities. During periods of drought, restoration efforts may focus primarily on removing invasive species that are moisture stressed, making removal treatments more effective (Bakker et al. 2003, Kimball et al. 2015). Control of invasive species is most effective during early stages of invasion to prevent spread, so monitoring to detect invasive species is critical. Combined damage and control efforts cost approximately $137 billion annually; for example, weed control, primarily by herbicides, costs about $11 billion per year (Kopp et al. 2014, Stitt et al. 2006).

During drought, dormancy in plants reduces uptake of herbicides, making chemical application ineffective. Biological control agents also may be less effective at controlling invasive species during drought. Mechanical treatments can reduce woody plant encroachment (Archer et al. 2011), but other methods result in less soil disturbance and erosion, which helps build or maintain drought-resilient ecosystems (Davies et al. 2013, Gifford 1982). Prescribed fire, during a drought year or in combination with herbicides, may control invasive species of cool-season grasses and woody plants and favor native species (DiTomaso et al. 2006, Ereth et al. 2017, Twidwell et al. 2016). Fire behavior during drought may be altered by lack of fine fuels to spread fire or by higher flammability.

Manipulation of grazing to focus on when invasive species are green and palatable and when native species have set seed may be another strategy, although determining the efficacy of this practice may take some time. Grazing to suppress cheatgrass, as an independent goal from altering fire behavior, must occur when the plant is palatable and when seed production can be interrupted or slowed (Mosley and Roselle 2006). This phenological stage is rather short in cheatgrass, but during this stage (roughly seedhead emergence through soft dough stage), cattle, sheep, and goats will readily consume it. After this stage, plants are unpalatable and livestock movements may serve only to assist in distributing and planting seed rather than consuming it.

Because of the additional effort in fencing and herding required to deliberately target cheatgrass, treating very large areas in a single year is infeasible. The BLM has initiated several targeted grazing projects to explore techniques, frequency of grazing, and capability (practicality) of permittees to manage livestock numbers and distribution, in order to achieve project objectives. The use of targeted grazing to improve rangeland resilience to drought represents an opportunity for managers to experiment with various species of animals. As a result, the BLM may authorize grazing specifically to target invasive plants during drought.

Effectiveness of this approach is not without dispute; research in Oregon evaluated cover and production of cheatgrass in grazed and ungrazed treatments and found no difference among grazed and non-use treatments (Bates and Davies 2014). A fuel-based restoration model for sagebrush-steppe has been proposed that incorporates pre-fire plant community composition, environmental factors, and ecological processes that control resistance and resilience (Hulet et al. 2015). This approach also identified 11 research objectives that require further exploration before reliable management planning and prescription can proceed.

Minimizing surface disturbance and scheduling grazing to maintain native community resilience are strategies for preventing introduction or establishment of invasive plants. Management options that can be used to prevent invasive plant establishment include:

- Refrain from grazing or moving cattle through populations of invasive plants while they are setting seed or when fruit is ripened.
- Purchase only certified weed-free seed for forage (required by many national forests year-round).
- Keep cattle and other livestock out of newly planted areas.
- Employ rotational grazing and other management strategies that minimize soil disturbance.
- Purge animals with weed-free feed for 5 days before moving them from infested to uninfested areas.
- Position activity boundaries to exclude areas infested with invasive species. If not possible, consider treating infested areas before other land-disturbing activities.
- Close or reroute public roads or trails in infested areas.

- Prevent pack animals from entering infested areas.
- Brush seeds off animals, equipment, shoes, and clothing.

Wildfire

Wildfire removes (at least in the short term) vegetation, exposing bare soil. In fire-adapted grasslands where fire may occur annually, few plants may die because perennial plants regrow aboveground vegetation (Gates et al. 2017). Fire removes dead plant material, allowing more light for new growth, and fire may be necessary for seed germination in some species, including grasses and forbs (Blank and Young 1998). Plants have higher forage quality following fire due to increased crude protein and decreased fiber content. For livestock, the benefit from burning can be comparable to that from supplemental feeding (Limb et al. 2016). Fire provides an opportunity to manage for varied disturbance and grazing intensity, rather than promotion of uniformity. If biomass has increased and ground cover is present, higher stocking during post-fire regrowth is an appropriate management response.

For post-fire restoration, a site should be evaluated prior to restoration efforts to determine if it is a reasonably intact, healthy ecosystem that may be resilient to disturbance, and has low density of invasive species (<15-percent cover). If so, then it may be best to wait a season to determine if revegetation will occur via the seed bank and remaining vegetation on site (Auffret and Cousins 2011, Farrell and Fehmi 2018, Lipoma et al. 2016). Natural revegetation through a seed bank is a viable option if the area has not experienced high disturbance (Farrell and Fehmi 2018). Delaying seeding a season for natural revegetation will maintain soil biocrusts, while ensuring persistence of plant material adapted to the local environment. The Burned Area Emergency Response (BAER) program used by the USFS uses various seed mixes and mulch for erosion control and installation of erosion control devices after fire. Seeded species must be able to establish and stabilize soil rapidly.

Federal agencies and managers may recommend resting burned areas for two grazing seasons to allow recovery of perennial plants and establishment of seeded species (Gates et al. 2017). The USFS does not have a national policy for rest after a fire. Instead, it is common practice to use a range-readiness evaluation to determine if the burned area can be grazed before the upcoming grazing season. Burned areas will recover at different rates depending on fire characteristics, weather, pre-burn vegetation, and other factors.

Vegetation regrowth in response to fire attracts more intensive grazing, resulting in a fire-grazing linkage that produces differential grazing intensity and heterogeneity across an area ("pyric herbivory"), in conjunction with other areas that are grazed lightly or not at all (Fuhlendorf and Engle 2009). Heterogeneous vegetation structure and plant diversity may be missing ecological attributes that are critical for declining animal species, such as grassland birds and pollinators. In contrast, unrelenting heavy grazing leads to a decrease in perennial grasses, an increase in invasive annual grasses, and a decrease in soil and fuel moisture. Under drought conditions or in arid regions (e.g., the Great Basin, where vegetation did not evolve under grazing pressure from American bison [*Bison bison*]), burned areas are likely to need protection from grazing. Vegetation may not recover well under limited water availability. In addition, fires that occur in winter expose soils for a long period of time before vegetation regrows, and potential soil damage through erosion may warrant protection from trampling and compaction.

Elevated risk of wildfire due to drought may increase expenditures on suppression, fuels management, and post-fire restoration. Fires force the closure of roads and recreation areas and destroy infrastructure, including fencing. Fires also cause financial losses due to reduced access for livestock grazing, and may damage infrastructure used for livestock management. Although the costs of conducting a prescribed burn on rangeland are relatively low, this option is financially risky for most private landowners due to laws in most States requiring reimbursement of fire suppression costs when a prescribed fire on private lands spreads onto public or adjacent private land.

Managed Herbivory

Livestock are a key economic driver in the Great Plains and are linked with drought and vegetation abundance. For example, the value of U.S. cattle production was $60 billion in 2015 and a record $82.1 billion in 2014 (USDA NASS 2018). Drought produces uneven livestock-based economic gains and losses in space and time. The 2014 Farm Bill authorized the Livestock Forage Disaster Program to provide compensation to eligible livestock producers for grazing losses due to a qualifying drought condition (this program was initially funded in 2008). Compensation is up to $30 per month for adult cattle for up to 5 months, depending on duration and severity of drought. Government payouts during 2014 were $4.4 billion, 84 percent of which were retroactive payments back to October 2011 (USDA ERS 2018) (box 7.3).

The southern Great Plains, which currently produces the most livestock in the Great Plains region, is more vulnerable to drought and loss of forage productivity than more northern locations. Texas has received the highest and second highest amount of supplemental and ad hoc disaster assistance payments between 2008 and 2016 (USDA ERS 2018). Ranchers in the southern Great Plains may need to rely on grazing management plans that vary with weather conditions, as well as consider using different livestock breeds. In the future, livestock production may shift northwards where water supplies and forage are more secure.

Stocking rates, timing, and location of livestock owned by grazing permittees may need to be adjusted in order to protect land and maintain vegetation for wildlife. A proactive strategy to manage rangelands before drought, in areas where forage species have evolved with grazing and fire, may be promotion of heterogeneity through a combination of fire and varying grazing intensities (Fuhlendorf and Engle 2001). Brief periods of heavy grazing combined with long intervals of low-intensity grazing may mimic historical disturbance. Reduced and deferred grazing during and after drought conditions allows for greater protection of a continuous vegetative layer. Resting rangelands for at least a season after drought may be necessary for recovery. Liquidating or relocating livestock is preferable to degrading rangeland and the cost of long-term loss of rangeland productivity. Stocking to 10–40 percent of historical levels during the past century has helped protect rangelands and provide other ecosystem services (Havstad et al. 2018, Wang et al. 2014), although some of this change has been offset by larger cattle size.

Decision making in the agricultural sector is complex, based on variability in weather patterns, along with shifts in market demands, consumer preferences, and State and Federal policies (Kopp et al. 2014). Ranchers may select conservative stocking as a long-term strategy or may stock more heavily and destock, with supplemental feeding and movement of cattle as additional actions in response to drought. Regular destocking and restocking due to forage insecurity is economically disadvantageous and risky (Neibergs et al. 2018), although flexible stocking and purchase of yearlings rather than maintenance of a base herd of cow-calf pairs may increase gains.

Maintaining a smaller core herd and incorporating yearling steers to economically increase stocking rates during drought years rather than merely having a conservatively sized constant herd may improve returns (Torell et al. 2010). In any case, aggressive destocking at the earliest detection of drought, when market prices are higher and cattle are heavier, may produce better economic outcomes while protecting natural resources and future productivity (Thurow and Taylor 1999). Measures that prolong predrought stocking rates, such as water availability and supplemental forage, may increase economic and ecological risk (Thurow and Taylor 1999). Managers may consider conservative constant rates versus flexible rates based on herd expansion with yearlings on public lands.

Flexibility in management prior to drought can be increased through the following actions:

- Maintain a reserve forage supply (e.g., stock conservatively, rest pastures, develop a grass bank).
- Improve infrastructure to allow pastures to be used in multiple seasons rather than just summer or just winter (e.g., water and shelter can be limiting factors).
- Ensure consistent water supply by installing wells and pipelines rather than relying solely on surface water; this will enable use of available forage if stock ponds go dry.
- Evaluate the potential for other forage sources, such as Conservation Reserve Program lands (if opened to grazing) or annual forages (cover crops).

Pasture recovery following drought can be enhanced through the following actions:

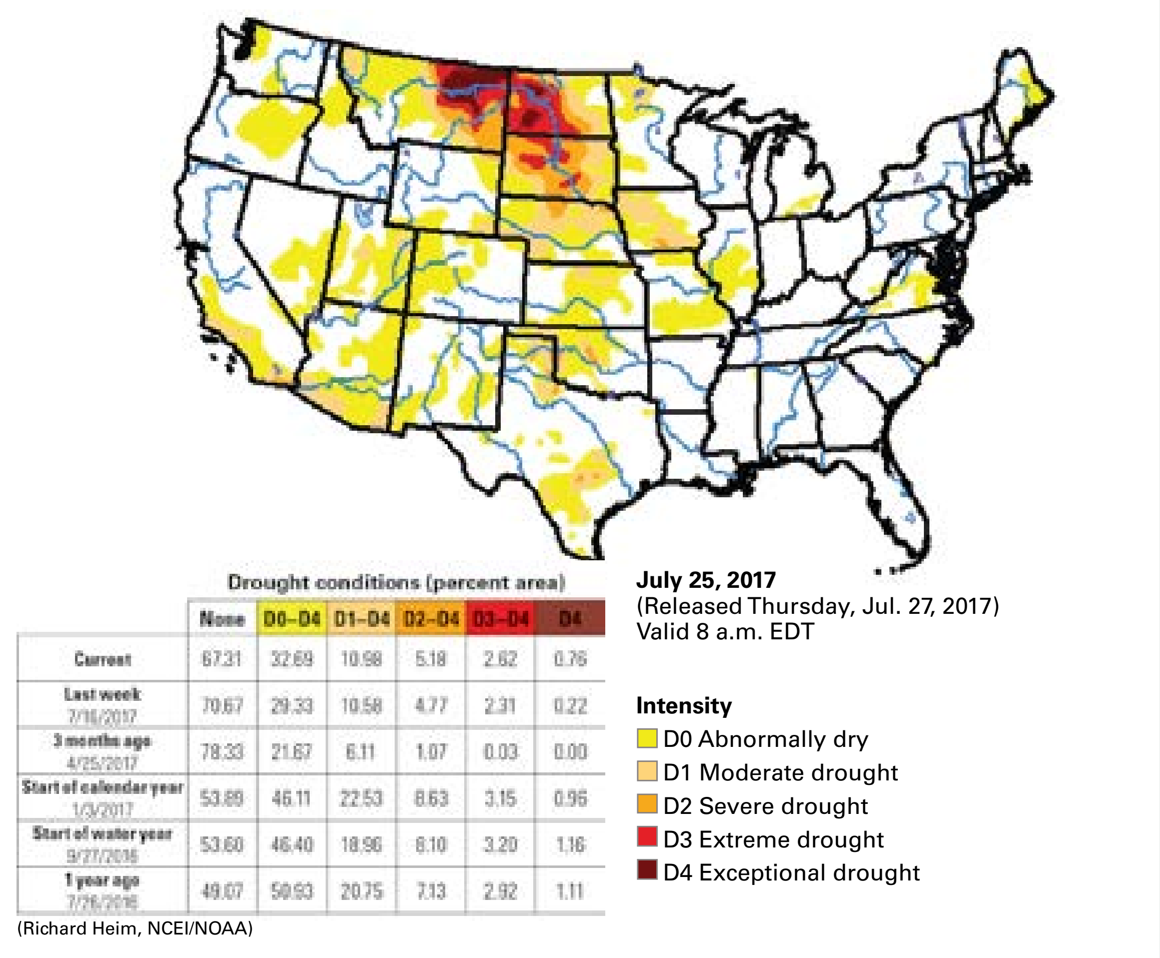
- Devote much of the year following drought to improving plant vigor and restoring protective residual vegetation and plant litter.
- Restore hydrological condition as a high priority for rangelands. The efficiency of precipitation is reduced until enough litter is accumulated to optimize infiltration and minimize evaporation. Delaying grazing when green-up occurs will allow this to occur faster.
- Restore plant vigor as the second highest priority by promoting rapid plant growth (which happens

BOX 7.3
Drought Intensity and Livestock Forage Program Payments

The U.S. Drought Monitor is used to trigger disaster relief payments for the Livestock Forage Program (LFP). A livestock producer is eligible if he or she owns or lease grazing land or pastureland physically located in a county rated by the U.S. Drought Monitor as having:

- D2 (severe drought) intensity in any area of the county for at least 8 consecutive weeks during the normal grazing period. The producer is eligible to receive assistance in an amount equal to one monthly payment.
- D3 (extreme drought) intensity in any area of the county at any time during the normal grazing period. The producer is eligible to receive assistance in an amount equal to three monthly payments.
- D3 (extreme drought) intensity in any area of the county for at least 4 weeks during the normal grazing period, or a D4 (exceptional drought) intensity at any time during the normal grazing period. The producer is eligible to receive assistance in an amount equal to four monthly payments.
- D4 (exceptional drought) in a county for 4 weeks (not necessarily 4 consecutive weeks) during the normal grazing period. The producer is eligible to receive assistance in an amount equal to five monthly payments.

For a map of counties eligible for LFP payments, see
https://www.fsa.usda.gov/programs-and-services/disaster-assistance-program/livestock-forage/index.



Drought conditions (percent area)

	None	D0–D4	D1–D4	D2–D4	D3–D4	D4
Current	67.31	32.69	10.98	5.18	2.62	0.76
Last week 7/18/2017	70.67	29.33	10.58	4.77	2.31	0.22
3 months ago 4/25/2017	78.33	21.67	6.11	1.07	0.03	0.00
Start of calendar year 1/3/2017	53.89	46.11	22.53	8.63	3.15	0.96
Start of water year 9/27/2016	53.60	46.40	18.96	8.10	3.20	1.16
1 year ago 7/26/2016	49.07	50.93	20.75	7.13	2.92	1.11

(Richard Heim, NCEI/NOAA)

July 25, 2017
(Released Thursday, Jul. 27, 2017)
Valid 8 a.m. EDT

Intensity

- 🟨 D0 Abnormally dry
- 🟧 D1 Moderate drought
- 🟧 D2 Severe drought
- 🟥 D3 Extreme drought
- 🟫 D4 Exceptional drought

when air temperatures and soil water are both favorable). Production and retention of photosynthetically active foliage are critical to restore belowground growth, which is reduced by drought stress and grazing stress.
- Expect a flush of broadleaf plants after drought breaks. Many forbs and native plants are highly nutritious and palatable at early growth stages. When these plants are grazed, pressure on desirable forage species recovering from drought is reduced.

The most popular drought management options focus on reserving forage supply, reducing herd size, and buying feed (Coppock 2011, Kachergis et al. 2014). The fact that many ranchers use similar drought management practices, potentially triggering major price fluctuations, highlights the market risks associated with drought. This reinforces the importance of flexibility in drought management strategies for drought adaptation because using diverse practices may help a producer reduce market risks (Kachergis et al. 2014).

Flexibility can be improved through the following actions:

- Vary stocking rate with forage supply (e.g., incorporate yearling livestock).
- Wean early to extend the forage base.
- Practice early and heavy culling of less productive cows, such as late-calving cows and older cattle.
- Remove yearlings from summer pastures early.
- Consider curtailing the production of replacement heifers for one year.
- Supplement bulls earlier than other classes of livestock if necessary, so they are in acceptable condition when the breeding season begins.
- Maintain a percentage of the livestock, such as yearlings or stockers, as a readily marketable class of stock.
- Consult with agency managers early to discuss which options are allowable under their permit (e.g., switching from cow-calf to yearling operation).

FEDERAL AGENCY GUIDELINES FOR DROUGHT MANAGEMENT

All USFS range managers and line officers are required to adhere to national and regional agency policies, and to follow their national forest/grassland plans and allotment management plans (AMP). These policies and plans match the number of livestock and/or season of use with forage produced and forage available for use, while considering rangeland conditions and long-term ecosystem health. Handbook directives are critical because they indicate the need for managers to build trusting relationships with stakeholders, especially permittees who are authorized to graze on USFS lands. It is good practice to proactively prepare for drought by having open discussions with permittees and to prepare solutions before the next drought begins, thus maintaining long-term productivity of rangelands and economic viability of livestock producers and communities.

Range managers in the USFS aim to not only protect landscapes but also aid local economies and social structures in dealing with drought. During drought, agencies can reduce the use of certain landscapes as well as assist local livestock producers. In an emergency, the USFS may withhold validation of a permit or require that livestock be removed from the range without advance notice to the permittee. However, permittees are rarely instructed to remove cattle without advance notice, even though plans are subject to change based on events such as fire and drought. Agencies can also authorize the use of available forage. During regional-scale droughts, temporary grazing permits may be issued to allow grazing use of USFS lands where such use will not result in resource damage.

Permittees, range extension specialists, and industry leaders have expressed the importance of helping permittees maintain a reduced core-allotment livestock herd. The core herd represents well-adapted, high-quality breeding stock. Livestock operators who are best positioned to maintain their core herds built over generations have some component of yearlings in their operation every year. Replacing a core herd is a long, expensive process.

Permittees have different abilities and desires to move livestock within an allotment or pasture (which is a subdivision of an allotment), and have different resources and conditions available to them outside of USFS lands. Moisture patterns can be significantly different from one allotment and even one pasture to the next. Allotments and pastures have different vegetation, topography, elevations, soils, rangeland health, forage production, and residual vegetation. It follows that rangeland management strategies are different for each allotment (e.g., fences, water, graze periods, pasture size, day herding, etc.). As a result, Federal managers are encouraged to develop strategies for each grazing allotment by involving permittees, most of whom follow weather, current range conditions, and projected forage growth conditions on their allotment.

Policy for drought management in the BLM exists at the Instruction Memorandum level and is not currently addressed in Handbooks. Instruction Memoranda with general policy are periodically issued from National Headquarters, as each drought becomes significant enough to be addressed, typically with a duration of 2–3 years. The principal guidance is the same as in the USFS: (1) work with affected permittees to adjust grazing use (timing of use, duration of use, livestock numbers) to maintain health of vegetation and soil resources, (2) allow temporary water hauling if appropriate, and (3) help find alternative forage in rested pastures or areas with non-use where appropriate for maintaining wildlife use. BLM regulations provide local officers with the authority to issue decisions to close allotments or portions of allotments, or to modify grazing when immediate protection of resources is needed because of drought, fire, flood, insect outbreaks, or potentially damaging effects of continued grazing.

The authorized officer consults with affected permit holders, interested parties, and appropriate State agencies before issuing the decision, which is effective immediately. This requires careful collaboration with stakeholders, especially permittees. Changes in grazing management or adjustments in season and number of livestock are either agreed upon by the permittee and BLM prior to making the adjustment, or implemented by BLM decision. Permittees may unilaterally decide to remove livestock from an allotment as a result of drought or other disturbance, then notify BLM of the removal. Ability to make adjustments on public land is often limited by availability of open water and its effect on distribution of grazing use.

PLANNING AND COLLABORATION

Proactive planning and collaboration can facilitate responsive management decisions during drought. Planning for the next drought must occur in advance because management options decline as drought intensifies. A drought preparation plan is strategic when it focuses on preparing an operation for drought in the long run (5–10 years) by identifying practices that can be implemented proactively to increase options for responding to drought (Hawkes et al. 2018). The rapid onset of droughts (i.e., flash droughts; see chapter 1) across the Great Plains suggests a need to incorporate these features in drought plans.

The primary goal in every drought management plan should be to maximize the number of potential management options in order to protect the resource before and during drought conditions, thus facilitating fast recovery in wetter years (Howery 2016). A drought plan should minimize financial hardships and hasten vegetation recovery following drought, identifying action to be taken at the first sign of drought as well as later. Plans for stocking rate adjustments need to be specific in terms of method and date, with timing of actions based on seasonal checkpoints associated with vegetation response. High plant vigor and good range condition are critical for rapid recovery from drought. There are no tools that can compensate for overgrazing, and timing and intensity of grazing are important factors in allowing pastures to recover from stress.

In some cases, an inventory of drought preparedness may be recommended to determine if it is feasible to implement the full range or a subset of responses. A drought preparedness inventory is a proactive practice that improves flexibility and demonstrates if a particular operation and location are indeed prepared for drought. A variety of management options should be considered to realize the full capacity of flexibility and where it may need improvement. Contingency options are limited if reliable infrastructure and resources are unavailable. Infrastructure (e.g., cross-fencing, water development, etc.) may need to be improved, repaired, or developed in order to implement a drought plan.

Working with all stakeholders to co-produce a strategic drought preparation plan helps build a shared vision, understanding, and realistic expectations and timelines. However, agencies and producers have different priorities, funding issues, and workloads that need to be understood and reconciled by collaborators. Each Western State has a drought management plan, and local and Tribal governments may also have plans. Being aware of the drought management plans developed by governmental entities that exist within each jurisdictional area helps ensure that local drought management efforts are compatible. Different agencies may participate in local drought management planning to coordinate information about needs and available resources. Building a collaborative vision and understanding is likely to result in a productive plan with feasible contingency options when critical responsive actions need to be implemented in a timely manner. The collaborative process also builds working relationships that improve trust, efficiency, and communication.

For managers of Federal lands, preparing contingency plans and identifying infrastructure needs begin with the National Environmental Policy Act (NEPA) process, AMPs, and annual operating instructions. These require time and make planning for drought in advance even more critical. By starting the planning during the NEPA or AMP process, proactive practices are implemented before responsive decisions are needed. In preparation for drought management decisions, having buy-in on the plan from all parties will trigger timely responses that protect resources. Managers may consider development of triggers that invoke automatic changes in management to reduce potential surprises. Such triggers are already being developed in the Southwestern Region, where the Standardized Precipitation Index (SPI) is being used to adjust management according to unfolding conditions. These triggers and linkages with SPI can be found in the Regional Supplement to the Grazing Permit Administration Handbook (Forest Service Handbook [FSH] 2209.13).

ROLE OF PUBLIC LAND MANAGERS IN PROMOTING RESILIENCE

Public land managers who work with private producers are uniquely positioned to promote resilience to drought in both the social and ecological dimensions of natural resource systems. Few people know the land base and what may work the best on a particular operation better than a private-sector ranch manager. Therefore, private landowners are increasingly recognized as key partners in the sustainability of multiple ecosystem services (Brunson and Huntsinger 2008, Charnley et al. 2014). Public land managers can act as knowledge brokers at the public-private lands interface to facilitate management for multiple uses and under extreme or variable weather conditions. Managers can serve as technical advisors to assist in drought planning and communicate about conditions on rangelands, promoting adaptive strategies that help limit the financial and ecological impacts of drought.

No allotment or operation exists in isolation from broader networks of social and ecological systems. At the allotment or ranch scale, adaptation can be influenced by belief in the ability to act (self-efficacy) (Marshall 2010). Managers who are well-informed about climate and weather can anticipate drought by developing drought management plans preemptively, employing conservative stocking rates and incorporating climate-adaptive breeds and genetic lines in livestock herds (Anderson et al. 2015, Derner and Augustine 2016). On a shorter time scale, they can anticipate variability using local knowledge and a growing number of weather-related decision-support tools and forecasts available (Reeves et al. 2015), although these may have limited adoption due to a lack of trust and skill (Marshall et al. 2011). Once drought occurs, managers can track variability through flexible stocking of diverse animal classes (e.g., with yearling or stocker animals) (Ritten et al. 2010, Torell et al. 2010). Use of spatial variability in the landscape and grass banking of stored forage are other tools to offset the effects of drought on forage supply (Derner and Augustine 2016, Gripne 2005).

At the community and regional scales, managers can promote flexibility by moving risk across space (movement of livestock to other areas) (Huntsinger et al. 2010), across time (storage of forage, water, or other resources), or across households (pooling labor, equipment, and information) (Fernández-Giménez et al. 2015, Mearns and Norton 2009). These risk-movement strategies can pair well with diversified agriculture and other market-based adaptation approaches on private lands to further enhance resilience to weather variability across landscapes (Sayre et al. 2012). Again, the adoption rate and success of adaptation strategies and tools, and the effectiveness of public agency involvement therein, depend on the structure and extent of social relationships across space and time (Fernández-Giménez et al. 2005, Marshall et al. 2011).

Natural resource social science offers insights for public land managers seeking to promote understanding and use of drought adaptation strategies. This research indicates that many producers have years or generations of experience with drought (Coppock 2011, Marshall 2010). Traditional grazing management practices, many of which maximize livestock and vegetation production in the short term, are imbedded in production cultures and have been co-produced over decades by researchers, public managers, and ranchers (Bement 1969, Sayre 2017). Needs-based communication efforts designed to promote a two-way exchange of ideas and listening build on existing manager knowledge (Pannell and Vanclay 2011). Effective communication can create opportunities to explore new strategies that will address more uncertain or variable climate/weather scenarios in the future.

Decision making on ranches is context specific (Roche et al. 2015), and ranching operations and operators are diverse. Operators have varying levels of willingness and ability to act for drought adaptation and may have limited proactive strategies in place to cope with reduced water and forage supply and market shifts (Darnhofer et al. 2016, Kachergis et al. 2014, Wilmer and Fernández-Giménez 2016). Permittees make decisions within place-based economic, ecological, and cultural contexts and serve in different decision-making roles throughout their tenure on family operations. This means that one best practice is unlikely to fit all operations over time, even within a small geographic area. Considerable value exists in diverse decision-making approaches that foster ecological variability and build capacity to manage for the effects of drought and other objectives (Wilmer et al. 2017). Risk management models, decision maps, peer-to-peer learning, and scenario planning activities can be used to communicate data and adaptive strategies (Dunningham et al. 2015).

Collaborative adaptive management (CAM) allows resource managers to develop a community of practice that is informed about variable weather and complex ecosystems (Armitage et al. 2009, Filipe et al. 2017, Lawson et al. 2017, Susskind et al. 2012). Collaborative adaptive management incorporates some elements of experimental design with facilitated outcome evaluation and decision making by a diverse group of stakeholders (Beratan 2014), allowing managers to test hypotheses and reduce uncertainty about ecosystem processes and drought response, rather than focusing solely on prescriptive management (Holling and Meffe 1996). Collaborative adaptive management also has the potential to empower managers to operationalize scientific and weather information for specific decisions (Dunningham et al. 2015). Effective CAM requires long-term commitment from participants and hosting organizations, attention to local political contexts, and explicit efforts to incorporate multiple types of knowledge in decision making (Filipe et al. 2017, Harrison et al. 1998, Hopkinson et al. 2017).

CONCLUSIONS

As the climate continues to warm in the future, weather in the Great Plains is expected to become increasingly variable and drought is expected to be more frequent. Monitoring tools and good communication can help range managers anticipate, detect, prepare for, and respond to drought. Sustainable management of native grasslands may be the best drought protection plan of all. Rangeland management differs based on local conditions, but core principles remain, primarily restoration or maintenance of diverse native species that nurture belowground ecosystem health and facilitate a range of species tolerances to meet changing conditions, including drought. Similarly, protection of the soil resource will maintain water-holding capacity and support vegetation cover, attenuating drought effects. Fire and variable-intensity grazing are primary disturbances in rangelands and provide mechanisms to increase vegetation heterogeneity. Where plant communities exhibit serious dysfunction in any of the three widely recognized attributes of rangeland health (soil stability, hydrological function, biotic integrity; National Research Council 1994), restoration of native species can be prioritized to promote competition with invasive annual grasses.

Numerous strategies are available for livestock producers to prepare for drought and buffer economic volatility, ranging from conservative stocking to economic diversification. Herd liquidation to prevent degradation of rangelands is a shared strategy during drought, which causes economic loss due to selling at the same time and buying simultaneously after recovery. Although economic downturns provide disincentives to reducing stocking rates, delayed response to drought may degrade rangelands if high stocking levels are decoupled from forage production, resulting in long-term productivity declines, which makes retention of a core herd more challenging. Information about drought scale, severity, and forecasts improves decisions on how to balance short-term gains and losses against risk of damage to future productivity.

Communication among livestock owners, grazing association boards, governmental agencies, and other stakeholders will help achieve favorable outcomes during drought years, facilitating a return to profitability and sustainability. Preparation of scientifically informed plans for addressing drought begins before drought conditions appear. Proactive practices increase management options and flexibility, and collaboration and positive relationships are crucial for the planning process before, during, and after drought. Successful practices can inform the next cycle of preparation for drought, a process that needs to become embedded in management of rangelands.

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Managing Effects of Drought in the Midwest and Northeast United States

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BACKGROUND

Severe droughts are relatively rare in the Midwest and Northeast compared to other parts of the United States. This 20-State region, hereafter referred to as the Northern Region, is defined as the States bounded by Maine, Minnesota, Missouri, and Maryland. Although the Northern Region has a cool, wet climate and is generally considered to have an abundance of water, model projections suggest that droughts may become more frequent and severe in the future. The Northern Region is densely populated (39 percent of the U.S. population) (U.S. Census Bureau 2018), so changes in precipitation may be especially disruptive. Impacts will affect forest ecosystems and the services they provide, including timber and nontimber products, water regulation and supply, erosion and pollution control, biodiversity protection, and recreation.

Nearly 43 percent of the Northern Region is forested (Oswalt et al. 2014), so management of this key resource is central to maintaining the economy and quality of life. Unlike much of the Western United States, the majority (74 percent) of forest land in the Northern Region is privately owned, mostly as smaller family forest holdings (Oswalt et al. 2014). This model of ownership is challenging from a management perspective because of difficulties facilitating change at the landscape scale when so many individuals are involved. Unlike government agencies that can alter land management practices more directly, making changes in management of privately owned land is largely accomplished through education and using incentives to achieve desired outcomes (e.g., cost-share payments for implementing specific management practices).

Most forests in the Northern Region are not currently managed with drought in mind. Because drought has historically had less of an impact on forest health compared to other regions, drought management tools and techniques are not well established. The increased probability of future drought in the Northern Region has created a need for information about both the impacts of drought on forests and the options for land managers to cope with acute and chronic reductions in water availability.

Forests in the Northern Region are typically energy-limited rather than water-limited, and widespread drought-induced diebacks are rare. However, drought has caused widespread tree mortality in some ecosystems in this region, especially in the lower Midwest (e.g., oak forests in the Ozark Mountains of Missouri; Jenkins and Pallardy 1995). When drought triggers mortality, the affected trees have usually been predisposed to drought by other stressors. Some of these stressors are associated with the dense human population, such as air pollution and the prevalence of pests, pathogens, and invasive species (Haavik et al. 2015, Jenkins and Pallardy 1995, Pedersen 1998).

Despite these issues, the Northern Region has a diversity of tree species, which may help enhance resistance and resilience to drought (Peters et al. 2015). This high biodiversity also increases management options by providing a broader selection of drought-tolerant tree species. However, how the region's trees may fare in the future is difficult to predict for several reasons: the unprecedented projected changes in climate, interactions with multiple simultaneously changing drivers (e.g., atmospheric CO_2, ozone, nitrogen deposition), and the relative dearth of research on drought impacts on forests in the Northern Region. Given these complexities and uncertainty in future climate, drought poses a challenge to land managers in the Northern Region and warrants consideration in management decisions.

DROUGHT DEFINITIONS AND TRENDS

Drought can be defined from many different perspectives, and each approach will lead to a different understanding of how drought is expressed on the landscape across both temporal and spatial scales. In this report, we consider three types of drought that are especially relevant to forest managers—meteorological, hydrological, and ecological drought—and describe past and projected future drought trends.

Meteorological Drought

Meteorological drought is often defined solely by precipitation, based on the degree of dryness and duration of the dry period (Wilhite and Glantz 1985). The thresholds for the duration and severity of meteorological drought are site-specific and are identified by evaluating deviations from normal (i.e., average historical) climatic conditions. An extreme drought or wet spell can be quantified statistically as the tails of the historical rainfall distribution (Smith 2011). Although this approach is limited by the availability of reliable data, analysis of tree rings (which can serve as historical proxies spanning centuries) and modeling (for projecting future climate trends) can greatly expand the capacity to assess longer term drought trends. Several indices (e.g., Palmer Drought Severity Index [PDSI] and Standardized Precipitation Evapotranspiration Index [SPEI]) have been developed to identify periods of meteorological drought and are valuable for monitoring long-term trends (e.g., Donat et al. 2013, Palmer 1965). However, these indices often require variables, such as soil moisture, that are rarely available for long periods across broad regions.

Within the Northern Region, tree-ring records indicate that severe meteorological droughts occurred before the 20th century (Cook and Jacoby 1977, Pederson et al. 2013, Stahle et al. 2007). There is evidence of a megadrought in the 1500s (Stahle et al. 2000) and then a series of repeated severe droughts during the middle of the 1600s (McEwan et al. 2011, Pederson et al. 2014). Over the 20th century, the frequency and magnitude of droughts have declined. Conditions in the early 21st century have been wetter (Pederson et al. 2015), and although droughts still occur (e.g., Sweet et al. 2017), they have not been as severe as the megadroughts of the past.

Average annual precipitation across States in the region ranges from 178 to 330 inches (NCDC 2017). Although some areas of the United States, such as parts of the Southeast and Northwest, receive more annual precipitation, the Northern Region is becoming wetter at a faster rate than any other region. Between the periods of 1901–1960 and 1986–2015, precipitation increased by more than 15 percent in the Northern Region (Easterling et al. 2017). Additionally, the Ohio River and Hudson River valleys have had more days with rain during the summer in the most recent 20 years than during the previous 40 years (Bishop and Pederson 2015).

These past trends in precipitation are consistent with future projections from general circulation models (GCMs) that show increases in precipitation through the end of the 21st century (Fan et al. 2015; Hayhoe et al. 2007, 2010). In contrast with the historical record, however, much of the future increase is expected to occur during winter, with either little change or slight declines in summer precipitation (depending on the model and greenhouse gas emissions scenario used). If recent trends continue, summer precipitation events are expected to come increasingly as short bursts of heavy, intense rainfall, with longer intervening dry periods (Easterling et al. 2017). Therefore, even though the Northern Region is getting more precipitation on average, there is heightened concern about future drought effects on forests because of both projected variability and extremes in precipitation and warming due to warming temperatures.

Future drought trends for the Northeast and Midwest areas of the Northern Region were also evaluated by modeling PDSI through the end of the century. A common issue with characterizing trends using drought and aridity indices (such as PDSI) is that they produce location-based, time series datasets that cannot be easily compared at broader spatial scales or among time periods. To remedy this, PDSI time series datasets were aggregated into weighted values, such that the frequency of drought events is weighted by their intensity. Using this approach, a single cumulative value can represent the relative potential for drought of a location, (see chapter 2 for details of the Cumulative Drought Severity Index [CDSI] calculations). Cumulative Drought Severity Index values were compared for two models each under two future greenhouse gas emissions scenarios—representative concentration pathway (RCP) scenarios 4.5 and 8.5 (Moss et al. 2008)—and for three 30-year periods: 2010–2039, 2040–2069, and 2070–2099. The 30-year period of 1980–2009 was used as a baseline. These four models, developed for the 2020 Resources Planning Act Assessment (Joyce et al. 2018), represent scenarios of warm-wet, hot-wet, hot-slightly dry, and hot-dry.

Results from this analysis show a projected rise in drought conditions for the second half of the 21st century, during which percentages of the Northeast and Midwest under some form of drought more than double spatially and/or temporally compared to the baseline period of 1980–2009 (fig. 8.1). None of the scenarios show great changes in drought or moist conditions through 2040, but change markedly after that. The hot-slightly dry and especially the hot-dry scenarios show the largest increases in extreme and severe drought in both regions by end of century, though the wetter scenarios also show increasing drought (fig. 8.1).

Most of the scenarios also show a reduction of moist classes, especially after mid-century (fig. 8.1). This trend appears to be more prominent in the Midwest as compared to the Northeast. These patterns generally agree with observed recent regional increases in precipitation and flooding, with moisture stress further exacerbated in some places because of higher temperatures and longer periods between significant precipitation events.

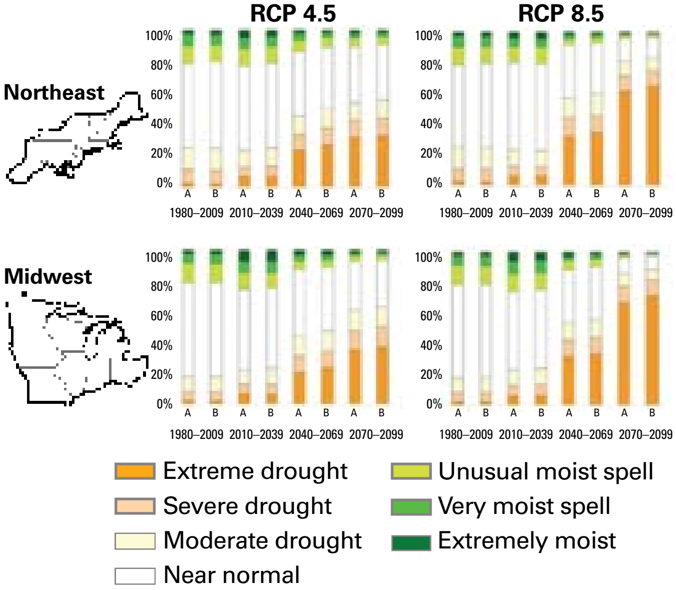


Figure 8.1—Palmer Drought Severity Index (PDSI) for the Northeast and Midwest regions under two greenhouse gas emissions scenarios, representative concentration pathways (RCP) 4.5 and 8.5. Palmer Drought Severity Index was calculated (A) with and (B) without a snowmelt function applied. Following Wells et al. (2004), drought classifications are as follows: extreme drought (PDSI ≤-4.00), severe drought (PDSI -3.9 to -3.0), moderate drought (PDSI -2.9 to -2.0), near normal (PDSI -1.9 to 1.9), unusual moist spell (PDSI 2.0 to 2.9), very moist spell (PDSI 3.0 to 3.9), and extremely moist (PDSI ≥4.0). Bars represent each PDSI class as a percentage of months out of each 30-year time period. See chapter 2 for more detail.

Hydrological Drought

Hydrological drought occurs when periods of low precipitation cause a reduction in surface and subsurface water supplies (i.e., streams, rivers, lakes, reservoirs, soil moisture, groundwater) (Van Loon 2015). This definition differs from meteorological drought in that hydrological droughts are influenced not only by a lack of rainfall, but also by other processes that affect water supply, such as evaporation, transpiration, storage, and runoff. Although hydrological records are not as old as some other indicators of drought, such as tree rings, they are the most useful for identifying water deficits.

Modeling is the only practical way to assess the effect of climate change on future trends in hydrological drought. However, two challenges are the uncertainty in the models and the climate scenarios used. Plant transpiration strongly regulates streamflow in the Northern Region, so a lack of understanding about how vegetation may change under future climate conditions complicates the ability to determine how changes in climate affect hydrology.

Analyses of hydrological data from the recent past have shown no obvious evidence of an increase in drought frequency within the Northern Region. In fact, because of increasing trends in precipitation in the Northern Region, stream and river flows have also generally increased (Burns et al. 2007, Campbell et al. 2011, Collins 2009). Other hydrological evidence of increasingly wetter conditions includes greater average annual soil moisture (Groffman et al. 2012) and higher groundwater levels (Dudley and Hodgkins 2013). Collectively, these records suggest that hydrological drought is becoming less common in the Northern Region.

Perhaps more important than changes in annual hydrological values are the seasonal shifts in the water balance that have occurred and their net effect on water supply. In the more northerly areas of the region, warming has caused a decline in the amount and duration of snowpack (Burakowski et al. 2008, Campbell et al. 2010, Hodgkins and Dudley 2006), resulting in a more muted spring snowmelt peak and higher winter flows (Campbell et al. 2011, Hodgkins et al. 2003, Novotny and Stefan 2007). A decline in snowmelt runoff could reduce groundwater recharge, which, when combined with a longer growing season and greater transpiration, could increase the risk of late-summer drought. However, historical evidence of this trend is lacking. Further, baseflows have generally increased during the growing season, at least in some portions of the Northern Region (Campbell et al. 2011, Novotny and Stefan 2007) because of higher precipitation in the spring, summer, and fall (Hayhoe et al. 2007). Whether this pattern will continue in the future is unclear. Results from models typically indicate increases in hydrological drought frequency (Hayhoe et al. 2007) and a greater tendency for drought stress in late summer through the end of the 21st century (Campbell et al. 2009).

The efficiency of tree water use depends on factors such as forest composition, amount of biomass, tree health, and the influence of changing atmospheric CO_2. Uncertainty about these factors makes future changes in hydrology difficult to predict. As a result, hydrological models have shown a broad range of responses to changing climate, with some showing increases in annual water yield and others showing decreases (Blake et al. 2000, Hayhoe et al. 2007, Ollinger et al. 2008, Pourmokhtarian et al. 2017). Future changes in climate, especially precipitation, will undoubtedly influence the hydrological drought regime, but the direction and extent of change remain highly uncertain.

Ecological Drought

Ecological drought is a relatively new term that more fully addresses the ecological impacts of drought, without the more constrained, human-centric emphasis of other definitions of drought (e.g., socioeconomic, agricultural, hydrological). Crausbay et al. (2017) defined ecological drought as an "episodic deficit in water availability that drives ecosystems beyond thresholds of vulnerability, impacts ecosystem services, and triggers feedbacks in natural and/or human systems." Thus, the definition of ecological drought integrates the ecological, climatic, hydrological, socioeconomic, and cultural dimensions of drought. Ecological drought emphasizes the underlying mechanisms that control individual or ecosystem responses to drought, and it is not directly tied to actual historical or projected future trends in precipitation. This definition also accounts for site-specific edaphic, topographic, and climatic characteristics that affect responses to drought, such as physical factors of a site that influence soil moisture available to vegetation (Gerten et al. 2008, Zeppel et al. 2014).

Although the Northern Region has experienced droughts in the past, they have usually not been severe enough to elicit a widespread threshold response with lasting broad-scale ecological impacts, such as a shift from forest to grassland. The impacts of past droughts have typically been subtler, but they nevertheless have had important ecological consequences. These include reductions in forest production, increased fire frequency and severity, outbreaks of pests and pathogens, spread of invasive species, and changes in the cycling of water and nutrients. Perhaps some of the most notable ecological droughts in the Northern Region are those that have caused tree dieback and mortality. The following sections highlight past observations and current understanding of potential future impacts of ecological drought on forests in the Northern Region.

FOREST DROUGHT IMPACTS

Vulnerability and Resilience

It is difficult to anticipate the full range of impacts of increasing future drought on forests within the Northern Region. Based on recent reviews and modeling experiments, possible responses include high vulnerability (e.g., Charney et al. 2016, Janowiak et al. 2018, Liénard et al. 2016, Martín-Benito and Pederson 2015, Rogers et al. 2017, Swanston et al. 2017), substantial resilience (e.g., Duveneck and Scheller 2016, Duveneck et al. 2017), or a mix of these two extremes (e.g., Brandt et al. 2014, Clark et al. 2016).

Evidence indicates that past droughts have caused tree mortality across the Eastern United States, including parts of the Northern Region (Millers et al. 1989). New research has shown that multiannual drought (defined as more than one standard deviation less than the long-term mean of summer precipitation) preceded observed tree mortality. This relationship holds regardless of where the observations occurred or when they occurred within the last 100 years (i.e., early 20th century compared to later 20th century) (Druckenbrod et al. 2019).

In the Southeastern United States, severe droughts in the 1980s and 2000s caused tree mortality (e.g., Berdanier and Clark 2016, Clinton et al. 1993, Jenkins and Pallardy 1995, Spetich 2004, Stringer et al. 1989), providing further insight about the effect of increased drought frequency or severity on forests in the Northern Region. However, latitudinal analyses of climatic sensitivity during the 20th century indicate that trees in more southern locations are more vulnerable to maximum temperatures than are trees farther north (Martín-Benito and Pederson 2015, Williams et al. 2010), suggesting that the impact of warming on the climatic balance in the Northern Region may be less than what has been observed elsewhere.

Several factors may help to mitigate consequences of drought to Northern Region forests. For example, northern temperate forests are characterized by high species diversity or structural complexity, which could help to offset impacts of extreme climate events, given the overall positive effects of diversity and heterogeneity on stability and resilience (e.g., Hautier et al. 2015, Isbell et al. 2015, Martín-Benito et al. 2008, Morin et al. 2014, Ratcliffe et al. 2017, Tilman 1999). Moreover, trees from different canopy layers have different sensitivities to climate (Canham and Murphy 2016, Orwig and Abrams 1997). For example, in a South American temperate broadleaf forest, severe drought-induced mortality in the canopy trees allowed understory trees, which were less vulnerable to moisture stress, to grow into the canopy (Rodríguez-Catón et al. 2015). Therefore, ecosystems may have the capacity to rapidly recover new vegetation following widespread mortality, albeit potentially with different species composition.

Long-lived trees growing in northern forests could also improve drought resilience. Old trees typically maintain large reserves of carbohydrates in their tissues that may be accessed during stressful periods to maintain critical growth and metabolic functions (Hoch et al. 2003, Richardson et al. 2013), providing an inherent safeguard against extreme events such as droughts. At the ecosystem scale, high biodiversity may provide a buffer to drought through shifts in species composition from drought-intolerant species to more drought-tolerant species, while maintaining critical ecosystem functions such as carbon cycling and hydrological regulation. Another consideration is that the projected trend of increasing drought in the future may overestimate the influence of warming in a mesic region if potential changes in future water-use efficiency result in wetter than anticipated soils (Mankin et al. 2017). Thus, such long-term increases in changes in species composition or efficiency of water use may help to offset future drought impacts. However, a recent analysis of yellow-poplar (*Liriodendron tulipifera*) and northern red oak (*Quercus rubra*) in southern New York indicated that soil moisture was still the dominant limiting growth factor, despite increased atmospheric CO_2 and a potential associated increase in water-use efficiency (Levesque et al. 2017). With longer and more severe drought events predicted for the future, once certain thresholds in warming or drying are reached, the inherent resistance of long-lived trees and the potential for physiological adjustments to changing environmental conditions may be exceeded.

Shifts in Species Composition and Diversity

Species compositional changes in the Northern Region over the past century have been dominated by "mesophication," defined as the gradual replacement of shade-intolerant, fire-adapted species (e.g., pines [*Pinus* spp.], oaks [*Quercus* spp.], hickories [*Carya* spp.]) with shade-tolerant, fire-sensitive species (e.g., maples [*Acer* spp.], birches [*Betula* spp.], beeches [*Fagus* spp.]) (Nowacki and Abrams 2008). This trend of mesophication is likely a response to two variables: wetter growing conditions (Pederson et al. 2015) and the closing up of overstory canopies following abandonment of widespread agriculture and grazing (Nowacki and Abrams 2015). Over long time scales, an increasing prevalence of drought could lead to shifts in species composition and diversity as more vulnerable species decline and more drought-resistant species increase in abundance.

Mesophytic species have been hypothesized to be especially vulnerable to future severe droughts (Abrams and Nowacki 2016). This hypothesis is consistent with the broad classification of drought tolerance based on each species' distributional range, optimal site conditions, physiological responses, and traits (Matthews et al. 2011, Niinemets and Valladares 2006, Peters et al. 2015). However, there are inconsistencies among studies in how different species are classified (Klein 2014, Loewenstein and Pallardy 1998, Martínez-Vilalta et al. 2014, Roman et al. 2015). Further, predictions based on drought-tolerance classification and actual field observations of drought impacts do not always agree (Gu et al. 2015, Hoffmann et al. 2011, Pedersen 1998, Roy et al. 2004, Voelker et al. 2008). More targeted research is needed to improve understanding of how species respond to drought and the long-term implications for forest community dynamics.

One approach to assess the effect of drought on forest composition is to use models to predict species responses to potential changes in suitable habitat (https://www.fs.fed.us/nrs/atlas; Iverson et al. 2008a, 2008b, 2011, 2019). Results from these modeling studies generally show that, under most scenarios of climate change, boreal species (e.g., black spruce [*Picea mariana*], red spruce [*P. rubens*], and balsam fir [*Abies balsamea*]) are projected to lose suitable habitat, but more southern species (e.g., American basswood [*Tilia americana*], black cherry [*Prunus serotina*], and northern red oak) are expected to gain suitable habitat. We used this modeling approach to assess the capability of tree species to cope with a changing climate, especially drought, at eight national forests across the Northern Region (table 8.1). Four variables were considered to develop a capability class: (1) projected change in suitable habitat by 2100, according to models using the RCP 8.5 scenario of emissions (Iverson et al. 2019); (2) adaptability of the species to a changing climate according to a literature review (Matthews et al. 2011); (3) reliability of the model as determined by a statistical analysis (Iverson et al. 2008b); and (4) current abundance of the species based on Forest Service, Forest Inventory and Analysis (FIA) data. We assumed that a species' capability to cope with a changing climate was decreased when the species showed a loss of suitable habitat following warming according to RCP 8.5, especially when it was an uncommon to rare species that was not particularly adapted to drought conditions. Each species was classified by its capacity to cope with changing conditions using the following scale: very good, good, fair, poor, very poor, lost, or new habitat. For example, if a species was modeled to gain substantial habitat according to the RCP 8.5 scenario of emissions, had some characteristics (e.g., resistance to drought or pests)

Table 8.1—Number of tree species (sorted west to east) by capability class (i.e., their ability to cope with a changing climate and drought) for nine national forests in the Northern Region, and current, potential (new habitat), and total number of species modeled in each national forest.

			CAPABILITY CLASS					NUMBER OF MODELED SPECIES		
National Forest	**Latitude**	**Longitude**	**Very good**	**Good**	**Fair**	**Poor**	**Very poor**	**Lost**	**New habitat**	**Total**
Hoosier	38	86	8	9	16	15	10	4	14	76
Wayne	39	82	4	7	18	20	10	5	8	72
Allegheny	41	79	5	8	7	16	5	7	17	65
Finger Lakes	42	76	4	9	8	23	5	9	13	71
Green Mountain	43	72	4	7	6	13	9	2	17	58
White Mountain	44	71	3	7	7	9	7	3	28	64
Chequamegon	46	91	2	6	15	7	4	1	19	54
Chippewa	47	94	2	8	9	10	1	1	15	46

that provided adaptability, had a reliable statistical model, and was currently abundant in the national forest in question, it was rated as 'very good' in capability to cope with the projected changes in climate.

Results indicated that current species abundance and drought tolerance predicted greater potential of a given species to remain. Species projected to experience a severe loss in habitat are those less able to cope with the changing climate. Northernmost forests (latitude >42 N) tended to have both less species diversity and fewer species with ratings of either very good or good drought-coping capability (table 8.1). The northeastern forests (Green Mountain and White Mountain National Forests) were, however, predicted to provide suitable habitat for more species that could increase diversity as species from the south move northward. This pattern of more potential migrations was not so true for the northwestern forests (Chippewa, Chequamegon, and Nicolet National Forests), however, as the tree diversity south of these forests is less due to its historic prairie state, lower rainfall, and high proportion of agriculture. Despite these predicted shifts in suitable habitat, however, other modeling studies (Iverson et al. 2004) and empirical evidence (Zhu et al. 2012) largely suggest that migration rates of tree species are far too slow to track such rapid changes in a suitable climate niche. The largest differences among forests for capacity to cope was from east to west. For the Hoosier, Wayne, Chequamegon, Nicolet, and Chippewa National Forests (longitude >80 W), an average of 58 percent of the current species rated fair or better, but for the Allegheny, Finger Lakes, Green Mountain, and White Mountain National Forests, only 40 percent of the current species had a rating of fair or better. These results support the hypothesis that species composition could change under the changing climate and that the Northeast may undergo the largest changes because of more potential migrations and fewer species with at least a fair capability to cope with climate change.

Insects, Pathogens, and Invasive Species

The most important drivers of forest disturbance in the Northern Region are wind, ice, insects, pathogens, invasive species, and to a lesser degree, fire (Dukes et al. 2009). Among the least well-understood aspects of forest responses to climate change, including drought, is how insect pests, pathogens, and invasive species will respond. Disturbances caused by these agents will continue and are likely to increase with global climate change, exacerbated by the gradual accrual of novel species introduced into forests (Aukema et al. 2010, Liebhold et al. 1995). Threats to forest resilience and sustainability include higher air temperatures, more variable and extreme weather events, biological invasion, shifting ranges, and local climatic mismatching (e.g., of remnant populations and/or species that are slower to migrate). Set against this backdrop, insects, pathogens, and invasive species rank among the top threats (Dukes et al. 2009, Lovett et al. 2006).

For both insects and pathogens, consequences of environmental change are likely to be complex. Changes in air temperature, as well in as the duration and severity of drought, can act either directly or indirectly on populations. Direct effects on insects and pathogen growth rates, fecundity, and survival are simple enough to document and examine experimentally, although extrapolating from lab or semi-field conditions can be challenging (Koricheva et al. 1998b). Indirect effects are much more difficult to predict and are likely to affect many systems (Kolb et al. 2016). For example, multiple changes are hypothesized in response to water stress (e.g., host plant nutritional quality, constitutive or induced defenses, and physiological responses to herbivory or pathogen attack), and these changes are likely to be nonlinear and context-dependent (Kolb et al. 2016, Mattson and Haack 1987). The rare empirical studies tend to show variable results that appear to be specific to the feeding guild or tissue preference of the insect or pathogen.

Other likely strong influences on phytophagous insect and pathogen populations are changes in the abundance, distribution, and seasonality within natural enemy and competitor populations (Weed et al. 2013) and, in some cases, alternative hosts (e.g., for rust fungi; Kinloch 2003). Insect and pathogen population responses to intermittent water stress differ from responses to long-term water stress and are influenced by the timing and duration of dry periods (Kolb et al. 2016). Despite these multifactorial challenges, research is improving understanding, and some general patterns are beginning to emerge (Jactel et al. 2012, Koricheva et al. 1998a).

One explanation for the lack of a clear relationship between drought and insect or pathogen abundance is that droughts are relatively rare, as is true for many other types of drought impacts in the Northern Region. However, some evidence suggests that interannual variation in precipitation is correlated with either the abundance of insects or pathogens or the severity of the damage they cause (e.g., Dukes et al. 2009). One example comes from a large-scale assessment of the role of climate in driving the dynamics of beech bark disease. For both causal agents of the disease (the scale insect, *Cryptococcus fagisuga*, and *Neonectria* fungi), a spatially replicated time series showed that both spring and fall precipitation were important predictors of three key population parameters: the strength of density dependence, predicted equilibrium abundance, and the contribution of exogenous (climatic) variation (Garnas et al. 2011).

As a second example, in areas that experience periodic water stress such as the forests adjacent to the Great Plains, wood-boring insects appear to increase under drought conditions (Haavik et al. 2015). Despite the relative lack of empirical evidence, these two examples suggest that drought has the capacity to influence pest and pathogen population dynamics in eastern forests. Other evidence for the effect of insects on forests comes from a recent meta-analysis of insect responses to plant stress, including drought (Chakraborty et al. 2014). The results suggest that, generally, cambium feeders may benefit the most from plant stress, followed by sucking, mining, and then chewing insects, with galling insects having the lowest relative survivorship. Drought may therefore favor insect pests such as the emerald ash borer (*Agrilus planipennis*, a phloem/cambial feeder) and hemlock woolly adelgid (*Adelges tsugae*, a sucking insect), while the black oak gall wasp, along with myriad species of defoliators, might be expected to decline. For the emerald ash borer, some empirical evidence suggests increased success during drought, at least under controlled conditions. Further, even where insects respond only minimally to drought (e.g., defoliators such as the gypsy moth [*Lymantria dispar*] or spruce budworm [*Choristoneura* spp.]), the effects of repeated defoliation on tree growth and survival are likely to be higher under water stress (Davidson et al. 1999). Trees with repeated and/or severe defoliation are less able to respond physiologically to drought and to recover during periods of high water availability (Jacquet et al. 2014), representing an alternative pathway by which drought and insects may impact forests.

The gypsy moth is one insect that has shown clear, though primarily indirect, positive responses to drought. Introduced near Boston, MA, in the late 1860s, the gypsy moth has become one of the most damaging tree defoliators in the United States. Although temporal patterns of gypsy moth outbreaks have not shown obvious correlations with periods of reduced precipitation or water stress, limited evidence suggests that increased drought frequency or severity could affect their population dynamics. For example, the introduced biocontrol fungus, *Entomophaga maimaiga*, suppresses caterpillar populations in most years. However, it strongly depends on high humidity, especially in spring (Hajek and Webb 1999). Therefore, drought could substantially limit suppression by this important top-down control on gypsy moth populations. In 2015–2016, drought was correlated with gypsy moth outbreaks in a number of Eastern States, and this relationship was largely attributed to drought-related reduction in *Entomophaga maimaiga* infection during this period (Reilly et al. 2014).

As with insects, few empirical examples suggest that drought is currently a driver of disease dynamics in forests in the Northern Region. In general, however, obligate biotrophs (microbes that feed primarily on living plant tissue) often need periods of high humidity and/or soil or leaf surface moisture for infection to occur. Thus, these pathogens might be expected to decline in response to drought, while those that respond to tree stress (i.e., early colonizing saprophytes, often living endophytically within tree tissues) are more likely to increase (e.g., Desprez-Loustau et al. 2006, Kolb et al. 2016). Similar to effects of defoliation, biotrophs that successfully invade trees may cause higher rates of mortality because they deplete the energetic and/or nutrient reserves of their hosts under stress conditions.

The response of invasive plants to drought is also likely to be idiosyncratic and complex. Invasive plants tend to be fast-growing and vigorous which often correlates with high water requirements (even with high-efficiency water use). This relationship suggests that invasive plants may suffer during drought. However, invasive plants are also often characterized by high phenotypic plasticity (specifically, the ability to tolerate a wide range of abiotic conditions) and more efficient water use, and they are often strongly associated with disturbance (Cordell et al. 2002, Davidson et al. 2011, Funk 2013, Heberling and Fridley 2013). Thus, if future drought causes widespread tree decline and mortality, invasive plants could respond quickly to elevated nutrient pulses and reduced shade. Invasive plants would also probably benefit if fire becomes increasingly relevant in these systems, at least in certain parts of the range (Flory et al. 2015).

Socioeconomic Impacts of Drought

Drought can influence the character, quality, and species composition of forests as well as the timing of many management practices. These changes could affect local and regional economies that depend on forest products. For example, changes in forest composition in the Central Hardwoods region (southern Missouri, Illinois, Indiana, and Ohio) are projected to destroy wildlife habitat and cause steep declines in the value of timber (Ma et al. 2016).

The consequences of drought can also affect a variety of forest-based cultural traditions, tourism, recreation, and seasonal activities. For example, drought-induced changes in species composition could affect Tribal communities that depend on certain tree species for their culture and livelihoods, such as paper birch (*Betula papyrifera*), northern white cedar (*Thuja occidentalis*), and quaking aspen (*Populus tremuloides*) (Fisichelli et al. 2014; Handler et al. 2014a, 2014b; Janowiak et al. 2014). Droughts can lower water levels in lakes and streams, affecting recreational activities such as boating, swimming, and fishing. During winter, even short-term droughts can have large consequences for winter recreational activities (e.g., snowmobiling, skiing), which are often critical to the economy of rural communities in the Northern Region. Droughts can alter the timing and duration of autumn leaf color (Xie et al. 2015) as well as wildlife tourism (e.g., hunting, fishing, birding) affected by shifting habitats and altered migratory patterns (Rodenhouse et al. 2008, Thomas et al. 2013).

Maple syrup production, another economically and culturally important forest-based activity in the Northern Region, will likely be affected by increasingly frequent drought in the future. Historical trends in sugar maple (*Acer saccharum*) decline may be related to drought, frequently in association with other, often interacting stressors such as insects, pathogens, and nutrient deficiencies (Bishop et al. 2015, Pitel and Yanai 2014). Changes in snowpack depth can alter the timing and length of the growing season and the occurrence of soil freeze-thaw dynamics in early spring. These variables in turn affect sugar maple health (Brown et al. 2015, Hufkens et al. 2012), the technical and operational activities related to sugar maple management, and the quantity and quality of syrup produced (Duchesne and Houle 2014, Matthews and Iverson 2017, Skinner et al. 2010).

Forest management decisions should also take into consideration the logistical and technical challenges of drought. From one perspective, drought may offer some advantages to logging operations. Winter drought may be helpful to loggers because a shallower snowpack may improve access to tree boles. If air temperatures are sufficiently cold, winter drought would also promote the development of soil frost, which reduces erosion and compaction from logging operations. A shallower snowpack may also shorten the duration of the mud season that follows spring snowmelt, when logging operations are typically curtailed.

Future projections, however, suggest more precipitation in winter, with more rain than snow, and an intermittent snowpack. These conditions could lead to longer periods of high soil water content that are unfavorable for logging, causing compaction and affecting the stability of forest roads. Further, although frozen soil may be beneficial for logging access, it has negative ecological effects, resulting in root mortality (e.g., Tierney et al. 2001), nutrient leaching (e.g., Fitzhugh et al. 2001), and decreased plant productivity (e.g., Kreyling et al. 2012). In the past 70 years in the upper Midwest, with warming winters, the duration of snowpack or frozen ground conditions suitable for winter harvest has been shortened by 2 to 3 weeks (Rittenhouse and Rissman 2015). This trend has had economic impacts on the forest industry, where forest operations are limited by lack of snow cover or frozen ground conditions necessary to access sites and operate harvesting equipment. With less winter snow cover and frozen ground conditions, seasonal restrictions on forest operations have increased (Evans et al. 2016), resulting in economic consequences to both forest industry and woodland landowners through reduced timber values (Conrad et al. 2017).

Many socioeconomic factors will dictate the degree and extent to which management is able to influence the vulnerability of forests across the Eastern United States to future drought events. Forest ownership patterns across this region are complex, with family forest owners owning the vast majority of forested areas. Large public and private ownerships are also important, particularly in the Lake States, northern Maine, and the Adirondack region of New York. Given the wide variety of landowner objectives, this ownership pattern complicates how forest management aimed at increasing drought adaptation will occur. Similarly, many silvicultural treatments for increasing drought adaptation either require investments in management (i.e., planting, tending treatments) or rely on markets for lower grade materials, creating potential economic barriers to widespread implementation. For these reasons, the likelihood is high that the most common management response on privately owned forests, especially small ones, will be to do nothing to prepare for increased future risk of severe drought. The management options outlined in the following section, and summarized in table 8.2, are in part to encourage forest managers to consider more active approaches to drought preparedness. Table 8.3 gives examples of drought-related management strategies that have been implemented as part of the Northern Institute of Applied Climate Science's Climate Change Response Framework (https://forestadaptation.org/demos).

Table 8.2—Summary of potential management practices to reduce drought impacts and enhance resilience in forest stands in the Northern Region

MANAGEMENT PRACTICE	GUIDELINES	DESIRED OUTCOMES
Thinning	• Regional stocking guides or density management diagrams provide optimal density targets. • Avoid excessively heavy thinning: trees with very large crowns and high leaf area-to-sapwood area ratios may be more vulnerable to drought.	• Optimal stand densities support healthy trees and sufficient water availability during dry periods. • Thinned forests are often more drought-resilient than unthinned forests.
Natural or artificial regeneration	• Facilitate natural regeneration of adapted local genotypes or species via seedbed treatment and/or microclimate amelioration. • Plant seedlings of genotypes or species better adapted to moisture stress. • Use assisted migration to introduce new species from habitats representing future conditions.	• Silvicultural practices with natural or artificial regeneration help to shift composition towards more drought-adapted species or genotypes, establishing more resilient forests.
Carbon sequestration	• Enroll forests in carbon offset programs to provide an economic benefit while contributing to climate change mitigation.	• Forests in the region provide long-term, significant increases in carbon sequestration.

CASE STUDY 8.1

Providence Water: Adapting forests to drought

Providence Water, in Rhode Island, is managing forests to be better adapted to future drought conditions. In keeping with goals to maintain and protect water yield and water quality, the public water utility is managing for a diversity of species, selecting those that may best tolerate extended drought conditions, and actively planting tree species from southerly seed zones on selected experimental sites within the project area.

The Scituate Reservoir and five smaller tributary reservoirs are the primary drinking water sources to approximately 600,000 people. The reservoirs are surrounded by 5 261 ha of mostly forested public land (formerly agricultural lands) that serves as "green infrastructure" filtering surface runoff, acting as the first step ("first barrier" in water resources engineering parlance) in the water treatment process.

The woodlands surrounding the reservoir are currently experiencing hardwood regeneration failure due to pests and pathogens (e.g., red pine scale, red pine adelgid, gypsy moth, orange-striped oakworm, chestnut blight) along with intense herbivory pressures. Anticipated future shifts in climate may interact to increase severe weather events and drought risks, further challenging regeneration of local species. Warming and altered precipitation patterns may result in less winter snow and persistence of drier conditions later into the growing season. Prolonged warm, dry, and drought conditions may harm forest species unable to tolerate hotter and drier conditions. A changing climate is likely to intensify forest stressors, including insect pests, forest diseases, invasive plant species, and deer herbivory.

Shown in autumn 2014, this site on Providence, Rhode Island, Scituate Reservoir watershed property shows the effects of multiple forest health stressors, including dry conditions, deer herbivory, and insect pests. (Photo courtesy of Christopher Riely)

Providence Water is experimenting with actions that promote ecosystem transition to a diverse forest that could be better adapted to future conditions. Using the U.S. Department of Agriculture, Forest Service publication, "*Forest Adaptation Resources: Climate Change Tools and Approaches for Land Managers*," (Swanston et al. 2016; https://www.nrs.fs.fed.us/pubs/52760), Providence Water designed the following specific management actions to prepare forests for a changing climate:

- In oak forests with regeneration failure, guide changes in species composition by planting tree species expected to be better adapted to future conditions (e.g., black oak, black locust, white oak, pin oak, persimmon, sweetgum, eastern red cedar, sassafras, and loblolly, pitch, and shortleaf pines), and tend/treat tree seedlings as needed.
- Plant tree seedlings better adapted to expected future conditions in areas where Providence Water could manage herbivory and protect these seedlings, including an oak forest within an existing deer exclosure fence (constructed prior to the adaptation project).
- In upland oak stands, harvest declining and poor-quality trees, and conduct enrichment planting with future-adapted tree seedlings (e.g., black locust, black oak, chestnut oak, persimmon, shortleaf pine, sweetgum, Virginia pine, white oak).

Providence Water will monitor success of these tactics, going beyond the forest inventory data they were already collecting to assess deer browse impacts and the growth and survival of the planted future-adapted seedlings. Two sites on Providence Water land have been planted with future-adapted species, and plans for more planting are under consideration (see https://www.forestadaptation.org/providence).

Table 8.3—Management strategies for drought in the Northern Region[a]

DROUGHT MANAGEMENT THEME	MANAGEMENT GOAL	MANAGEMENT TACTIC	CASE STUDIES
Soil moisture	• Reduce competition for moisture, nutrients, and light. • Promote diverse age classes.	• Cut shelterwood with reserves to increase structural and species diversity while maintaining aspects of the mature forest. • Focus on removing crowded, damaged, or stressed trees. • Manage aspen in multiple blocks, with the goal of creating several age classes in 5-year increments.	**Massachusetts Dept. of Conservation & Recreation: Bristol Lot Timber Sale** (https://www.forestadaptation.org/bristol) **Gogebic County: Mosinee Grouse Enhanced Management System** (https://www.forestadaptation.org/node/544)
Heat- and drought-tolerant tree species	• Favor native species adapted to future conditions. • Introduce species expected to be adapted to future conditions.	• Harvest declining and poor-quality trees to improve the growth of the residual stand. • Conduct enrichment planting and seeding of tree species expected to be better adapted to future conditions.	**Florence County: Climate-informed Forest Restoration** (https://www.forestadaptation.org/flo-co) (case study 8.2) **Providence Water: Planting Future-Adapted Forests** (https://www.forestadaptation.org/providence) (case study 8.1)
Pest and pathogen pressures	• Maintain or improve the ability of forests to resist pests and pathogens.	• Created a mix of species, age classes, and stand structures to reduce the availability of host species for pests and pathogens (e.g., blight-resistant American chestnut [*Castanea dentata*] that is more resistant to gypsy moth). • Implement forest management practices to reduce the long-term effects of hemlock woolly adelgid and maintain stream shading.	**Massachusetts Dept. of Conservation & Recreation: Bristol Lot Timber Sale** (https://www.forestadaptation.org/bristol) **Trout Unlimited: Adapting the Riparian Areas and Water of the North River** (https://www.forestadaptation.org/tu-ne)
Herbivory	• Manage herbivory to promote regeneration of desired species.	• Plant tree species expected to be better adapted to future conditions within an existing deer exclosure.	**Providence Water: Planting Future-Adapted Forests** (https://www.forestadaptation.org/providence) (case study 8.1)
Invasive species	• Prevent introduction and establishment of invasive plant species; remove existing invasive species.	• Control existing invasive species; map and monitor populations of new invasive species across the property. • Seed logging trails after harvest to reduce erosion and prevent invasive species.	**Leopold Foundation: Leopold-Pine Island Important Bird Area** (https://www.forestadaptation.org/leopold)
Fire	• Restore or maintain fire in fire-adapted ecosystems. • Guide changes in species composition at early stages of stand development.	• Use prescribed fire to sustain a mixed-oak ecosystem and control invasive exotic or undesirable species.	**Massachusetts Dept. of Conservation & Recreation: Bristol Lot Timber Sale** (https://www.forestadaptation.org/bristol) **Leopold Foundation: Leopold-Pine Island Important Bird Area** (https://www.forestadaptation.org/leopold) **Michigan Dept. of Natural Resources: Barry State Game Area** (https://www.forestadaptation.org/Barry)

[a] Management strategies are likely to be case-specific and dependent on site characteristics and the values of the landowner (Northern Institute of Applied Climate Science's Climate Change Response Framework, https://forestadaptation.org/demos).

(*continued*)

Table 8.3 (*continued*)—Management strategies for drought in the Northern Region[a]

DROUGHT MANAGEMENT THEME	MANAGEMENT GOAL	MANAGEMENT TACTIC	CASE STUDIES
Shorter winters, altered harvest timing	• Reduce damage to soils and nutrient cycling. • Realign significantly disrupted ecosystems to meet expected future conditions.	• Reduce site impacts by using tracked equipment. • Protect soils to maintain water storage capacity by minimizing disturbance to sensitive areas (seeps or enriched areas) during harvest. • Prioritize areas most likely to support a summer harvest given ground conditions and potential costs.	**Vermont Land Trust: Increasing Opportunities for Sustainable Timber Harvest on the Atlas Timberlands** (https://www.forestadaptation.org/atlas)
Diversity and density management	• Promote diverse age classes. • Maintain and restore diversity of native species.	• Use variable-density thinning to improve structural and species diversity. • Diversify planting to improve species diversity in gaps and openings.	**Superior National Forest: Mesabi Project** (https://www.forestadaptation.org/mesabi)
Biological legacies	• Retain biological legacies.	• Retain habitat elements of the mature forest (e.g., mast production, vertical structural diversity, large-diameter trees).	**Massachusetts Dept. of Conservation & Recreation: Bristol Lot Timber Sale** (https://www.forestadaptation.org/bristol)
New mixes of native tree species	• Establish or encourage new mixes of native species.	• Use red pine and jack pine (*Pinus banksiana*) as nurse trees for oak plantings; harvest the pines as the oak establishes.	**Michigan Dept. of Natural Resources: Barry State Game Area** (https://www.forestadaptation.org/Barry)
Infrastructure for stream crossings	• Restore hydrology. • Design infrastructure to meet expected conditions.	• Assess and upgrade road-stream crossings to handle lower and higher peak streamflows and enhance aquatic organism passage. • Decommission roads to increase groundwater recharge.	**Chequamegon-Nicolet National Forest: Marengo and Twentymile Creek Watersheds** (https://www.forestadaptation.org/cnnf-water) **Monongahela National Forest: Lambert Restoration Project** (https://forestadaptation.org/LambertDemo) **Trout Unlimited: Adapting the Riparian Areas and Water of the North River** (https://forestadaptation.org/tu-ne)
Wildlife habitat	• Prioritize and maintain sensitive or at-risk species or communities. • Reduce landscape fragmentation. • Manage habitats over a range of sites and conditions.	• Establish a savanna complex of 60 ha in collaboration with adjacent landowners. • Enhance available habitat for migratory waterfowl available in dry fall migrations.	**Michigan Dept. of Natural Resources: Barry State Game Area** (https://www.forestadaptation.org/Barry) **Ducks Unlimited, Inc.: Improving Bottomland Hardwood Forest and Wetland Resiliency** (https://forestadaptation.org/BottomlandHardwoods)

[a] Management strategies are likely to be case-specific and dependent on site characteristics and the values of the landowner (Northern Institute of Applied Climate Science's Climate Change Response Framework, https://forestadaptation.org/demos).

CASE STUDY 8.2

Florence County, WI: Restoring a forest after drought

Florence County foresters manage more than 14 570 ha of forest land in northeast Wisconsin for timber production and a range of public uses such as hunting, fishing, and camping. The county is restoring 160 ha of forest lands that were significantly affected by drought and forest pests, with the goal of becoming better adapted to future drought conditions. Florence County contains large forested areas on sandy, low-fertility sites. The declining precipitation in northern Wisconsin over the past several decades has stressed forests, causing mortality in some areas. The stands selected for this project had experienced close to 90-percent mortality because of a combination of persistent drought and forest pest infestations (e.g., two-lined chestnut borer [*Agrilus bilineatus*]). Into the future, this site may continue to be susceptible to drought and forest health stressors due to sandy soils and a changing climate trending towards warmer temperatures, earlier snowmelt, and longer, drier growing seasons.

Florence County foresters are motivated to keep this area forested, so they worked with partners to use the online Adaptation Workbook (https://www.adaptationworkbook.org) to devise adaptation tactics to improve forest resilience to drought. Florence County foresters chose to salvage the stand, reserving healthy pockets of scrub oak and northern red oak. They conducted a large-scale planting of native species expected to be better adapted to future drought conditions (jack pine, red pine, and white pine in the uplands, and white pine and swamp white oak in lower, wetter areas). They also added wood-based soil amendments (wood ash and biochar) to 40 ha of the project area to improve soil water-holding capacity, nutrient exchange, and microbial communities.

This is the first large-scale field trial of soil amendments in midwestern forests. Monitoring is underway to measure the survival and growth of planted seedlings, as well as soil factors such as water-holding capacity, bulk density, soil pH, and cation exchange in soil amendment areas (Richard et al. 2018).

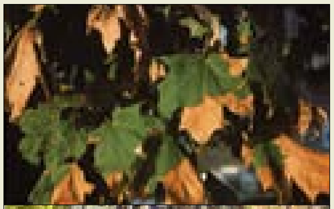
This project is a collaborative partnership with the Sustainable Resources Institute, Forest Service, Michigan Technological University, Wisconsin Department of Natural Resources, Verso Paper Corporation, and the Northern Institute of Applied Climate Science. Project funds were awarded through the Wildlife Conservation Society Climate Adaptation Fund in 2014. The support to establish the Climate Adaptation Fund was provided by the Doris Duke Charitable Foundation.

Florence County maintains dual certification under Sustainable Forestry Initiative (SFI) standard and the Forest Stewardship Council (FSC) standard.

Identifying symptoms of drought

Symptoms of tree drought stress can be difficult to identify because they may vary by species and location and look similar to symptoms of other stressors (e.g., insect pests, pathogens, nutrient deficiencies). Some key indicators are:

- Leaves turn from shiny to dull
- Loss of leaf turgor—wilted or drooping foliage
- Leaf scorch—leaves turn brown, often along the edges
- Chlorosis—paling or yellowing of green leaves
- Early fall color
- Premature leaf or needle drop
- Dieback of twigs or whole branches



Leaf scorch on sugar maple leaves. (Photo by Robert L. Anderson, USDA Forest Service)

Drought-stressed saplings begin to shed their leaves early in a Michigan forest. (Photo courtesy of USDA Forest Service)

DROUGHT MANAGEMENT OPTIONS AND CONSIDERATIONS

Thinning Treatments

The use of thinning has long been advocated as a strategy to maintain the growth and vigor of residual trees by reducing levels of resource competition in forest stands (Smith et al. 1997). Thinning is a proposed strategy to mitigate potential drought impacts in that it reduces moisture stress, thus minimizing growth declines and mortality (Aussenac and Granier 1988, Grant et al. 2013, Kohler et al. 2010, McDowell et al. 2006). Early experience with this strategy in U.S. forests was primarily in semi-arid regions (McDowell et al. 2006). However, recent studies from temperate forests in the Lake States and New England have demonstrated the benefit of density management to minimize growth declines during droughts and enhance postdrought recovery (Bottero et al. 2017, D'Amato et al. 2013, Gleason et al. 2017, Magruder et al. 2013). The ability to use thinning to minimize drought impacts in the Northern Region will hinge on the availability of markets for the low-grade materials that are often a large proportion of the volumes removed by these treatments. Thinning can also have unintended consequences, such as stimulating understory growth that may reduce soil water available for residual trees (Nilsen et al. 2001).

The effectiveness of thinning to mitigate drought impacts varies across regional aridity gradients of the Northern Region (i.e., from the Lake States [Michigan, Minnesota, Wisconsin]) to the Northeastern States. Overall, the greatest benefit of thinning has been observed in more arid climates. For example, research on effects of stand density on drought responses across pine-dominated forests suggests that thinning was more likely to reduce drought vulnerability on drier sites; however, thinned forest stands in temperate areas were also more resilient to drought than unthinned stands (Bottero et al. 2017). Similarly, drought had a greater effect on growth in thinned forests in the more arid midwestern forests than it did in New England (Gleason et al. 2017). Thinned, lower density stands had less depressed growth during drought in northeastern forests (northern hardwood and Acadian spruce-fir; Gleason et al. 2017). Thus, thinning may be an important management strategy to enhance resilience during drought, even in more humid parts of the Northern Region.

Beyond regional climate effects on thinning, forest developmental stage and structural conditions may also influence the effectiveness of thinning at reducing drought impact. For example, in a study of the long-term influence of density management on the drought resilience of red pine (*Pinus resinosa*) forests in Minnesota, stands thinned to very low densities (31–61 square feet per acre) were less affected by drought at young stand ages but were more vulnerable at older ages, relative to stands thinned to higher residual densities (92–153 square feet per acre; D'Amato et al. 2013) (fig. 8.2). This age-related shift in the benefits of thinning reflects the influence of early heavy thinning on long-term development of tree-level architecture: larger and older trees are often more vulnerable to drought (Skov et al. 2004). The greater drought vulnerability of larger, older trees in low-density stands has been attributed to their larger leaf areas and high leaf area-to-sapwood area ratios, which create water demands that are difficult to meet during drought periods (Kolb et al. 2007, McDowell et al. 2006). Increased allocation of biomass to crown development in response to greater resource availability has recently been linked to drought-related dieback around the globe (Jump et al. 2017).

These findings further underscore the potential vulnerability in the Northern Region, where sustained or severe drought has been largely absent over the last few decades: larger trees that have long experienced little drought stress are more vulnerable to future drought. Based on these and other findings, thinning to more moderate densities may be an effective strategy to reduce moisture stress and encourage the development of sustainable tree-level architecture. An encouraging finding, based on much of the research on thinning and drought, is that ideal densities for minimizing drought impacts correspond to the densities recommended by regional stocking guides and density management diagrams for generating optimal stand-level growth (Clark et al. 2016).

Artificial Regeneration of Adapted Genotypes or Species

One consequence of increased drought frequency and severity is that microclimate conditions may change in ways that limit natural regeneration by affecting processes of seed germination and seedling establishment. Local genotypes may also be maladapted to future climate conditions, limiting the potential for new seedlings to successfully regenerate following natural disturbance or harvesting. Further, the

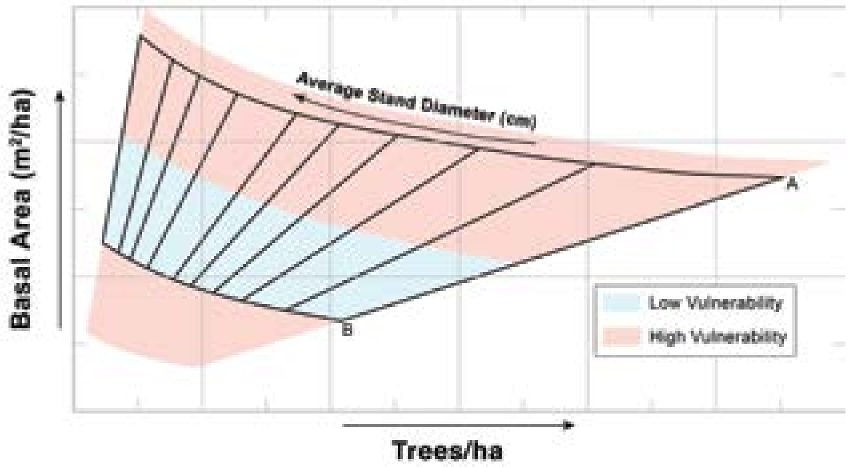


Figure 8.2—Generalized stocking guide showing zones of low and high drought vulnerability based on long-term research in red pine and northern hardwood forest ecosystems (D'Amato et al. 2013, Gleason et al. 2017). Zones of low vulnerability generally correspond to levels of residual stocking traditionally recommended for maintaining high levels of stand-level growth and vigor. Zones of high vulnerability correspond with highly stocked stand conditions in which inter-tree competition for resources causes drought-induced declines in growth, increased mortality, and low stocking conditions that favor tree-level architecture (high leaf area-to-sapwood area ratio) vulnerable to moisture stress.

projected rate of climate change will likely be greater than the migration rates of trees; thus, the potential for better adapted genotypes or tree species to move quickly enough to keep up with their bioclimatic envelope (i.e., future habitats that are suitable for their growth and survival) may also be severely limited (Dobrowski et al. 2013, Loarie et al. 2009). These potential impacts are especially relevant for forest management because sustainability of the production of timber and other forest products directly depends on the capacity of forest managers to successfully promote seedling regeneration and forest growth. Three forest management options for addressing these concerns are microclimate manipulation to facilitate natural regeneration, artificial regeneration of existing species, and assisted migration of non-local species, as well as a combination of these approaches (Grady et al. 2015).

Silvicultural treatments can improve microclimate conditions that favor seed germination, seedling establishment, and growth of desired species that have seed sources already present. For example, when conditions are safe, the seedbed can be improved using prescribed burning (Hutchinson et al. 2012, Iverson et al. 2017), manipulation of harvest residues and mulching (D'Amato et al. 2012), or mechanical scarification (Willis et al. 2015, Zaczek and Lhotka 2004). These treatments can facilitate access by roots to a stable moisture supply and reduce competition. To ameliorate moisture stress and buffer temperature extremes, additional shade can be provided by extending the period during which overstory trees are maintained on the stand (with shelterwood or variable retention harvest systems), especially during drought years and in the early phases of seedling establishment (Kellner and Swihart 2016). Moreover, given that forest stands with high species diversity may be more resilient to climate change, using silvicultural systems that promote high species diversity may enhance the sustainability of forest production under changing climate regimes. Examples include irregular shelterwood systems (Arseneault et al. 2011, Raymond and Bédard 2017) and adapting silvicultural treatments to existing environmental variation and species regeneration dynamics (e.g., Frey et al. 2007).

To promote the establishment of individuals that are more likely to survive and adapt to more frequent future drought, artificial regeneration can be used to seed or plant seedlings of genotypes or species considered better adapted to soil moisture deficit. Combining artificial regeneration with underplanting seedlings beneath existing canopies may provide additional benefits. Often, species expected to have greater success under future climate conditions are also intolerant to moderately intolerant of shade. As such, harvesting of overstory trees as part of a regeneration method should be included in silvicultural prescriptions that underplant these species. Another consideration when making decisions about artificial regeneration is that certain species, such as oaks, often have more limited success when planted compared to seedlings established by natural regeneration (Craig et al. 2014).

Assisted migration (i.e., assisted gene flow) involves the translocation of individual species or genotypes from outside a geographic region to facilitate adaptation of planted forests to climate change (Aitken and Bemmels 2016). Sources to identify promising genotypes to target for assisted migration plantings include information from provenance trials and knowledge about the environmental conditions within a species' distributional range (Aitken and Bemmels 2016, Aitken et al. 2008). For example, white pine (*Pinus strobus*) populations are predicted to decline in response to climate change. A proposed viable management response is to transfer white pine provenances from southern regions (e.g., Virginia) into more northern regions (e.g., Ontario) that are predicted to maintain habitats similar to the current distribution of those provenances (Joyce and Rehfeldt 2013).

Maintaining Timber Production

Models of forest productivity under a changing climate in the Northern Region generally show increases in net primary productivity (NPP) over the next century (Ollinger et al. 2008). However, those potential increases may be mitigated or even negated because of confounding and interacting factors, such as native and nonnative pests and pathogens, invasive plant species competition, disturbance from windthrow and ice storms, and increased drought stress (Rustad et al. 2012). The magnitude of potential impacts on forest productivity is uncertain, so landowners in the Northeast with timber objectives must adopt management strategies that facilitate the resilience of forest stands to a changing climate (e.g., Gunn et al. 2009). However, forest product markets and the ecological context in the Northern Region present some limitations on how forest managers can ameliorate consequences of drought.

The economic importance of the forest products sector in the Northern Region is well documented. The economic output of the forest products sector within the Midwest alone has been estimated at over $122 billion annually (Ballweg 2016, Deckard and Skurla 2011, DIS 2016, Henderson and Munn 2012, Leatherberry et al. 2006, Leefers 2017, McConnell 2012, Settle et al. 2016). Across the region, much of this economy was underpinned by the production of pulp and paper, which also supports a sawmill economy tied to the building sector. Between 2014 and 2017, closures of mills (and shutdown of paper machines within extant mills) and biomass power facilities have reduced the marketplace for low-grade wood by 40 percent in New England. Between 2006 and 2016, Minnesota has seen a similar decrease (-38 percent; MN DNR 2016). This state of the market for low-grade wood is compounded by a slow recovery of the housing market in the United States since bottoming out in 2007–2009 (U.S. Endowment for Forestry and Communities 2017).

Although the harvest of high-quality and high-value sawlog material for the building sector is fundamental to the bottom line of landowners and loggers, investment in growth and yield to improve silvicultural practices on investment ownerships has been minimal, implying that productivity is becoming a minor concern for landowners interested in timber value (D'Amato et al. 2018). For example, in Maine the acreage devoted to timber stand improvement and herbicide treatments remains low relative to the acreage harvested annually (Maine Forest Service 2017). This trend is further emphasized in a recent study that documented a lack of clear silvicultural goals for recent harvests throughout New England and New York (Belair and Ducey 2018). More than one-third of the recent harvesting in Maine can be categorized as using nonsilvicultural practices such as "commercial clearcut" or "high-grade" (Belair and Ducey 2018). Similar trends have been observed in studies examining family forest ownerships in the region (Maker et al. 2014). Still, global demand for forest products remains high, and the Northern Region forest sector infrastructure will likely be maintained for the foreseeable future, although perhaps at levels lower than in recent years (Levesque 2018). If the sector is to remain economically viable in the long term, forest managers will need to adjust management practices accordingly.

Silviculture in the Northern Region is rarely intensive, and investments in intermediate treatments are generally minimal. Therefore, management options for coping with drought, such as the density management option suggested earlier, are difficult to implement in the Northern Region because of the associated economic challenges. Industrial forest owners may be in the best position to execute more costly management strategies to mitigate the impacts of drought stress on productivity, such as shortening rotation durations and implementing thinning treatments. In contrast, small family forest owners may not have professional forestry assistance to support long-term management decisions in a changing climate with increased risk from drought (Butler et al. 2016). The management dynamics of forests in the Northern Region would need to change dramatically to implement practices that reduce impacts from drought and climate change in general.

Carbon Sequestration

Net sequestration of atmospheric carbon by forests in the United States offsets the equivalent of nearly 10 percent of carbon emissions from the transportation and energy sectors combined (Wear and Coulston 2015). Through conservation, restoration, and improved management, forests in the Northern Region have the potential to be even more influential in mitigating climate change (Griscom et al. 2017, Nave et al. 2018). Any potential increase in tree mortality and decrease in forest productivity places this crucial carbon sink at risk. Although this risk is important to understand for broader carbon accounting purposes, a more practical concern is the emerging carbon offset marketplace, which is a critical component of climate change mitigation efforts (Anderson et al. 2017).

Developing carbon markets and regional climate change policies allow emitters of greenhouse gases to offset their emissions through forest-based carbon sequestration projects. In 2015, the worldwide market in forest carbon offset trading was $761 million (Goldstein and Ruef 2016). Several significant transactions have occurred in the Northern Region on private forest lands that demonstrate the potential benefits of this market to landowners. For example, the Downeast Lakes Land Trust of Grand Lake Stream, ME, recently achieved the first formal forest carbon offset project verification in the Northern Forest, on 19,119 acres in eastern Maine. The project received an initial issuance of nearly 200,000 compliance-eligible carbon offsets, which are expected to have a value of over $2 million upon conversion to the California Air Resources Board (ARB) program. As this project illustrates, significant revenues could be available to landowners under specific circumstances. Identifying these opportunities requires a comprehensive understanding of how financial and legal risks are influenced by natural disturbances.

Each carbon offset program has its own rules and requirements for premature, intentional, and unintentional project termination (termed reversal). The Climate Action Reserve (Forest Project Protocol) requires a 100-year commitment to maintain stocks. To address reversal risk, a percentage of credits is set aside as a buffer in case of a reversal, based on a project-specific risk evaluation (this can be reduced further by the use of a qualified conservation easement). Offset projects using the American Carbon Registry require a 40-year commitment, and a project-specific risk assessment determines the amount of credits that must be placed in the buffer pool, secured from an approved alternate source of offsets, or the level of insurance coverage that must be purchased.

Participation in the carbon marketplace is limited by uncertainties surrounding the risk of reversal for a given project and compounded by the long commitment periods. The risk of reversal of carbon offset projects is influenced by at least three factors: (1) the severity, duration, and frequency of natural disturbances, including fire, insect damage, and severe weather; (2) the response of trees to increasing atmospheric CO_2 concentrations and changes in climatic conditions; and (3) landowner behavior (Galik and Jackson 2009). Landowner behavior can be addressed through legal mechanisms. However, to support both carbon offset project development and policies that seek to use forests as part of a regional climate mitigation strategy, more understanding is needed of reversal risk based on natural disturbance regimes in a changing climate (e.g., increased risk of ice storms, microbursts, and fire or stress related to severe summer droughts).

The nature of the standards and methodologies that govern how forest offset credits are generated may put these projects at risk. The most financially viable forest carbon offset projects involve forests that have higher than average biomass volume (i.e., carbon stocks) at the time of project initiation (Russell-Roy et al. 2014). These forests with larger and older trees are typically also at higher risk from drought stress (Skov et al. 2004). Uncertainty and risk are two major factors that may hinder more widespread use of this climate mitigation tool, even though it has many co-benefits for forest conservation and associated ecosystem services. Forest owners who want to engage in the carbon offset marketplace will need to develop and implement management strategies to minimize or mitigate that risk.

Fire Management and Risk

Historic fire data show a low probability of fire occurrence for the Northeast and upper Midwest, according to modeled outputs from limited fire scar data (Guyette et al. 2010, 2012). In these regions, high-severity fires occurred roughly every 30–75 years in much of the region, and the probability was much lower for certain ecosystems (e.g., up to 1,200 years for hemlock-white pine-northern hardwood forests [Whitney 1986] and more than every 800 years for northeastern spruce-fir forests [Lorimer 1977]).

Farther south within the Northern Region, the probability of fire occurrence was every 15–30 years. In recent times, fires throughout the region have become less frequent because of both human efforts to rapidly extinguish them and the highly fragmented nature of forest lands. Large fires can occur in the Eastern United States, however, as witnessed by the large complex of fires in the Great Smoky Mountains National Park and vicinity (2016) and significant fires in the White Mountain National Forest in New Hampshire (autumns of 2016 and 2017).

These kinds of exceptional fires seem to be on the rise worldwide. The 2017 wildfire season was especially unusual, with numerous severe fires occurring around the world, including Chile, the Mediterranean, Russia, Western North America, and even Greenland (Nature Climate Change Editors 2017). Climate projections, such as those presented in this document, indicate that the hot, dry conditions that facilitated these fires may become more common in the future. Thus, the forests of the Northeast and Midwest are likely to become more flammable. This flammability, with the very high human population density in the wildland interface, may increase the likelihood of fire, including catastrophic fire, challenging the institutional and infrastructural resources in place to manage them.

The fire season for the Northern Region tends to occur before leaf-out in spring, when solar radiation dries the forest floor. Wildfires in this region are generally small (<4 ha) and result from human activities, both intentional and unintentional, rather than by lightning (Cardille and Ventura 2001, Miranda et al. 2012, Peters and Iverson 2017). However, flash droughts, especially in the autumn, can lead to large fires, such as the Great Smoky Mountains National Park fires of 2016 (Wehner et al. 2017). Prescribed fire is used throughout the Northern Region—more so in the Midwest than in the more humid Northeast—as a tool to manage forests and savannas, often to promote oak and dissuade maples and other mesophytic species from dominating in the next forest (Brose et al. 2014). Using prescribed fire to restore communities is not easy, even in the drier Midwest. The burn windows are narrow, and multiple fires are often needed to obtain desired outcomes related to the diverse goods and services provided by forests (Hutchinson et al. 2012, Iverson et al. 2017).

Hydrological Functions and Services

Compared to other land uses, forests provide the cleanest and most stable supply of water for human uses (NRC 2008). In the Northern Region, the abundant, high-quality water filtered through forests serves multiple needs for residential, agricultural, industrial, and commercial uses, including drinking water, irrigation, recreation, wastewater assimilation, and power generation. Although severe droughts are relatively rare in the region, they affect water quality and quantity when they do occur because of the dense human population and the heavy reliance on water resources. Lakes, streams, and wetlands in forested watersheds are also critical habitat for many organisms and therefore enhance biodiversity. As drought severity progresses and surface waters dry out, water temperatures and nutrient concentrations increase, and refugia for aquatic species diminish (Vose et al. 2016). Because of the clear relationship between forests and water, management plans must be developed that sustain water resources. In some cases, such as watersheds that serve as a source of drinking water (see case study 8.1), the paramount forest management objective is to supply a sufficient amount of high-quality water for public consumption.

Linkages between forest management activities and streamflow and water quality have been evaluated comprehensively in the region (e.g., Brown et al. 2005, Hornbeck et al. 1986). Impacts of forest harvesting on streamflow are generally short-lived: increases in water yield seldom exceed 10 years after cutting (Hornbeck et al. 1993). Stream responses to cutting vary, depending on the harvesting intensity and site conditions (e.g., slope steepness, soil characteristics, forest cover type), and they can be extended with herbicide use and by making intermediate cuts. Transpiration rates of the regenerating forest generally recover rapidly, though, so harvesting practices are not typically considered a long-term, economically viable management strategy to minimize drought impacts on water yield. However, if the regenerating forest contains species with different transpiration rates or canopy interception than the forest it replaced, long-term effects on streamflow are possible (Hornbeck et al. 1993). Given the increased likelihood of both high and low flows in the future, it is improbable that forest managers will select for tree species based on transpiration and interception alone. Rather, a more tactical approach would involve establishing a diversity of species and age classes to ensure the continued functionality of forests under a broad range of conditions. For example, increasing biodiversity makes forests less vulnerable to insects and disease. Maintaining the structural diversity of forests, including trees of different age classes and levels of shade tolerance, can enhance recovery after disturbance.

Although managing water resources is typically not the primary forest management objective, many of the best forest management practices that have been established are designed to maintain water supply and quality. Practices that avoid compaction and promote infiltration act to reduce surface runoff and replenish groundwater supplies that sustain streamflow during dry periods. Leaving buffer strips along stream channels helps to maintain stream temperatures and reduce nutrient inputs. Further habitat protection can include the addition and retention of coarse woody debris in streams to establish pools that serve as refugia for aquatic organisms during droughts (Warren et al. 2010).

CONCLUSIONS

Although drought has not been a major concern for forest managers in the Northern Region in recent memory, climate change projections suggest that the frequency and severity of drought will likely increase in this region in the future, especially under "worst case" climate change scenarios. Our understanding of how different tree species and whole ecosystems will respond to greater moisture stress is limited, largely because of the historical lack of drought in the region. However, based on climate change projections, future forest responses to drought are likely. These could include mortality of more sensitive species, shifts in forest composition towards more drought-tolerant species, including exotic species, and potential migration of tree species into more suitable habitats outside of current geographic ranges. Such drought-related effects could in turn impact many forest provisions, including timber and nontimber products, water supply, carbon sequestration, wildlife habitat, and cultural benefits. Consequently, forest managers, landowners, and other stakeholders should consider a range of potential actions to mitigate and adapt to drought conditions. In this review, we highlighted a range of management options available to enhance the adaptive capacity and resilience of forest ecosystems to drought in the Northern Region, and we presented case studies to show where some of these activities have already been implemented. We also identified areas where knowledge is currently lacking, and where more targeted research is needed to better inform management decisions. Finally, a key theme throughout this chapter is that, even though the Northern Region is currently relatively wet and not moisture-limited, forest managers are likely to face new challenges related to water availability. Efforts should be directed at preparing forests for uncertain future conditions, while also taking measures to reduce the rate of climate change.

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CHAPTER 9

Managing Effects of Drought in the Southeast United States

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INTRODUCTION

The Southeast United States (i.e., Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, Tennessee, Texas, South Carolina, Virginia) is considered to be a water-rich region. In an average year, precipitation is about 20 times more than is needed for human use within the region (Sun et al. 2008). However, the precipitation is not evenly distributed over time and space, and periodic droughts can occur almost anywhere in the region and at any time throughout the year. If drought is not considered in forest management, the risks of forest mortality, insect and disease outbreaks, wildfires, and other disturbances all increase. (McNulty et al. 2013). This chapter explores why droughts occur in the Southeast; how these droughts can affect ecosystem structure, function, goods, and services; and how forest managers can reduce drought impacts through forest management. This information will become even more valuable in the future as climate variability increases (IPCC 2014).

Climate of the Southeast

The climate of the Southeast is variable and is influenced by many factors, especially the region's topography, proximity to the ocean, and latitude. Generally, the average temperature decreases with latitude and elevation, and precipitation tends to decrease further inland from the Gulf and Atlantic coasts. The Southeast often receives systems capable of producing floods, but the region also has frequent droughts. Compared to droughts in the Southwest and Great Plains, droughts in the Southeast are relatively short (i.e., usually 1–3 years) (Seager et al. 2009). Drought conditions can rapidly develop across the region, caused by a lack of tropical cyclone activity, warm-season rainfall variability, higher rates of plant evapotranspiration (ET), and increased water usage (Kunkel et al. 2013). The position of the Bermuda High in the northwest quadrant of the Southeast strongly influences summer precipitation. The Bermuda High is a semi-permanent high-pressure area in the Atlantic Ocean. Shifts in the location of this high can cause drought across the Southeastern United States (fig. 9.1).

Another influence on the precipitation patterns across the Southeast is the El Niño-Southern Oscillation (ENSO). Unlike the Bermuda High, the strongest ENSO effects typically occur during the winter months. El Niño-Southern Oscillation consists of two phases determined by sea surface temperatures (SST) across the equatorial Pacific. If the SSTs are above normal, then ENSO is considered an El Niño, or warm phase. If the SSTs are below normal, then ENSO is a La Niña, or cool phase. An El Niño causes above-average precipitation across the region and reduces the probability of winter temperature extremes across the Southeast (Higgins et al. 2002). Unlike El Niño, La Niña is associated with drier weather, a higher risk of drought (Mo et al. 2009), and warmer than normal temperatures (Higgins et al. 2002).

The Southeast is one of the few regions of the world that did not show a statistically significant warming

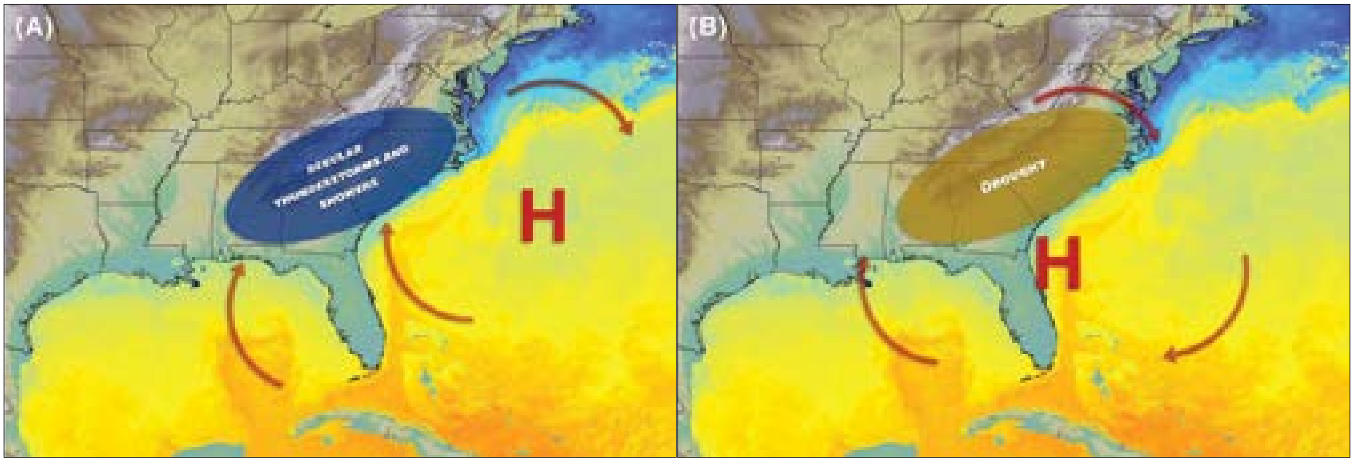


Figure 9.1—The Bermuda High position during the summer months. The left figure (A) indicates when the high pressure is just offshore, consequently causing thunderstorms across the region. The right figure (B) depicts when the high pressure is closer inland, causing drought conditions to materialize across the Southeast United States. The arrows indicate the surface air circulating around the high-pressure system. (Source: State Climate Office of North Carolina: http://climate.ncsu.edu/images/drought_images/BermudaHigh_Droughtwide.png, http://climate.ncsu.edu/images/drought_images/BermudaHigh_Typicalwide.png)

trend during the 20th century (IPCC 2014). Instead, the region varied in both annual and seasonal air temperature. A warm peak occurred during the 1930s and 1940s, followed by a brief midcentury period of cooler temperatures. From 1901 to 2016, the average temperature of the Southeast increased 0.46 °F (Vose et al. 2017). Since the 1970s, mean temperatures have increased by about 2 °F. For most regions, mean temperature has increased over the 20th century, mostly because minimum air temperatures have increased (Powell and Keim 2015), especially in the summer (Kunkel et al. 2013). Since the late 20th century, the number of days exceeding maximum temperatures of 95 °F has been increasing, and the number of days below 10 °F has decreased (Kunkel et al. 2013).

Southeast annual precipitation has also varied during the 20th century. However, two overall trends emerged. First, the summer months had significantly less precipitation, by about -2.54 mm per decade (Kunkel et al. 2013). Second, extreme precipitation events increased over the 20th century (Powell and Keim 2015, Wuebbles et al. 2014), particularly since the 1970s (Easterling et al. 2000). Many parts of the region showed an overall decrease in the number of consecutive wet days but an increase in very wet days (Powell and Keim 2015). Thus, precipitation events are becoming more intense, especially over Louisiana, Mississippi, Georgia, Florida, and Tennessee.

Historical drought in the Southeast—Based on paleoclimate data, historical drought conditions were frequent across the Southeast (Cook et al. 2007, Seager et al. 2009) and were most severe during the 14th and 16th centuries (Cook et al. 2007). Although drought conditions are common across the Southeast, and severe and extreme drought occurred intermittently during the 20th century, no long-term trend emerged for this period (Easterling et al. 2000).

However, changes in temperatures and precipitation occurred during the 20th century. Summers (but not the whole year) had a pronounced warming trend, a significant decrease in annual precipitation (Kunkel et al. 2013), and more time between precipitation events (Powell and Keim 2015), which in turn increased soil evaporation and reduced soil moisture. Between 1948 and 2012, the number of consecutive wet days decreased, and the number of days of extreme precipitation increased (Powell and Keim 2015).

Widespread drought conditions occurred across much of the Southeast during 1998–2002 and again in 2007–2008. Although not as geographically large as the Dust Bowl of the 1930s, the 1999–2002 drought set meteorological and hydrological records across the region (NOAA NCEI 2003). The precipitation totals from December 1999 to September 2000 were the lowest on record for the Deep South (i.e., Alabama, Georgia, Mississippi, and South Carolina), and the 2000 hydrological year was the fourth driest on record (NOAA NCEI 2001). The record dry conditions from 2001 continued into 2002, with extreme dryness affecting almost the entire East Coast. Overall, precipitation deficits were well below the annual average for the entire drought period of 1998–2002. Between August 2001 and July 2002, precipitation totals for Virginia, North Carolina, South Carolina, and Georgia were the lowest on record (NOAA NCEI 2003).

Another abnormally dry period began in December 2006 and continued throughout 2007. During the spring and summer months, the position of the Bermuda High deflected tropical storms away from the Southeast. By the summer of 2007, La Niña conditions were present across the equatorial Pacific, contributing to the drought. The culminating effect caused every month in 2007 (except October and December) to be drier than average (NOAA NCEI 2008). By November 2007, parts of the Southeastern United States experienced the worst drought on record while others ranked among the top 10 worst recorded droughts (Maxwell and Soulé 2009).

Types of drought—There are five types of drought: meteorological, agricultural, ecological, hydrological, and socioeconomic (Wilhite and Glantz 1985). Meteorological drought is defined as lack of precipitation and is region-specific. Agricultural drought occurs when precipitation shortages affect crop production. Ecological drought relates to the negative impacts of drought on ecosystem services. Hydrological drought refers to the effects of precipitation shortages on surface or subsurface water supply (e.g., groundwater, streamflow, lake levels). Socioeconomic drought refers to the effect of drought on the supply and demand of economic goods or on people's behavior, and it is the most difficult to quantify.

Several indices are used to describe types of meteorological and hydrological drought. The Standardized Precipitation Index (SPI) measures meteorological drought by comparing observed precipitation values to the climatic normal (Keyantash

2016). Anomalies determine abnormal wetness or dryness for short- and long-term droughts compared to a reference period (Keyantash 2016). An extension of the SPI is the Standardized Precipitation Evapotranspiration Index (SPEI), which incorporates potential ET along with precipitation (Vicente-Serrano 2015). The Palmer Drought Severity Index (PDSI) measures hydrological drought, using temperature and precipitation data to determine relative dryness. The PDSI is a measure for long-term droughts (over 12 months) and can capture effects of changing climate through potential ET (Dai 2017). The PDSI increased at a rate of about 0.04 per century (Cook et al. 2014), indicating a slight shift towards wetter conditions across the Southeast. Over the latter part of the 20th century, the frequency of both very wet and very dry summers increased (Groisman and Knight 2008, Wang et al. 2010), and drought conditions were more likely to result from rainfall deficits from the previous spring than from rainfall deficits during the summer (Wang et al. 2010).

Forecast for future drought in the Southeast—A lack of precipitation causes drought conditions, and warming temperatures can exacerbate these conditions (Strzepek et al. 2010, Zhao and Dai 2015). Climate projections agree that average temperature will rise during the 21st century, but there is less agreement on the direction, magnitude, and timing of changes in precipitation (Easterling et al. 2017, Kunkel et al. 2013, Sobolowski and Pavelsky 2012, Wuebbles et al. 2014).

Future climate in the Southeast was modeled using the Coupled Model Intercomparison Project Phase 3 (CMIP3), using high and low greenhouse gas emissions scenarios (Kunkel et al. 2013). Relative to the reference period of 1971–1999, the high emissions scenario model projected increases in mean annual temperatures of 3.5–5.5 °F by 2055 and 4.5–8.5 °F by 2085 (Kunkel et al. 2013) (fig. 9.2).

The North American Regional Climate Change Assessment Program (NARCCAP) uses multi-model regional climate model simulations (fig. 9.3) to project mean annual temperatures; it gives similar results to the CMIP3 model and includes seasonal projections (Kunkel et al. 2013). Relative to the 1971–1999 reference period, 2041–2070 mean temperatures will increase in all seasons in the Southeast. Summers will be 3.5–6.0 °F warmer (with the greatest warming in the northwestern part of the region), autumn will be 3.0–5.0 °F warmer (with most warming in the northern and western part of the region), winters will be 2.5–5.0 °F warmer (with the greatest warming in the northern part of the region), and springs will be 2.5–3.0 °F warmer throughout the region. Similarly, by the middle of the 21st century, summer surface temperatures are predicted to increase by 5.4 °F across most of the region, with intense warming continuing into the fall (Sobolowski and Pavelsky 2012). Winter and spring surface temperatures are also predicted to increase by 2.7 °F and 3.6 °F, respectively.

Future precipitation in the Southeast was also modeled using the CMIP3 and NARCCAP multi-model simulations. The CMIP3 evaluated high and low emissions scenarios for 2021–2050, 2041–2070, and 2070–2099, relative to the 1971–1999 reference period (Kunkel et al. 2013) (fig. 9.4). Overall, both emissions scenarios showed little change (<3 percent) in the amount of precipitation on average across the region throughout the 21st century. Less precipitation is predicted in the western part of the Southeast and more in the central and eastern parts. The largest predicted changes occur under the high emissions scenario for 2070–2099. However, some States could observe changes in precipitation that are larger than the regional average. By late in the 21st century, annual precipitation may increase up to 3–6 percent in North Carolina and Virginia and up to 12 percent in parts of Louisiana (Kunkel et al. 2013). Overall, annual precipitation rates in the Southeast are not expected to change much from current levels, but the seasonality and precipitation rates for a specific location could be more variable than the regional average.

The NARCCAP multi-model regional climate simulations (fig. 9.5) show differing results from the CMIP3. According to the NARCCAP high emissions scenario, annual precipitation is expected to increase across much of the Southeast, with the largest projected increase along the Gulf Coast (about 9–12 percent) and the largest projected decrease in southern Florida (up to 6 percent) (Kunkel et al. 2013).

NARCCAP simulations also predict increases in precipitation for every season (except summer) (Kunkel et al. 2013). Greatest precipitation increases are expected in the winter in the northern tier of the region and southern Florida (>15 percent), and in the fall along the Gulf Coast (>15 percent). In the spring, precipitation increases generally are predicted throughout the Southeast (15–20 percent), but with decreases (>10 percent) predicted in southern Florida and western Louisiana. Using NARCCAP, Sobolowski and Pavelsky (2012) determined similar results for precipitation. By the middle of the 21st century, precipitation is predicted

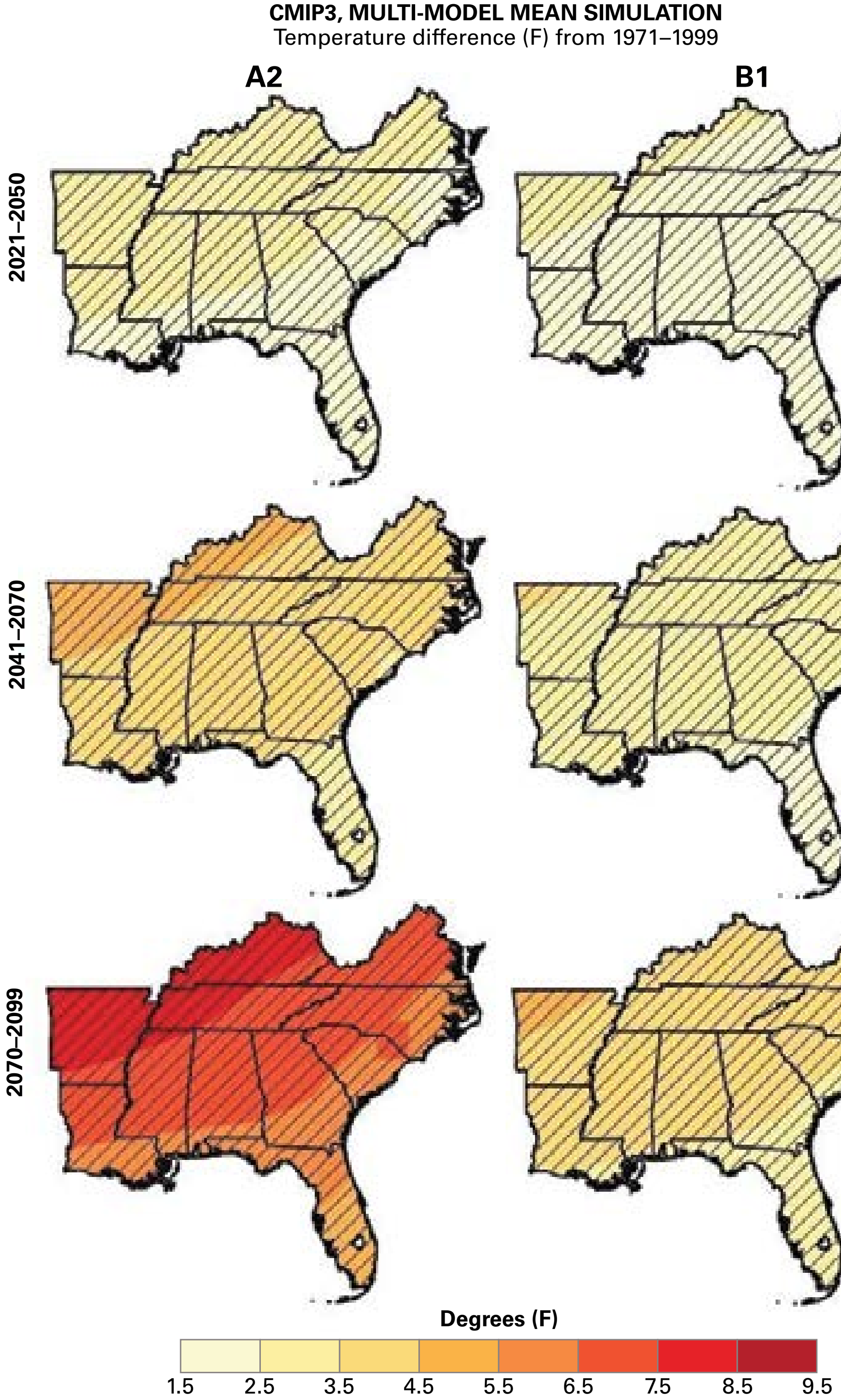
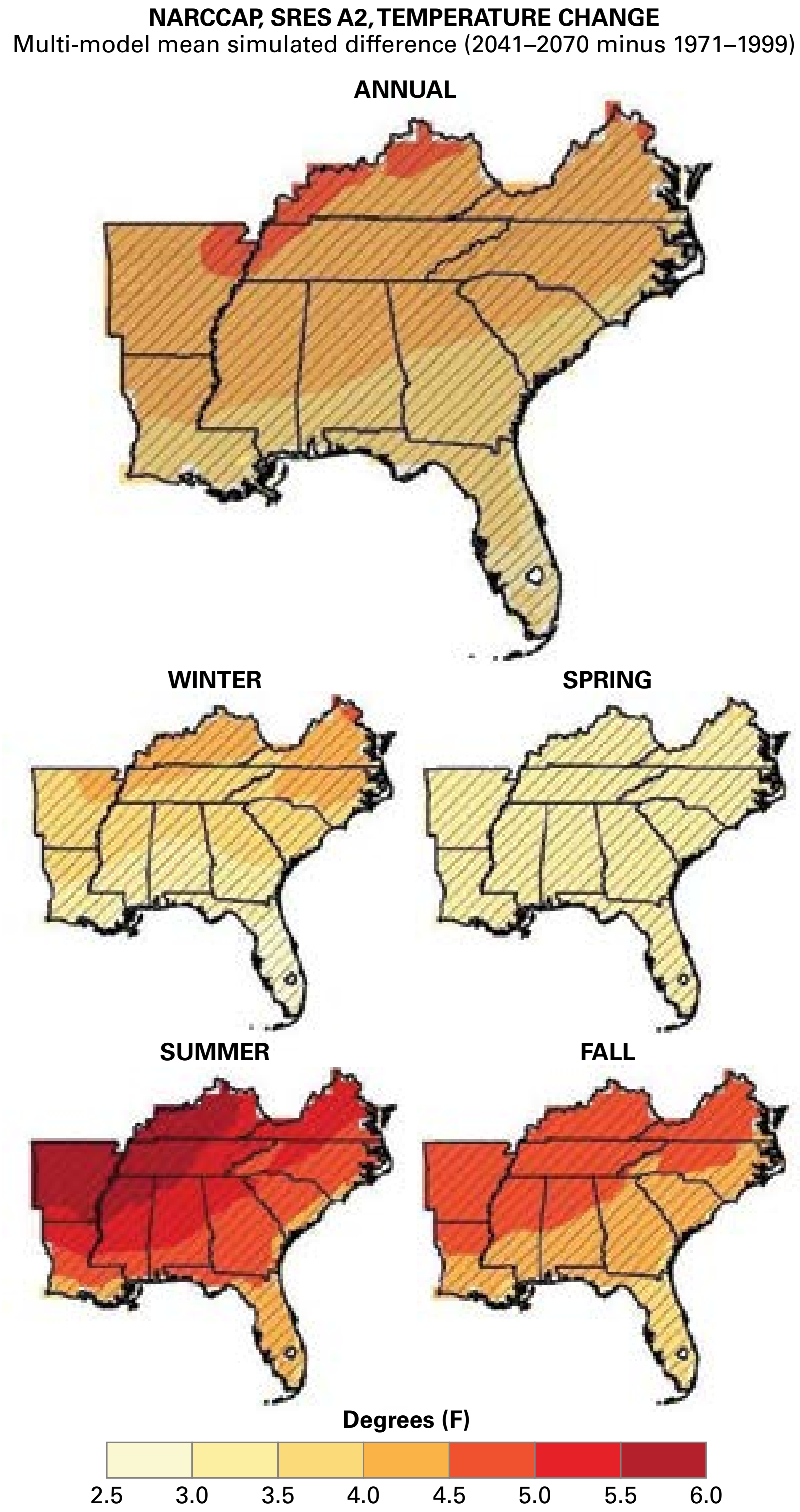


Figure 9.2—Projected annual mean temperatures (°F) across the Southeast. Both high (A2) and low (B1) emissions scenarios are shown over three time periods: 2021–2050, 2041–2070, and 2070–2099, relative to the reference period of 1971–1999. Annual mean temperature is positive for each emissions scenario and each model period. Hatching indicates that >50 percent of the models agreed that the change in temperature is statistically significant and 67 percent agree on the sign change. CMIP3 = Coupled Model Intercomparison Project Phase 3. (Source: Kunkel et al. 2013)



NARCCAP, SRES A2, TEMPERATURE CHANGE
Multi-model mean simulated difference (2041–2070 minus 1971–1999)

ANNUAL

WINTER

SPRING

SUMMER

FALL

Figure 9.3—Projected annual and seasonal mean temperatures (°F) across the Southeast. The projections are for the high emissions scenario (A2) during 2041–2070 with a reference period of 1971–1999. The annual and seasonal mean temperature is positive across the entire region. The hatching indicates that >50 percent of the models agree there is a statistical significance and 67 percent agree on the sign change. NARCCAP = North American Regional Climate Change Assessment Program. (Source: Kunkel et al. 2013)

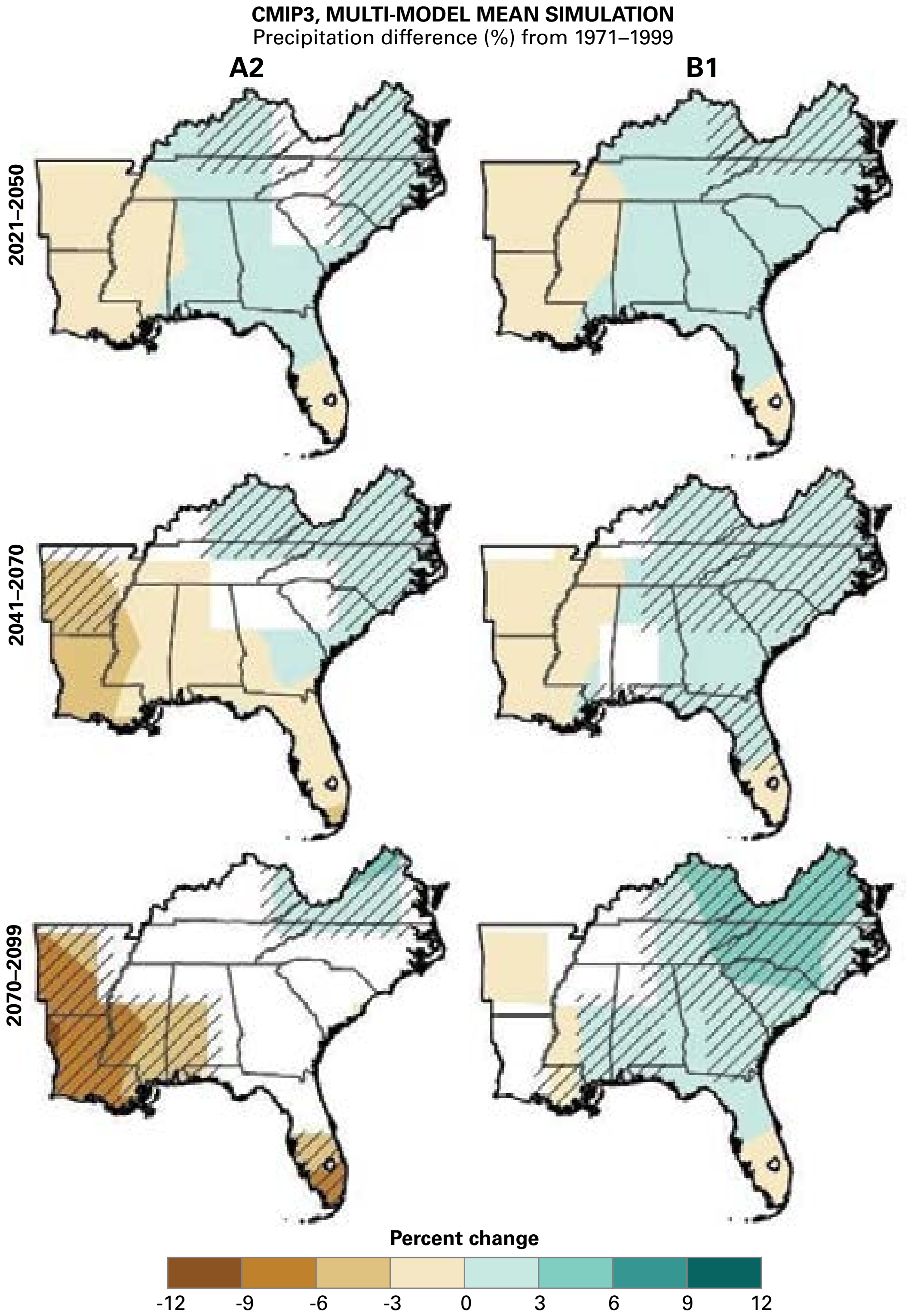


Figure 9.4—Projected difference in annual precipitation (percent) across the Southeast. Both high (A2) and low (B1) emissions scenarios are shown over each time period (2021–2050, 2041–2070, and 2070–2099). The reference period is 1971–1999. Color only indicates that <50 percent of models determined the change is statistically significant. Color with hatching indicates that >50 percent of the models agree there is a statistical significance and 67 percent agree on the sign change. CMIP3 = Coupled Model Intercomparison Project Phase 3. (Source: Kunkel et al. 2013)

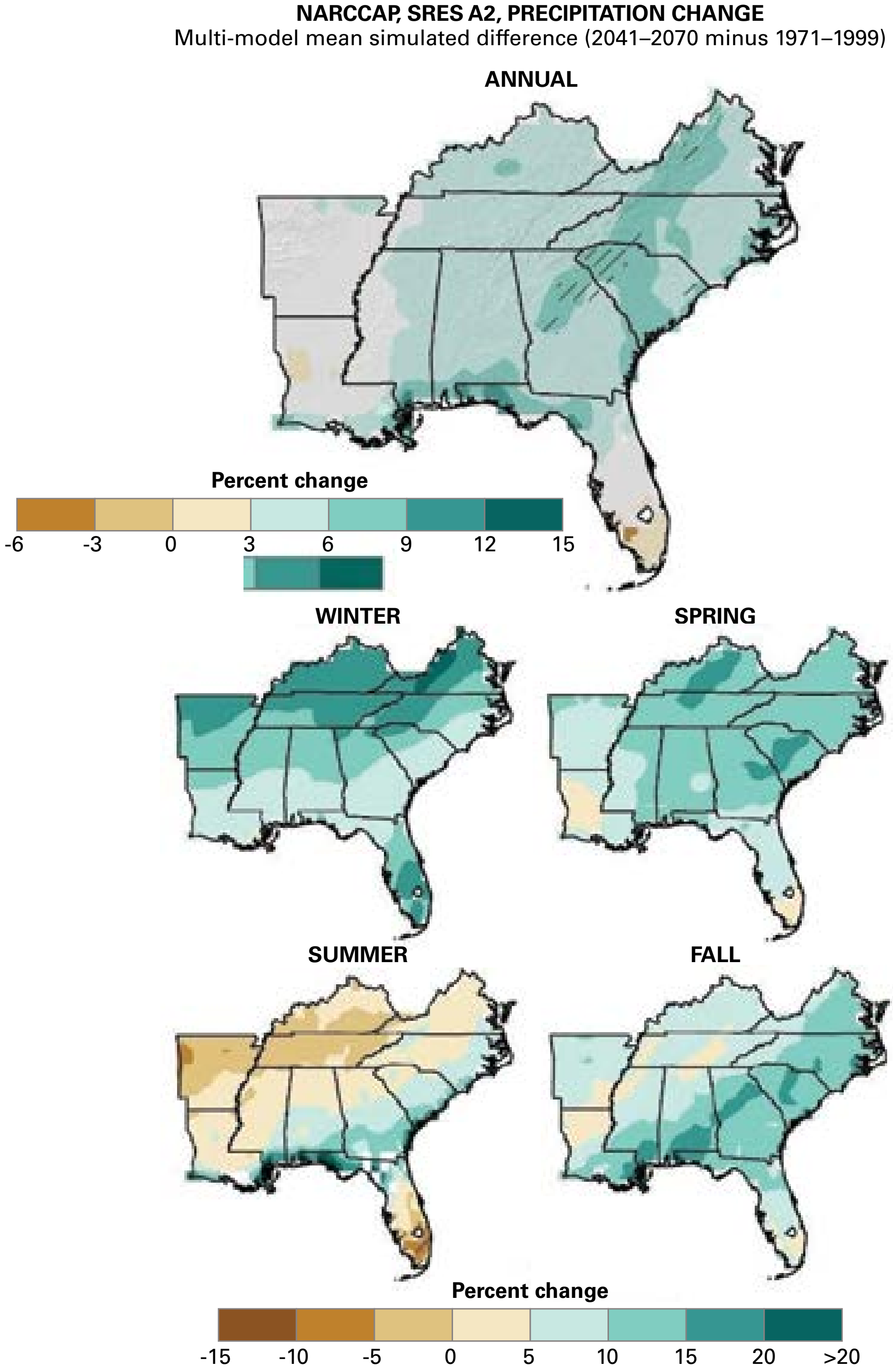


Figure 9.5—Projected annual and seasonal precipitation change (percent) across the Southeast. The projections are for the high emissions scenario (A2) during 2041–2070 with a reference period of 1971–1999. Color only indicates that <50 percent of models determined the change is statistically significant. Color with hatching indicates that >50 percent of the models agree there is a statistical significance and 67 percent agree on the sign change. NARCCAP = North American Regional Climate Change Assessment Program. (Source: Kunkel et al. 2013)

to decrease most (about 15 percent) during summer, and increase most (10 percent) across most of the region during the winter and spring, as well as along the southeast coast in the fall.

Variability in summer precipitation is strongly correlated with the location of the Bermuda High (Li et al. 2012). The position of the Bermuda High can cause drought conditions across the Southeast (Li et al. 2012) (fig. 9.1). Simulations suggest that rainfall will become more variable in the 21st century (Li et al. 2011, 2013; Wuebbles et al. 2014) due to a western shift in the Bermuda High that may lead to both exceptionally wet and exceptionally dry summers (Li et al. 2013, Wuebbles et al. 2014).

In addition to these likely future increases in summer precipitation variability, the overall net surface water gain in the Southeast is projected to significantly decrease in all seasons except summer under a high emissions scenario (Sobolowski and Pavelsky 2012). Furthermore, drought is more likely to occur when rainfall deficits start in the previous season (Wang et al. 2010). The findings taken together—the likelihood of future warming temperatures, a possible westward shift of the Bermuda High, and more summertime precipitation variability—suggest that summertime droughts may occur more frequently in the Southeast by the middle or end of this century.

In another simulation study of future precipitation in the Southeast, Swain and Hayhoe (2015) projected a standardized precipitation index (SPI) for the spring and summer seasons using two emissions scenarios (high [8.5] and low [4.5]) and three future periods (2020–2039, 2050–2069, and 2080–2099). Regardless of emissions scenario and time period, the Southeast is projected to experience future drier conditions in the spring (fig. 9.6), as well as in the summer for Florida and the Gulf Coast. However, the rest of the region is projected to become wetter during the summer (fig. 9.7).

Despite projections that precipitation will increase throughout most of the Southeast, drought frequency and intensity are projected to increase throughout the 21st century (Strzepek et al. 2010, Zhao and Dai 2015). As air temperature increases, so do ET rates, which lead to reductions in soil moisture and the development of drought conditions. As a result, moderate hydrological drought may increase by 5 percent, and severe hydrological drought may increase by 30 percent (Zhao and Dai 2015).

By the late 21st century, even the low emissions scenario predicts that moderate agricultural drought conditions may increase by as much as 50–100 percent, and severe agricultural drought may increase by 100–200 percent (Zhao and Dai 2015). Both short-term (4–6 months) and long-term (12 months) soil moisture deficits are projected to increase throughout the 21st century, and the spatial extent of soil moisture deficit conditions may also increase (Sheffield and Wood 2008). Based on the 3-month SPEI, the spatial extent of drought will increase the most during the summer (Ahmadalipour et al. 2017). Regardless of emissions scenario, drought intensity and frequency are projected to increase throughout this century (Ahmadalipour et al. 2017) (fig. 9.8).

Factors Interacting With Drought

Fire—Available fuel is often the determining factor for wildfire risk. For a wildfire to ignite, fuel must be of a certain size and moisture content. Large-diameter wood is more difficult to ignite and slow to dry, whereas small-diameter wood (i.e., twigs, sticks, small branches) has a high surface-to-mass ratio, and thus more exposure to oxygen and less moisture.

Fire can be either prescribed (i.e., intentional) or wild (i.e., unintentional). Prescribed fires are important to forest management, especially in pine forests to reduce hardwood competition. Prescribed fires can also be a cost-effective management practice to reduce competition, restore nutrients to the soil, and change competition for soil water (Renninger et al. 2013, Waldrop and Goodrick 2012). Roughly 9 million acres are burned in prescribed forest fires each year. Approximately 7 million acres of these fires occur in southeast forests (Melvin 2015). Most prescribed burning in the Southeast is conducted during winter and spring to help contain the fire and more effectively manage smoke.

Wildland fires, or wildfires, are often contained through fire suppression. Unlike prescribed fires, wildfires are destructive, causing over $5 billion in property damage in the United States between 2007 and 2017 (III 2017). Although most of the fire-burned acreage occurs in the Western United States, about 45,000 wildfires and 1 million acres burn annually across the Southeast. By the middle of the 21st century, climate change and other factors could triple the incidence of wildfire across the Southeast (Barbero et al. 2015).

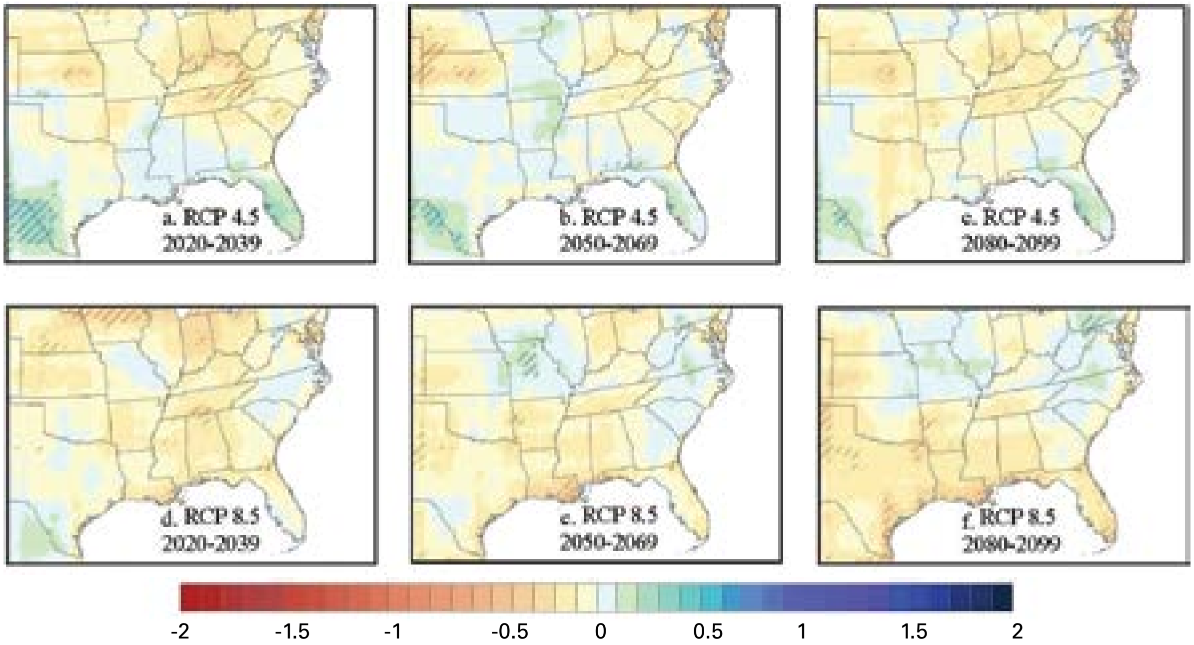


Figure 9.6—Ensemble mean Standard Precipitation Index (SPI) anomalies in spring (March, April, May) across the Southeast at three future time periods (2020–2039, 2050–2069, and 2080–2099) and under two emissions scenarios (RCP 4.5 and RCP 8.5). Anomalies were calculated as the future SPI minus the SPI for the historical base period of 1971–2000. Blue hatched areas: significantly higher SPI (wetter). Red hatched areas: significantly lower SPI (drier). RCP = representative concentration pathways. (Source: Swain and Hayhoe 2015)

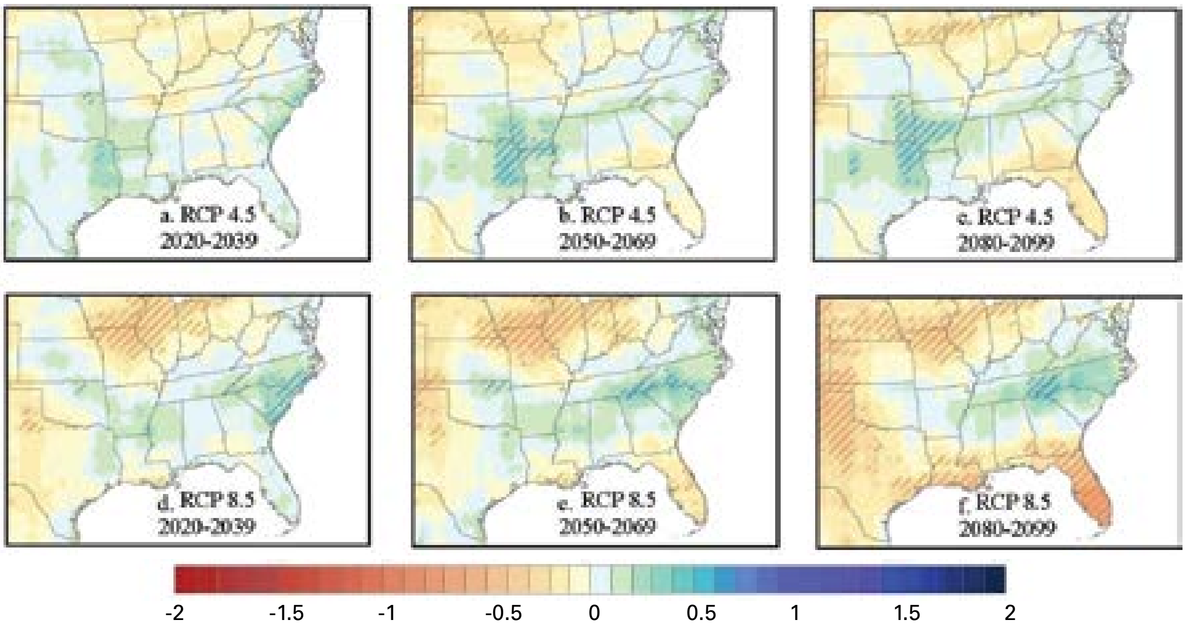


Figure 9.7—Ensemble mean Standard Precipitation Index (SPI) anomalies in summer (June, July, August) across North America at three future time periods (2020–2039, 2050–2069, and 2080–2099) and under two emissions scenarios (RCP 4.5 and RCP 8.5). Anomalies were calculated as the future minus a historical base period of 1971–2000. Blue hatched areas are projected to experience significantly higher SPI (wetter). Red hatched areas are projected to experience significantly lower SPI (drier). RCP = representative concentration pathways. (Source: Swain and Hayhoe 2015)

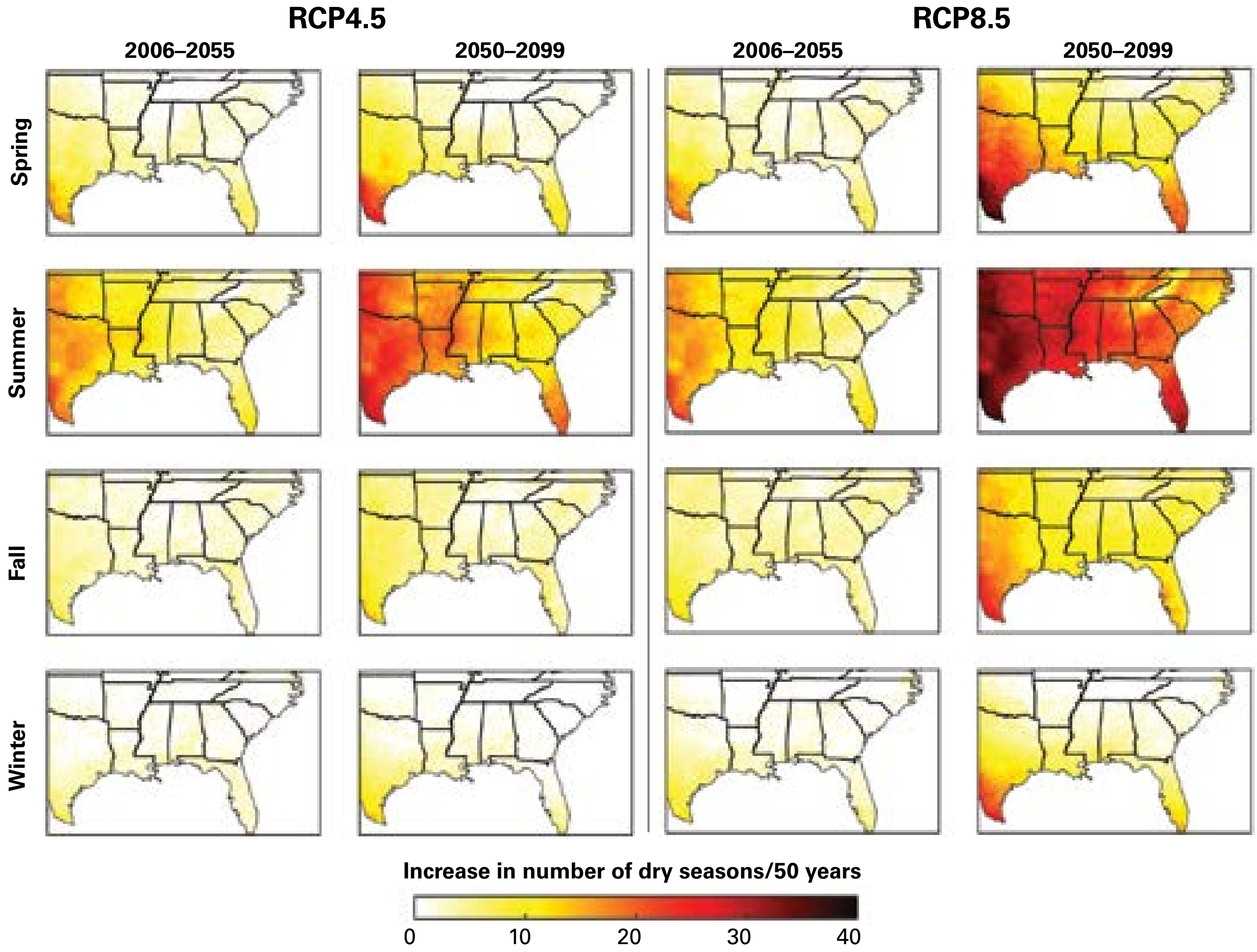


Figure 9.8—Predicted increases in the number of moderate or worse drought events in the Southeast by season according to the 3-month Standard Precipitation Index. Predictions are shown for two time periods (2006–2055 and 2050–2099) under two emissions scenarios (RCP 4.5 and RCP 8.5). RCP = representative concentration pathways. (Source: Ahmadalipour et al. 2017)

Although wildfires can be highly destructive to property, they are a natural component of many fire-adapted ecosystems. For example, pitch pine (*Pinus rigida*) and longleaf pine (*P. palustris*) are both fire-adapted species. Longleaf pine has a thick bark that protects the cambial layer from excessive heat, and both pine species benefit from the high temperatures associated with a fire for seed dispersal (Burns and Honkala 1990).

Drought is critical to wildfire occurrence and management. A drought requires several weeks or months to develop and can last for weeks or years. During these periods, forest rates of ET exceed rates of precipitation, and over time the soils lose moisture. With sufficiently severe loss, forest trees will lose leaves and could even die. Dead trees will begin to dry out, with smaller diameter material drying out first. This dry material becomes a potential source of wildfire fuel. For example, a 0.5-cm diameter stem can achieve a tissue moisture content of 15 percent within 2 days. As the fuel load dries out, fire risk increases. Once started, a fire can generate enormous amounts of heat and further decrease surrounding fuel moisture. As the fire grows, previously wet fuel and green living vegetation can dry out and become flammable sources of ignition.

Wildfire suppression activities aim to prevent loss of human life and destruction of natural and human-made assets. Severe droughts increase the risk of catastrophic and costly wildfires. The cost of wildfire suppression as a result of drought is thus a way to quantify the economic consequences of drought.

The Palmer Hydrological Drought Index (PHDI) (NOAA 2017), a widely used indicator of drought severity, represents the difference between the amount of water supplied by precipitation and the amount released by ET or lost as runoff. For the years 1995–2016, wildfire suppression in the Southeast averaged $12 million per year, but during drought years, suppression averaged $16 million, a 25-percent increase above the long-term average cost.

Insects and pathogens—Drought and the associated environmental conditions impact the population dynamics of forest insects, either through direct effects on the insects themselves or through indirect effects on their host plants, natural enemies, or environment (Bentz et al. 2010, Mattson and Haack 1987). Direct drought-related effects on insects include altered growth rates and fecundity. Indirect effects, mediated through host plants, include changes in plant palatability, attractiveness, nutrition, and defensive traits (Mattson and Haack 1987). Drought-related impacts by forest pest insects vary with the severity, timing, and duration of the drought, as well as the infestation, forest stand and site conditions, host species, insect-feeding guild, and type of plant tissue colonized (Huberty and Denno 2004, Jactel et al. 2012, Koricheva et al. 1998, Rouault et al. 2006). Discussed below are drought-related effects and management considerations with regard to forest insects of importance in the Southeast.

Pine bark beetles, such as the southern pine beetle (SPB) (*Dendroctonus frontalis*) or pine engraver beetles (*Ips* spp.), are generally secondary pests that colonize weakened trees. However, periodic outbreaks of the SPB are characterized by aggressive expansion of infestations. In periods of moderate water stress that result in decreased tree growth, more carbon is available for defensive resin production, potentially reducing pine susceptibility to SPB (Reeve et al. 1995). Under more severe drought, both growth and defense are compromised, and fewer beetles are needed to overwhelm trees, increasing the trees' mortality risk (Reeve et al. 1995, Schowalter 2012). Although local bark beetle outbreaks are often associated with drought-stressed trees, climatic variables have not been clear quantitative predictors of regional SPB outbreak dynamics. This is because outbreaks are driven by many factors, including stand density and condition, soils, and predator-prey interactions (Asaro et al. 2017, Hunter and Dwyer 1998).

Although sap-feeding insects may benefit from drought through mechanisms such as increased availability of nitrogen and other nutrients in plant tissue, they may be handicapped by decreased turgor pressure, increased sap viscosity, or inhospitable temperatures (Huberty and Denno 2004, Mattson and Haack 1987). The hemlock woolly adelgid (HWA) (*Adelges tsugae*) is an invasive sap-feeding insect in the Southeast, where it causes widespread mortality of eastern hemlock (*Tsuga canadensis*) and Carolina hemlock (*T. caroliniana*) (Vose et al. 2013). Hemlock woolly adelgid feeding induces a hypersensitive response in the tree, with physiological effects similar to water stress (Domec et al. 2013). Higher densities of HWA were found on experimentally water-stressed hemlock seedlings (Hickin and Preisser 2015), and evidence suggests that drought has exacerbated hemlock mortality in the presence of HWA in the Southern Appalachian Mountains (Ford et al. 2012). Water stress also reduces the ability of trees to take up systemic insecticide treatments, limiting HWA management options during drought conditions (Coots et al. 2015). Conversely, extreme heat may cause high summer mortality of dormant HWA (Sussky and Elkinton 2015).

Drought can affect tree pathogens and both increase and decrease tree disease (Desprez-Loustau et al. 2006). The direction and magnitude of the drought-pathogen interaction often depend on the specific host and pathogen, as well as the intensity, duration, and timing of the drought (Schoeneweiss 1986). Schoeneweiss (1986) linked pathogen aggressiveness with water stress and disease development, suggesting that nonaggressive, secondary pathogens produce disease after a threshold of water stress is reached. As pathogen aggression to primary pathogens increases, the effect of water stress on disease development decreases.

To date, most research has focused on interactions between specific hosts, pathogens, and water stress. More research is needed at the stand level on both biotic and abiotic stresses and their role in competition between trees. Two recommendations for forest management are to (1) reduce water stress to trees during drought, and (2) promote healthy trees and environments that discourage damage caused by pathogens (Breda et al. 2006).

Generally, water stress is thought to decrease damage from primary pathogens and increase damage from secondary pathogens (Desprez-Loustau et al. 2006), and this hypothesis generally seems to hold true in the Southeast. However, research is limited, and the interaction between drought and most diseases is unknown, but there are notable exceptions.

Pitch canker, caused by *Fusarium circinatum*, is more likely to infect hosts under periodic moisture stress, and trees at high stand densities are even more vulnerable (Blakeslee et al. 1999, Wingfield et al. 2008). With increasing drought in the future, damage from pitch canker is likely to increase. Heterobasidion root disease, caused by *Heterobasidion irregulare*, will also probably increase in severity with drought because water stress increases the susceptibility of loblolly pine (*Pinus taeda*) to this disease (Redfern and Stenlid 1998, Towers and Stambaugh 1968). Bacterial leaf scorch, caused by *Xylella fastidiosa*, predisposes hosts to canker-causing fungi, and both the bacterial and fungal infections are more severe during drought (Desprez-Loustau et al. 2006, Hopkins 1989, Sherald et al. 1983).

In an apparent exception to the rule, fusiform rust, caused by *Cronartium quercuum* f. sp. *fusiforme,* might cause less damage under drought conditions because drought decreases the available moisture needed for new infections (Desprez-Loustau et al. 2006, Schmidt et al. 1981).

Ink disease caused by *Phytophthora cinnamomi* interacts with drought, but how drought will affect this disease is not clear because impacts vary with the host species (Desprez-Loustau et al. 2006, Lewis and Arsdel 1978, Marçais et al. 1993).

Interactive stress—Stresses often interact because environmental conditions associated with one type of stress often contribute to another. For example, droughts often occur when stationary high-pressure systems develop that prevent moisture-laden, low-pressure systems from bringing rain to an area for an extended period (often months or longer). If nitrogen oxide levels are sufficiently high, stagnant, hot air masses are also conducive to ozone formation. Ozone can damage leaf stomata, increasing tree transpiration and reducing streamflow (Sun et al. 2012). As trees continue to evapotranspire without enough precipitation, soil moisture levels will drop. If the drought persists, soil moisture may be insufficient to maintain tree water demand. As tree moisture declines, oleoresin production may also decline, increasing tree susceptibility to insect attack of the cambial layer. Southern pine beetle outbreaks can occur during periods of tree water stress because the insects are more likely to create egg galleries in the phloem tissue without being pitched out by the resin.

Other interactive stresses may have no direct relation to drought but can predispose a forest to drought stress. For example, nitrogen is often a limiting factor in forest growth (Galloway et al. 2004). Therefore, over most forests (95 percent), the deposition of nitrogen is a benefit to forest productivity and carbon sequestration (Fenn et al. 1998). Added nitrogen can increase leaf area while reducing root mass because less root mass is required to satisfy tree nitrogen demands. As leaf area increases, so does tree water demand, while reduced root mass can reduce a tree's ability to acquire water (McNulty et al. 2014). Thus, although nitrogen deposition increases forest productivity, the morphological response to nitrogen deposition can elevate the risk of mortality during droughts.

Effect of Drought on Key Regional Resource Areas

Drought does not affect all regions or all resources in a region equally. Within the Southeast, Texas and Georgia have historically been the most drought-prone areas, and the resources in these areas will be particularly vulnerable to future drought. In addition to inequitably impacting certain areas, drought impacts also vary by ecosystem service.

To examine how historic droughts have affected forest water yield and gross primary productivity (GPP), Sun et al. (2015b) applied a validated Water Supply Stress Index model to 170 national forests (NFs) in the conterminous United States. The authors selected the top five extreme drought years during 1962–2012, defined as the top five years with the least annual SPI3 (i.e., Standardized Precipitation Index on a 3-month timescale). The extent of extreme droughts, measured by the number of NFs and total area affected by droughts, has increased during the 2000s. The extreme drought during the 2000s occurred in 2002, reducing mean water yield by 32 percent and GPP by 20 percent. On average, the five extreme droughts represented a reduction in precipitation by 145 mm yr^{-1} (22 percent), reducing water yield by 110 mm yr^{-1} (37 percent) and GPP by 65 g C m^{-2} yr^{-1} (9 percent). The responses of forest hydrology and productivity to these droughts varied spatially due to different land-surface characteristics (e.g., climatology and vegetation) as well as drought severity at each NF (figs. 9.9, 9.10). The Southeast has the highest streamflow rates in the United States, so similar losses in precipitation have less impact on streamflow in the Southeast compared to other regions (fig. 9.9).

Recreation and tourism—Recreation and tourism are integral sectors of the economy throughout the Southeast. Many outdoor activities are water-based and are therefore affected by drought. For example, about 12 million people in the Southeast participate in floating activities (e.g., canoeing, kayaking, and rafting), and another 21 million recreationists participate in motorized water activities (USDA Forest Service 2016). The amount of seasonal and annual precipitation, whether as rain or snow, can substantially impact recreational opportunities. Some recreational uses such as swimming, fishing, and boating directly depend on adequate water levels in streams, rivers, lakes, and reservoirs. Other activities such as skiing rely on adequate snowfall. Although less important in the Southeast than in other regions, limited snowfall can result in a modest snowpack, which, as it melts, provides inadequate streamflow to maintain water levels in lakes and reservoirs desirable for recreation. Drought also indirectly affects the level of recreation and tourism in forested areas through impacts on disturbance regimes. Because drought leads to increased risk of fire and forest pests, the resulting loss of forest cover and scenic beauty means fewer forest visitors (Ding et al. 2011). For areas that economically depend on recreation and tourism, the consequences of drought can be lasting. Research to date is limited on the connection between drought events and the recreation and tourism industry (Thomas et al. 2013).

Water levels in lakes and reservoirs directly impact recreational use. At four North Carolina reservoirs, higher water levels throughout the summer and fall led to more visits to the reservoirs and economic gains of millions of dollars per lake per year (Cordell and Bergstrom 1993). Studies of lowered water levels due to sedimentation (Eiswerth et al. 2000) and increased water withdrawal (Neher et al. 2013) showed similar results. Higher water levels in lakes and reservoirs were correlated with more visitation and therefore more tourism expenditures. Consistent with these findings, the 1985–1991 California droughts were correlated with fewer visits to reservoirs in the Sacramento district. As reservoir levels dropped, both day use visits and camping visits declined (Ward et al. 1996).

Although these studies do not show a causal connection between drought and tourism/recreation, the correlational evidence indicates that the conditions associated with drought (e.g., lower water levels) have had a consistent impact on this sector of the economy. The predicted increase in severity of future droughts in the Southeast could lead to a decline in tourism and recreation, and this in turn could negatively affect many areas where the regional economy depends on recreation and tourism dollars.

Water—By definition, drought limits water resources. A lack of precipitation recharge can affect any water resource: a stream, lake, reservoir, or groundwater. In vegetated landscapes in the Southeast, water use by plants (i.e., transpiration and evaporation) consumes a large proportion of precipitation (Vose et al. 2016). After plant water demand is satisfied, excess water becomes streamflow or groundwater recharge. Therefore, a moderate drought may have limited consequences to forest vegetation but a large effect on streamflow and aquatic systems (a.k.a., hydrological drought). The

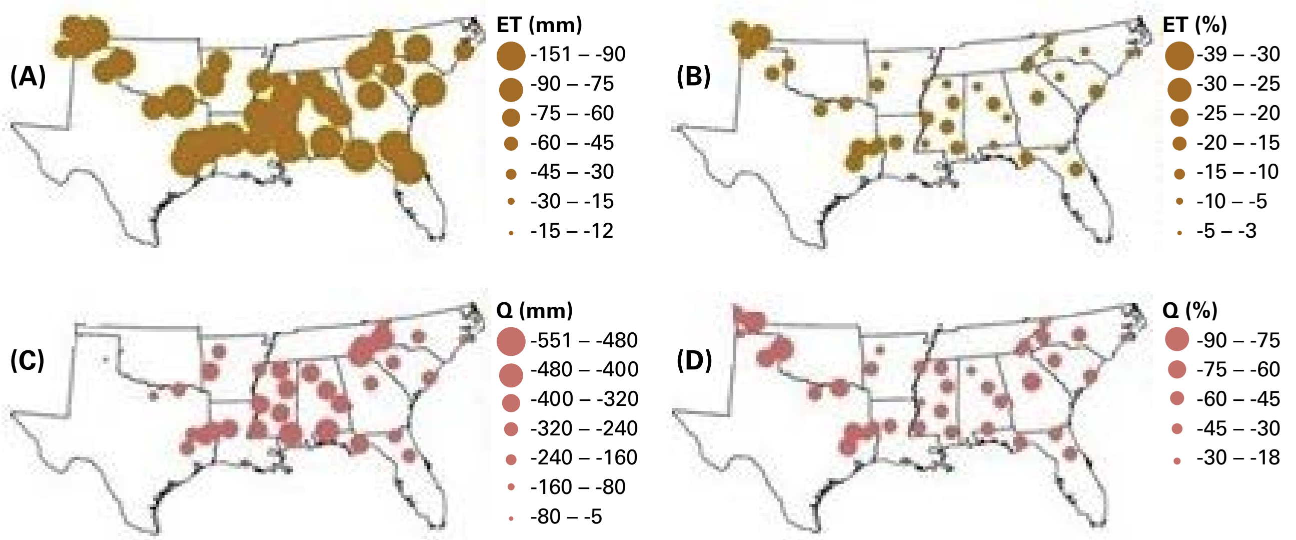


Figure 9.9—Differences in mean annual evapotranspiration (ET) and streamflow discharge (Q) between the years with five most severe droughts and the period 1962–2012. (A) ET difference (mm), (B) ET difference (%), (C) Q difference (mm), and (D) Q difference (%). (Source: Sun et al. 2015b)

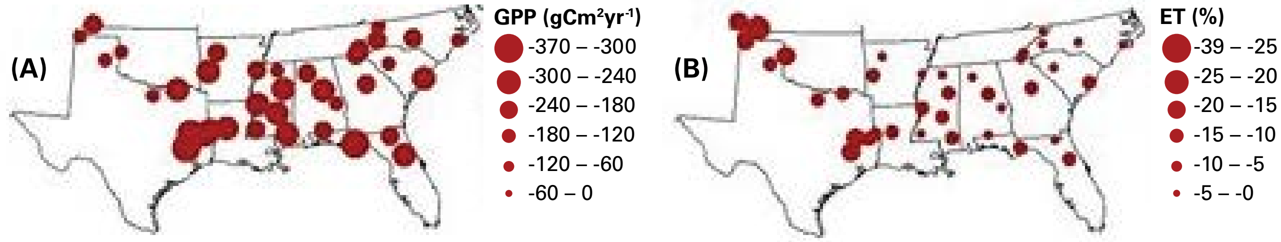


Figure 9.10—Deviations of (A) absolute values and (B) relative values of gross primary productivity (GPP) for the five most severe drought years from the long-term (1962–2012) averages. (Source: Sun et al. 2015b)

lack of precipitation recharge can also deplete shallow groundwater supplies.

Sun et al. (2015b) examined hydrological sensitivity to climatic and vegetation change in the United States using the Water Supply Stress Index (WaSSI) water balance model that runs at a monthly timestep, and a series of hypothetical scenarios. Hydrological responses to external disturbances varied greatly due to regional differences in background climate (i.e., potential ET and precipitation), vegetation (leaf areas index and species), and soils (fig. 9.11). Overall, a temperature increase of 2 °C could decrease water yield by 11 percent. Reductions of precipitation by 10 and 20 percent could decrease water yield by 20 and 39 percent, respectively. The direction and magnitude of water yield response to the combinations of leaf area index (+10 percent), climate warming (+1 °C), and precipitation change (±10 percent) were dominated by the change in precipitation. However, other evidence suggests that a large increase in air temperature (mean temperature >5 °C) due to global warming may offset the influence of precipitation on water supply in the United States by the end of the 21st century (Duan et al. 2017).

Fisheries—Historic increases in ET have resulted from land use intensification in both the agriculture and forestry sectors. These increases have already had a large effect on aquatic ecosystems during drought (Brantley et al. 2017, Golladay et al. 2007, Petes et al. 2012), and this effect may be further amplified by climate change. Streamflow is considered a 'master' variable that controls the ecological structure and function of streams and rivers (Poff and Zimmerman 2010). However, no single measurement can characterize streamflow; instead, multiple variables are used to quantify the magnitude, duration, frequency, timing, and rate of change in both common and uncommon events (e.g., low flows, base flows, and flood pulses) (McNulty et al. 2018, Olden and Poff 2003, Poff et al. 2010). The underlying assumption of this approach is that the maintenance of hydrological

Response of forest water yield to precipitation

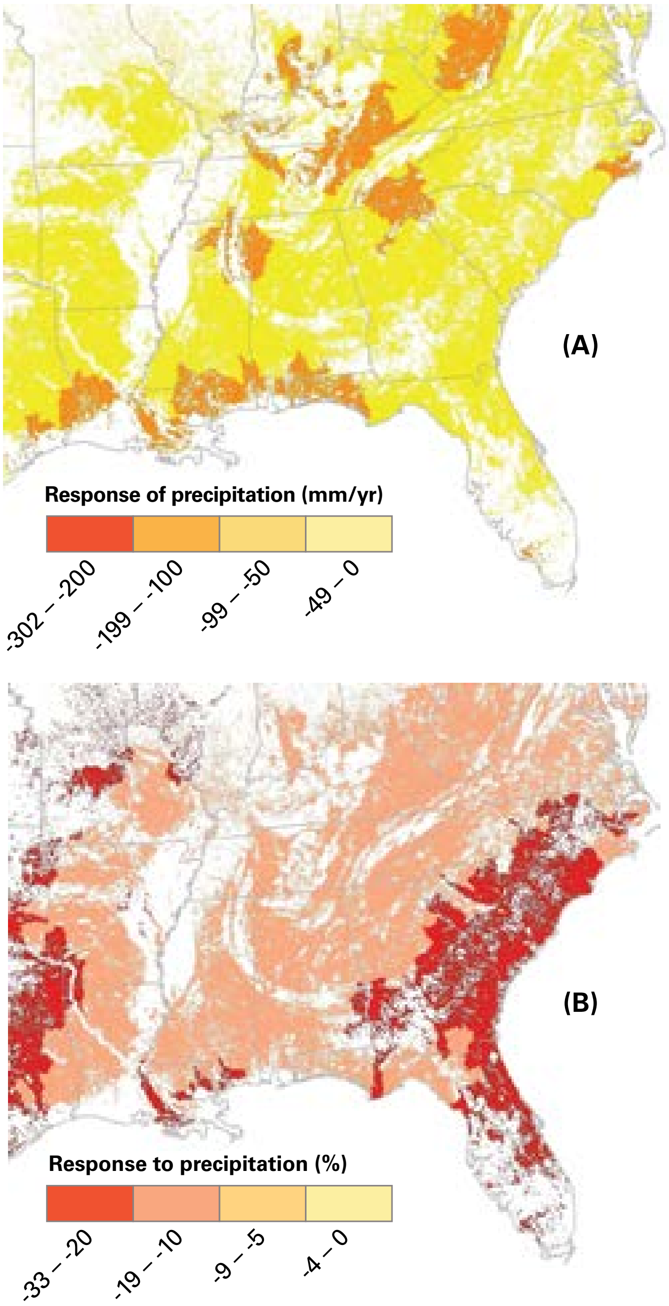


Figure 9.11—Forest water yield response across the United States to a 10-percent reduction of precipitation, as simulated by the Water Supply Stress Index model: (A) absolute values, (B) relative values. (Source: Sun et al. 2015a)

diversity conserves the structure and function of streams and rivers, even with water extraction (Poff et al. 2010). Hydrological diversity is assumed to promote ecosystem services (e.g., biological richness, assimilative capacity, recreation, fisheries) beyond simple water supply (Claassen et al. 2018).

Stream biota respond to drought and drying based on their life history characteristics, adaptations, and physiological tolerances. Traits of interest include dispersal ability, ability to find refugia during dry periods, desiccation-resistant life stages, reproductive rates, and life cycle duration (Griswold et al. 2008). Rheophilic fauna (e.g., brook trout, shoal bass, freshwater mussels) prefer perennial swift-flowing streams; they tend to have longer life cycles, poor dispersal abilities, and poor tolerances for low oxygen and high temperature (Williams 1987, 1996). As a group, rheophiles resist high flows and may even benefit from periodic flooding (Griswold et al. 2008). Rheophobes prefer less flow velocity so that they can better disperse and produce multiple generations per year (Griswold et al. 2008, Smith 2015). Some rheophobes can produce diapausing life history stages and can tolerate lower dissolved oxygen and higher water temperatures than rheophiles. As regional droughts develop, assemblages of aquatic biota may shift from dominance by rheophiles to rheophobes (Griswold et al. 2008, Smith 2015), depending on drought duration, intensity, and frequency.

Reduced summer streamflow and higher stream temperature have implications for ecological communities in rivers. The Southeast is an epicenter of global mussel diversity, and freshwater mussels, a group of regional concern, have already experienced declines in abundance associated with extended droughts (Emanuel and Rogers 2012, Golladay et al. 2004). Declines in sensitive mussel species are expected to continue. Similar drought-related changes in mussel assemblages have been observed in Oklahoma rivers (Allen et al. 2013).

Elevated stream temperatures have also been associated with the displacement of native crayfish by invasive species in the Southeast (e.g., Sargent et al. 2011). Responses of other invertebrate groups in the Southeast are less well understood, but changes in invertebrate assemblage structure, life history characteristics, and environmental tolerance have all been observed in response to drought (e.g., Griswold et al. 2008, Smith 2015). Shifts in fish assemblages would also be expected, with rheophilic species likely to show the greatest declines in response to unusual low flows (Freeman et al. 2012). Lower streamflows in the summer and during extended drought reduce access to and the availability of critical refuges from warm water. In addition to these direct ecological effects, low streamflows also reduce the seasonal volume of water available to receive permitted discharges. On top of these expected ecological changes, increased contaminant discharge may alter river assimilative capacity and increase water treatment costs for downstream users.

Droughts can impact fisheries more than terrestrial ecosystems. If water evaporation rates and outflows (natural or human-caused) exceed inputs, these systems can cause lakes and reservoirs to lose volume. The loss of volume may be accelerated because dry air associated with droughts increases water body evaporation rates. Human-centered demands for water for agriculture and residential irrigation place further stress on existing water supplies.

Wildlife—The effects of drought on upland wildlife in the Southeast are poorly studied. White-tailed deer (*Odocoileus virginianus*) were more selective of forage under drought conditions because fewer types of plants met their nutritional needs (Lashley and Harper 2012). Within a longleaf pine-dominated forest in southwestern Georgia, small mammal populations were heavily influenced by prescribed fire, with cotton rat (*Sigmodon hispidus*) abundance declining precipitously following fire events (Morris et al. 2011). Effects of precipitation among game species are perhaps best illustrated by the northern bobwhite (*Colinus virginianus*). Recent evidence from southern Texas suggests that landscapes with prominent woody cover may buffer drought effects in northern bobwhites; shading by shrubs may increase soil moisture, providing forage and cover during droughts (Parent et al. 2016).

More evidence exists for effects of drought on semi-aquatic wildlife, which depend on seasonally inundated wetlands. Numerous species depend on wetlands for all or part of their life cycle, and many, such as amphibians, are adapted to periodic droughts. These species are able to aestivate in suitable microhabitats within wetlands, move to more permanent water bodies, or have a terrestrial stage that allows them to persist until wetlands refill. However, changes in rainfall in the Southeast, including longer dry periods in summer, may threaten amphibians that depend on seasonally inundated wetlands (Walls et al. 2013a, 2013b). Specifically, these expected changes in rainfall may alter the timing and duration of the wetland hydroperiod. If this occurs, amphibians with an aquatic larval stage cannot completely develop, and the numbers of wetlands suitable for their habitat will decline.

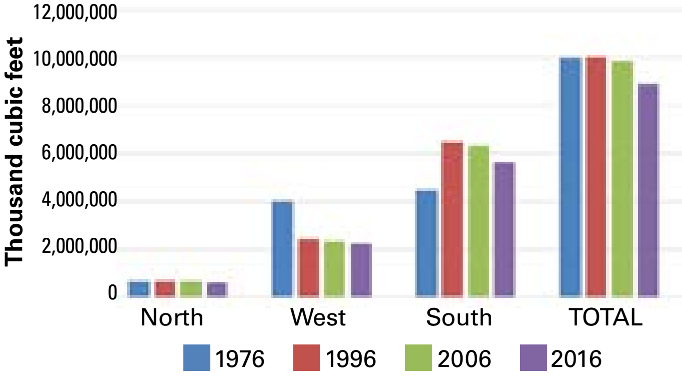
Forest productivity and carbon sequestration—Drought can have consequences for ecosystem services provided by forests, including timber and nontimber resources. Wood fiber in the form of timber, pulp, and fuelwood are important forest outputs across the Southeast. In addition to these traditional forest commodities, carbon sequestration is a more recent area of interest as a process by which climate change can be slowed.

Although more is known about the consequences of droughts in western U.S. forests, where large-scale dieback events have occurred, eastern U.S. forests are also vulnerable to increasing drought (Clark et al. 2016). The effects of drought on southeastern U.S. forests are not well understood, and these effects may vary by species and ecological condition.

For example, tree growth and mortality rates across the Southeast measured from 1991 to 2005 indicate that pines and mesophytic species were more vulnerable than oaks (*Quercus* spp.) to increasing drought (Klos et al. 2009). In contrast, during the worst 1-year drought recorded in Texas (i.e., 2011), pine species coped fairly well relative to oaks and other species groups (Moore et al. 2016). In a recent analysis of regional species vulnerability to increasing temperature and drought, commercially important pine species such as loblolly pine and shortleaf pine (*Pinus echinata*) responded almost as much to drought (i.e., reductions in soil moisture) as they do to availability of light (Clark et al. 2014). Drought has influenced forest regeneration in the Southeast, with larger declines in the growth rate for mesophytic and oak species than for pines (Hu et al. 2017).

Despite uncertainty about specific effects of drought on tree species in the Southeast, the influence of drought on forests is of concern because of the importance of the timber industry in this region (fig. 9.12). Plantations in the Southeast are critical to national supplies of softwood timber, and the region contains the largest area dedicated to planted pines in the United States (Robertson et al. 2011). In 2016, the Southeast provided 63 percent of the national softwood growing-stock removals (fig. 9.12A) and 53 percent of hardwood growing-stock removals (fig. 9.12B). Together, the total

(A) Softwood growing stock removals



(B) Hardwood growing stock removals

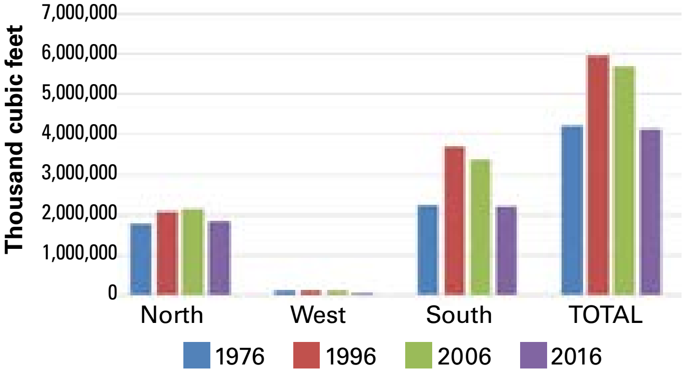


Figure 9.12—Removals of (A) softwood growing stock and (B) hardwood growing stock by region and year (Oswalt et al. 2019).

growing-stock timber removals from the Southeast accounted for 60 percent of all U.S. timber harvests (2017 RPA Database). The plantations of the Southeast are also a source of wood pellets for the European Union. In 2013, <5 percent of total timber removals in the Southeast were used for pellets (Jefferies 2016). Production of both pellets and paper products requires the same kind of timber inputs, so economic theory implies that an increase in the demand for timber in pellet production would cause an increase in small roundwood prices and thus a decrease in paper production. Due to the increased risk of drought, the Southeast timber market could be at risk for potential shortages. Drought impacts on productivity could further limit timber supplies in the upcoming decades (Clark et al. 2014).

The impact of drought on specific tree species in southern forests is uncertain, but the evidence reviewed to date suggests the possibility of declines in forest growth and inventory. For example, an estimated $558 million of standing merchantable trees were killed by the 2011 drought in Texas (Anderson et al. 2012), a substantial loss to forest landowners and roughly double the average stumpage value of timber harvested over the previous 3 years. However, economic analyses of drought impacts on forests are limited.

MANAGEMENT OPTIONS

Strategies and Tactics To Address the Impacts of Drought on Fire and Insect Outbreaks

Projections of increased drought frequency and duration in many regions of the Southeast will present challenges for land managers to reduce the likelihood of wildfire occurrences and limit area burned (Lafon and Quiring 2012, Terando et al. 2016). Fire season length has already shown a significant increase in the eastern U.S. Coastal Plain (Jolly et al. 2015), and several models using global climate scenarios, coupled with indices of fire danger, predict significant increases in wildfire area burned and fire severity in the future (Bedel et al. 2013, Flannigan et al. 2009, Lafon and Quiring 2012, Liu et al. 2012, Mitchell et al. 2014). Wildfire risk is compounded by a growing wildland-urban interface in many areas of the Eastern United States (Wear and Greis 2012). In pine forests, prescribed fire is widely used for multiple benefits, including to reduce fuel loads and to promote fire-tolerant/fire-dependent species/ecosystems such as longleaf pine (Mitchell et al. 2014). Although less widely used, prescribed fire in hardwood forests has been advanced as a tool to favor more drought- and fire-tolerant species such as oaks (Vose and Elliott 2016). Management options to reduce fire risk in the Southeast have mostly focused on reducing fuel loads through frequent prescribed burning (Mitchell et al. 2014). However, additional actions may be required to address limits to the widespread use of prescribed fire due to air quality concerns and unfavorable burn conditions associated with climate change (e.g., too dry, too hot). Examples include reducing fuel loading through planting trees at lower densities, thinning natural stands and existing plantations, reducing live and downed fuels mechanically with mastication treatments, and reducing live fuels with herbicide (McIver et al. 2012). If wildfire becomes more frequent, managers may also need to consider allowing some of these fires to burn to reduce future risk. However, the growing wildland-urban interface will likely limit those opportunities.

Thinning or other preventive silvicultural practices that, among other benefits, reduce vegetative competition for water and improve pine vigor (Guldin 2011, Nowak et al. 2015) may help mitigate drought-related insect damage (e.g., SPB and other bark beetles). During stand establishment on drier/upland sites, planting or regenerating more drought-tolerant species (e.g., longleaf pine instead of loblolly pine) could also help reduce drought-related impacts (Schowalter 2012). However, the conversion of natural forests to pine plantations can reduce tree tolerance to long-term drought (Domec et al. 2015).

Strategies and Tactics To Address the Impacts of Drought on Key Regional Resource Areas

Hydrology—Efforts to mitigate drought impacts on water resources for either ecosystems or people have to target both supply and demand. Thinning can increase water availability for tree growth (Grant et al. 2013) by reducing both stand transpiration and canopy interception. Prescribed burning that kills forest understories may reduce competition for soil water and increase groundwater recharge (Hallema et al. 2017). A study of the effects of potential thinning (i.e., reduction of leaf biomass) on water yield across the United States predicted that, if forests are thinned 50 percent, water yield in the Southeast's low coastal plain area may increase 40–80 percent (Sun et al. 2015a) (fig. 9.13).

In some cases, converting forest cover from coniferous species to deciduous species can reduce total water loss and increase watershed water yield. Species with different xylem structures and of different ages vary in their amount of water use. For example, in the Southern Appalachian Mountains and under the same climate, red oak (*Quercus rubra*) trees with a 50-cm trunk diameter transpire an average of 30 kg of water per day, but black birch (*Betula lenta*) trees transpire as much as 110 kg of water per day (Vose et al. 2011). Thus, to anticipate water supply stress from drought, one option is to use native drought-tolerant species that need less water for growth.

Innovative adaptations are needed to reduce or adapt to severe drought in the context of climate change and variability, as well as to anticipate ecological consequences, such as water supply shortages for forests and people, habitat loss, and increased wildfires (Marion et al. 2013). As the best general adaptation approach to drought, forest management practices are recommended that enhance ecosystem resilience to climate disturbances and maintain ecosystem services, including climate moderation and mitigation.

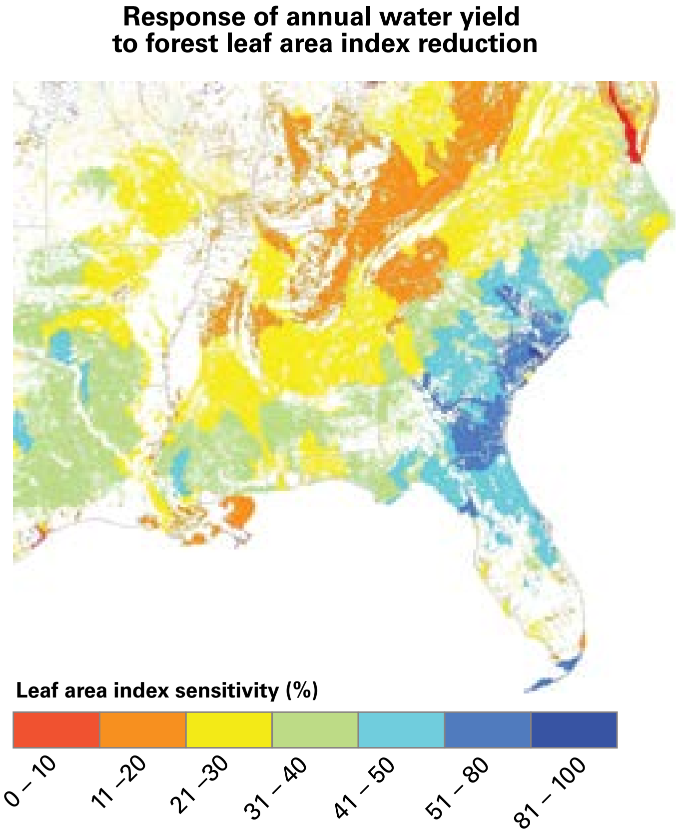


Figure 9.13—Water yield response to 50-percent reduction of leaf area index as simulated by the Water Supply Stress Index model. (Source: Sun et al. 2015a)

Streamflow, fisheries, and aquatic biodiversity—Given the projected expansion in the human population as well as changes in regional rainfall and temperature, managing forests to sustain linked aquatic ecosystems may become a higher priority (Claassen et al. 2018). Under generally accepted climate change scenarios for North America, warmer temperatures and increasingly variable rainfall will result in a trend of hydrological change in many regions. Likely changes could produce more severe drought impacts in many forested watersheds including lower growing-season streamflow. If current rates of water demand persist, then the projected increase in the human population would create even more stress on limited water resources, exacerbating climate effects, particularly during the growing season and during droughts.

To predict drought effects and develop watershed management strategies that maintain aquatic biological diversity and ecosystem function, it is critical for managers to understand and predict biological responses (Richter 2009, Richter et al. 2011). Methods for characterizing riverine hydrological regimes are well developed (e.g., Gao et al. 2009, Olden and Poff 2003). However, information about biotic responses to altered hydrological regimes is site-specific at best and is often lacking (Freeman et al. 2012). Assessment of hydrological change requires long-term streamflow records and a continuous record (typically at least 15–20 years) that spans climate variability and management efforts. Metrics for analysis must have ecological relevance to the biota of the particular stream (Olden and Poff 2003, Poff et al. 2010). What is needed is an ongoing commitment to aquatic monitoring that is equivalent to forest inventory, along with an improved modeling capability that predicts flow responses to landcover change.

Managing forests to protect linked aquatic ecosystems from drought will be challenging and will require a long-term perspective. Fortunately, existing management activities such as forest thinning and prescribed fire, which are already used to improve forest resilience, will likely also reduce total ET. Control or eradication of invasive plant species that increase water use should also be emphasized, although more research is needed on specific impacts of invasives on water budgets (Brantley et al. 2015). Finally, managing forest composition through selective harvest practices that focus on more water-dependent tree species may also be valuable (Brantley et al. 2017, Douglas 1983).

Forest mesophication, defined as the change in forest composition from drought- and fire-tolerant species to drought- and fire-intolerant tree species that use relatively more water (Nowacki and Abrams 2008), has negative effects on water yield (Caldwell et al. 2016). Reversing this trend through management would improve the resilience of linked aquatic systems by reducing ET. Tree species with higher stomatal sensitivity to drought conditions, such as longleaf pine, might also be favored in some management applications.

Although forest managers inherently focus on management activities that improve tree growth and reduce tree mortality from drought, strategies are also needed to mitigate effects of drought on linked aquatic ecosystems. Small streams that originate from forested watersheds and geographically isolated wetlands embedded within forested landscapes are intimately connected with forest processes and can be highly sensitive to drought.

The positive link between forest cover and water quality is well known, but not all southeastern forests are equal at promoting water quantity (Brantley et al. 2017, Caldwell et al. 2016). Forest management can promote higher water yield and thereby contribute to higher stream runoff and a longer wetland hydroperiod (Douglas 1983, Ford et al. 2011). Reducing forest ET through management is particularly critical during dry years. Stand-level ET tends to show relatively little interannual variation compared to rainfall (Oishi et al. 2010), and variations in precipitation tend to be reflected more strongly in water yield.

Wildlife—Management options to maintain wildlife biodiversity during drought depend on the specific habitat on which wildlife depend. Wetlands, including geographically isolated wetlands (GIWs), represent critical wildlife habitat in the Southeast. Many of the same concepts that relate forest management activities to streamflow are also relevant to maintaining wetland hydroperiod (Jones et al. 2018) and thus the quality of wetland habitat.

Geographically Isolated Wetlands may be more susceptible to surrounding landcover change than streams or other wetland types due to their relatively small volume and limited watershed area. For example, vertical water infiltration and shallow groundwater transport, rather than surface runoff from rainfall, are thought to control water levels in wetlands in undisturbed pine forests (Clayton and Hicks 2007). However, when hardwood trees become established within and around wetlands, transpiration can increase, significantly reducing subsurface flows to the wetland and shortening hydroperiod (Clayton and Hicks 2007). Upland land management may affect wetland hydroperiod in much the same way that it affects streamflow, but at more localized scales. Forest management practices (e.g., thinning, fire reintroduction, species selection) that reduce ET in the contributing area of GIWs or alter the timing of ET (e.g., favoring evergreens over hardwoods) have the potential to affect wetland hydroperiod, which may ameliorate effects of drought for wildlife dependent on these habitats.

Relationships between drought, forest management, and terrestrial wildlife are weaker. Thus, management prescriptions are harder to specify. Favoring woody plants with low ET may mitigate drought effects in some terrestrial wildlife populations in the Southeast during a drought (Parent et al. 2016). Some woody species may also redistribute groundwater to surface soils through hydraulic lift, where the water can be taken up by herbaceous vegetation (Domec et al. 2012, Espeleta et al. 2004) and possibly provide increased moisture in forage. More research is needed on drought effects on terrestrial wildlife populations and how forest management may mitigate those effects.

As climate change intensifies the length and severity of droughts in the Southeast, wildlife managers in this region may need to adopt techniques used in the Western United States to provide water to drought-stricken terrestrial wildlife (Bleich et al. 2005, 2006; Glading 1947). In addition to logistical issues, providing water sources during periods of drought may create other management concerns. For example, wildlife would be expected to congregate at watering sources, much as they concentrate at wildlife feeders. This increased concentration of wildlife may increase predation risk (Cooper and Ginnet 2000, Jones et al. 2010) and the likelihood of disease transmission (The Wildlife Society 2006). Before widespread application of artificial watering sources is considered, potential tradeoffs such as these should be identified and their risk quantified to guard against unintended consequences.

Timber resources—To mitigate economic losses, management strategies include reducing rotation age, diversifying stand species to include drought-resistant species, thinning, and intensification of stand management (Clark et al. 2016, Klos et al. 2009, Sohnhen and Tian 2016). For example, longleaf pine may confer more drought tolerance compared to loblolly or slash pine (*Pinus elliottii*) due to longleaf pine's more efficient hydraulic structure (Samuelson et al. 2012).

Longleaf pine forests were once a dominant forest ecosystem in the Southern United States, covering tens of millions of ha (Oswalt et al. 2012). During the 18th century, longleaf pine forests were valued for providing naval stores (e.g., tar, pitch, and turpentine) for the British navy (Outland 2004, Perry 1968). In the mid- to late 1800s, improved harvesting (i.e., water-powered sawmills) and timber transportation technology (i.e., steam skidders and railroads) increased the harvests of highly valued longleaf pine timber. The introduction of pulp mills in the 1950s favored trees that grew rapidly. Any second-growth longleaf pine stands were clear-cut and replanted with loblolly pine or slash pine due to their faster initial growth rates. Intensified timber production, along with the conversion of stands for agriculture and urban development, resulted in a loss of >95 percent of the initial land area of longleaf pine forests by 1990 (Oswalt et al. 2012).

There is now renewed interest in restoring longleaf pine for wood products, pine straw, wildlife, and biodiversity benefits, which has led to the creation of the America's Longleaf Restoration Initiative (ALRI). America's Longleaf Restoration Initiative is a collaboration of public and private partners who seek to create and conserve "functional, viable longleaf pine ecosystems with the full spectrum of ecological, economic, and social values inspired through a voluntary partnership of concerned, motivated organizations and individuals" (America's Longleaf 2009). The overall goal of ALRI's conservation plan is to increase longleaf pine acreage from 3.4 million to 8 million acres by 2025.

Integrating drought risk into land management planning—Efforts to restore ecological integrity are necessary strategies to increase drought resilience, particularly where current drought regimes are still within historical ranges of variation and future changes are highly uncertain. The restoration of longleaf and shortleaf pine ecosystems is a broad effort organized across the historic range of both ecosystems. Both longleaf and shortleaf pine provide numerous benefits for responding to current and future climate change, including resistance to wildfire, increased productivity during drought periods, and increased disease and pest resistance (Boensch 2016, Slack et al. 2016).

In addition to ecosystem restoration, significant effort in the Southeast focuses on improving general forest health across national forests and private lands. This effort has significant benefits for drought resilience because reducing forest density through thinning is the most common drought prevention practice. For example, the Southern Pine Beetle Program was developed after major outbreaks in 1999–2003 that caused >$1 billion of damage (USDA Forest Service 2017b). The program has since accomplished >1 million acres in SPB treatments (e.g., thinning, prescribed burning [USDA Forest Service 2005]) across private and public ownerships. This program is a successful model for how forest health strategies can be applied across large geographic areas to produce multiple benefits.

The periodic development of land management plan revision is required under the National Forest Management Act (USDA Forest Service 1976) and directed by the Planning Rule (USDA Forest Service 2012). These guidelines provide the necessary framework to assess and plan for drought, including the development of adaptive management strategies to promote ecological integrity and resiliency. The planning process is highly collaborative, with emphasis on coordinating with research and development partners to address drought and other climate-related stressors (case study; table 9.1).

As Federal land management plans are implemented through projects across the landscape, opportunities are presented to integrate drought management into the projects' purpose and need, including identifying resources that are particularly sensitive to drought. This integration is especially important in regions like the Southeast, where drought is becoming increasingly variable. Therefore, there is a need to identify change, and appropriate responses include proposed actions, development of alternatives, and analysis of effects. Sectors affected by drought that may benefit from departure analysis involve terrestrial and aquatic ecosystems; watersheds; air; soil and water resources; threatened, endangered, and proposed candidate species; social, cultural, and economic conditions; recreation; and infrastructure (USDA Forest Service 2012).

Table 9.1—Potential adaptation options for managing forest hydrological impacts (quantity, quality, timing) and ecosystem risks in response to hydrological drought

HYDROLOGICAL IMPACTS	RISK TO ECOSYSTEMS AND SOCIETY	ADAPTATION OPTIONS
Increased water supply stress	Water shortage; drying up of drinking wells; degradation of aquatic ecosystems with impacts on socioeconomics and business	Maintain watershed health; thin forests; reduce groundwater and surface water use for irrigation of croplands and lawns; enhance water conservation
Decreased transpiration	Reduced tree growth and productivity; tree mortality	Use native tree species; reduce tree stocking; irrigate
Increased soil evaporation	Hydrological droughts; wildfires; insect and disease outbreaks	Mulch; use solid waste applications in plantation forests
Decreased base flow	Water quality degradation; loss of fish habitat; reduced transportation capacity	Reduce off-stream water withdrawal; adjust water outflow from reservoirs; reclaim wastewater
Changes to wetland hydroperiod	Wildlife habitat loss; CH_4 and CO_2 emission change	Plug ditches; adjust water outflow from reservoirs
Higher streamwater temperature	Water quality degradation; loss of cold-water fish habitat	Maintain riparian buffers and shading
Increase in soil erosion from vegetation degradation; increased sedimentation	Water quality degradation; siltation of reservoirs; increased water treatment cost	Enhance forest road best management practices; redesign riparian buffers
Increased pollutant concentrations	Water quality degradation; increased water treatment cost	Maintain streamflow quantity; use forest best management practices

Source: Marion et al. (2013).

CASE STUDY

Francis Marion National Forest: Creating a master plan for drought

The Francis Marion National Forest (FMNF) in the coastal plain of South Carolina integrated drought adaptation into its recently revised land management plan (USDA Forest Service 2017a). This case study illustrates how creating a master plan to manage for drought and climate change could affect management decisions in a number of forest sectors.

The first phase of this process was to complete an assessment. Guided by the Agency's Planning Rule (USDA Forest Service 2012), the assessment consisted of three components: (1) key ecosystem characteristics, (2) developing plan components, and (3) developing monitoring. The planning team evaluated current conditions and trends using the comprehensive land management plan framework previously stated. Climate variability, in general, and drought in particular, were recognized as important ecosystem drivers and stressors. The presence of diverse native ecosystems, particularly the longleaf pine ecosystem, was recognized as a critical component of ecological integrity and sustainability. A key finding of the assessment was the need to respond to ecological challenges, including drought, thus necessitating changes to the land management plan.

Key ecosystem characteristics—The planning team recognized drought and other climate-related stressors as key ecosystem characteristics within the ecological framework required for planning. This laid the groundwork for addressing drought during the development of the plan, including through monitoring and adaptive management strategies.

Developing plan components—Drought was directly incorporated into the FMNF plan by specifying key characteristics desired for ecological integrity and explicitly identifying the influence of drought on specific ecosystems (table 9.1). These descriptions were designed to help planners and managers recognize the effects of drought as a disturbance process, which is necessary to maintain the function, structure, and composition of the ecosystem, and hence ecosystem sustainability. Although drought was identified as an important driver of forest structure and function in FMNF and the surrounding landscape, the assessment found that postdrought conditions typically return to normal quickly and vegetation recovers accordingly. Therefore, the plan supplied land managers with useful information regarding drought management, including the fact that drought management options for the FMNF are not necessary for all drought occurrences.

Developing monitoring—Given the importance of drought in the FMNF ecosystem, the plan's monitoring program described indicators of climate change, including drought, and proposed adaptive management strategies to address potential drought impacts (table 9.2). Studies (e.g., Ahmadalipour et al. 2017, Sheffield and Wood 2008) suggest that drought could become more frequent and severe in the future, therefore necessitating the need to monitor for drought impacts in the FMNF. Monitoring for drought impacts could provide early detection of change in the ecosystem and the need to implement adaptive management strategies.

Table 9.2—Plan-level monitoring question from the Francis Marion National Forest Plan that addressed climate variability and drought through indicators (I) relevant to the scale of evaluation, with relevant sources/partners and adaptive management strategies shown for each indicator

Monitoring Question: Is climate change, including changes in drought frequency and severity, influencing maintenance and ecosystem restoration?

INDICATORS (I)	SOURCES/PARTNERS	ADAPTIVE MANAGEMENT STRATEGIES
(I-1) Trends in climate, including extremes, disturbance patterns, and long-term ecological processes	National Oceanic and Atmospheric Administration (NOAA) – State of the Climate Reports NOAA – U.S. Climate Extremes Index NOAA – Severe Weather Data Inventory South Carolina Drought Response Committee Remote sensing and change detection products (e.g., ForWarn)	**Alert:** Increasing trends in frequency/magnitude of climate extremes and related disturbance **Response:** Strengthen disturbance response capabilities and assess implications during project development
(I-2) Trends in forest health status and risk	Forest Health Technology Enterprise Team (FHTET) Forest Pest Condition FHTET National Insect and Disease Risk Map University of Georgia, Center For Invasive Species and Ecosystem Health – Early Detection & Distribution Mapping System	**Alert:** Nonnative invasive species introductions/increases in forest health risk **Response:** Rapid detection and treatment
(I-3) Trends in fire return intervals and seasonality	Monitoring Trends in Burn Severity (MTBS)	**Alert:** Inability to meet desired fire return intervals **Response:** Adjust prescribed burning schedules and take advantage of desirable conditions
(I-4) Status and trend of isolated wetlands	Natural Resources Conservation Service groundwater monitoring	**Alert:** Wood encroachment/changes in hydrology **Response:** Vegetation management if feasible/hydrological restoration
(I-5) Status of frosted flatwood salamander habitat		**Alert:** Habitat degradation or loss due to climate influences **Response:** Promote amphibian habitat through the placement of coarse woody material piles and other features that retain moisture during dry periods
(I-6) Focal species: longleaf pine, red-cockaded woodpecker, Bachman’s sparrow, pitcher plants, and American eel		**Alert:** Declines attributable to climate influences **Response:** Species specific

Note: Measurable changes on the plan area related to climate change and other stressors.

Source: USDA Forest Service (2017a).

CONCLUSIONS

Drought has always been integral to ecosystems in the Southeast (Seager et al. 2009). Associated natural wildfires during periods of drought have helped to maintain natural open ecosystems and promote biodiversity (Christensen 2005). Since the 1900s, climate change and climate variability have added to the existing variability of regional drought. Although parts of the region experienced little or no increase in air temperature during much of the 20th century, the entire Southeast is now seeing warming air temperatures relative to historic levels (IPCC 2014). Even when precipitation does not change, higher air temperatures increase ecosystem water loss, and this is exacerbated by associated increases in ET in vegetation (e.g., forest, grassland, agricultural lands) and water body evaporation (Diffenbaugh et al. 2015).

A growing human population and the corresponding increase in water demand (McNulty et al. 2008) further complicate drought in the Southeast. Water is one of the primary ecosystem services that forests can provide, and with proper care, forest water can continue to be a resource in the future. However, even if drought conditions remain constant, water shortages will probably worsen for commercial, agricultural, residential, and industrial use. To prepare for unexpected droughts, forest management adaptation practices are needed now and will be needed even more in the future.

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CHAPTER 10

Managing Effects of Drought: Key Messages and Conclusions

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Changing drought conditions in the remainder of the 21st century will present significant challenges for natural resource managers as they plan and implement actions to increase the adaptive capacity of the Nation's forests and rangelands to resist and recover from current and future droughts. The combination of warmer temperatures and more variable precipitation regimes across most areas of the United States suggests that although the nature of drought (magnitude, timing, duration) will differ among and within regions, most forests and rangelands will be affected by more frequent and/or intense drought by the end of the 21st century (chapter 2).

In areas where meteorological drought is common, forest and rangeland species have the capacity to survive most droughts through a variety of mechanisms that mitigate drought impacts and facilitate recovery (e.g., deep rooting, leaf shedding, stomatal regulation). However, new drought regimes (e.g., droughts combined with warmer temperatures) may overwhelm this capacity, causing lower vegetation productivity and increasing vegetation mortality, with far-reaching effects on ecosystem conditions and services. Areas where droughts are currently uncommon may be especially vulnerable because species that are not well adapted to drought may be greatly affected by even minor droughts. Secondary impacts of drought, such as more frequent and larger wildfires and large-scale insect outbreaks, may have even greater impacts (magnitude and spatial extent) than direct drought effects. Hydrological drought is a major concern in areas dependent on reliable flows of surface water for aquatic species and habitats, groundwater recharge, and drinking water supply.

Most of the chapters in this General Technical Report discuss management options for minimizing the adverse impacts of drought when they occur, facilitating postdrought recovery, and creating ecosystem conditions that might help minimize impacts of future droughts. For forests, a common theme among regions is reducing water demand by managing stands at a lower density and favoring species that either require less water or can tolerate drought. In many ways, this proactive approach essentially allows active management to guide and facilitate changes in forest conditions that would likely occur without management. For example, wildfires, insect outbreaks, tree mortality, and reduced growth and reproduction of drought-intolerant species are likely to create reduced stand density and favor drought-tolerant species over the long term. However, undesirable outcomes such as loss of forest products and carbon storage, risks to humans and property in the wildland-urban interface, and reduced water quality are more likely without management. Responses to hydrological drought include restoring riparian areas and wetlands to improve functionality, ensuring that aquatic habitats for fish and other organisms provide refugia and passage during low streamflow conditions, and carefully managing consumptive uses during droughts for livestock grazing, recreation, agriculture, and drinking water supplies.

Riparian restoration helps to maintain water quality and quantity during drought events. (Photo by Kirsten Severud)

For drought management strategies to be most effective, timely implementation is needed across large spatial scales. Optimal responses can be developed by integrating existing policies and practices with new information and by timely reporting of current conditions. Coordination by Federal agencies with other agencies and stakeholders is needed for effective management of drought effects across large landscapes. If drought-informed thinking is institutionalized as part of agency operations, then planning and management will be more effective, and "crisis management" in response to drought can be avoided.

This report provides a range of regionally specific management options that can help natural resource managers anticipate and respond to current and future droughts. Despite large differences in biophysical conditions across regions, many of the concerns and potential management responses are similar. Key messages from the regional chapters are summarized below.

Mountains in Sonoran Desert, California. (Photo by Gerald Holmes, California Polytechnic State University at San Luis Obispo, Bugwood.org)

ALASKA AND PACIFIC NORTHWEST (Chapter 3)

- Water is important for wildlife and people, providing critical habitat for salmon, which are culturally and economically valuable species.
- Timber production has declined in recent decades, and recreation has emerged as a major revenue source.
- Across both regions, rising temperatures, decreasing snowpack, and less summer water availability will affect both people and ecosystems in the future.
- 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.
- Limiting livestock, fishing, and recreational uses in key habitats, and removing physical and biological barriers to fish movement, will help fish survive when streamflow is low.
- In dry forests characterized by historically frequent fire, decreasing stand densities and hazardous fuels can increase resilience to drought and fire by mitigating the effects of past fire exclusion.
- Addressing altered fire regimes, overgrazing, and invasive species will help to maintain rangeland productivity and ecosystem resilience under changing conditions.

CALIFORNIA (Chapter 4)

- Extreme droughts will become the norm by the middle of the 21st century, but even moderate droughts can have significant, long-lasting effects on the structure and function of ecosystems.
- Management options for addressing drought impacts vary by ecosystem, but goals are to (1) shift systems back within the natural range of variation (including disturbance regimes) to the degree possible and (2) facilitate a transition to plant species better adapted to future droughts.
- In forests and woodlands, drought management focused on the use of mechanical thinning and prescribed burning will decrease stand densities and promote the growth and vigor of desirable tree species.
- In chaparral, frequent disturbances are stressors, so soil disturbances need to be limited as much as possible to reduce the spread of invasive, nonnative annual plants that promote wildfires. Invasive plants are also a major problem in grasslands, where they should be removed and replaced with native grasses and forbs, if possible.
- In grasslands, prescribed fire may be useful to manage nonnative species and increase perennial plant cover to make grasslands more drought resilient. In rangelands used for livestock grazing, conservative stocking rates, supplemental feeding, and resting pastures can be considered during times of drought.
- For drought management strategies to be most effective, timely implementation is needed across large spatial scales.
- As the frequency and magnitude of droughts increase, our ability to better quantify and project impacts on ecological and human systems, and to develop and implement appropriate management actions, will become more critical.

HAWAI‘I AND U.S.-AFFILIATED PACIFIC ISLANDS (Chapter 5)

- Future temperatures in Hawai‘i and U.S.-Affiliated Pacific Islands (USAPI) are expected to increase, and the trade wind inversion is projected to become more frequent, resulting in drying, particularly at high elevations. Even if rainfall does not change, drought severity and frequency will increase because of higher evaporative demand.
- Drought increases the risk of wildfire in grasslands and savanna vegetation, which then increases the vulnerability of adjacent forest. The capacity of native

Continued drought conditions in the Marshall Islands force many to rely on freshwater filling stations. (Photo courtesy of the Marshall Islands Journal)

forests to recover afterward can be reduced by the rapid establishment of nonnative species, many of which increase the probability of future fires.
- Preparing for wildfire before a drought is critical to mitigate drought impacts. Preparation includes (1) building up or maintaining fire suppression and emergency responder capacity and readiness and (2) preparedness at the level of individuals, households, communities, and large landowners and land managers.
- Extreme drought reduces streamflow and groundwater levels. Lower groundwater levels exacerbate the potential for saltwater intrusion and can degrade drinking water wells and nearshore and marine ecosystems that rely on the discharge of fresh groundwater.
- Continued drought conditions force many populations—suppliers of municipal drinking water, domestic users, and agricultural irrigation systems—to rely on more expensive delivery from groundwater sources.
- The most important aquifers in the region consist of freshwater lenses floating on denser seawater, and the groundwater in these aquifers is sustained by deep percolation of rainfall.
- Management options for preparing for water shortages include increasing water capture and storage capacity, improving delivery efficiencies, securing alternative water sources, improving end-user efficiencies, and providing education and outreach.
- Many communities in Hawai‘i and the USAPI rely on traditional knowledge developed over thousands of years and on the resulting community-based approaches, practices, tools, and institutions that have supported communities during drought periods from the distant past into the present.
- Management will need to expand efforts to engage multiple interacting stressors: invasive species, altered fire regimes, altered climate regimes, insects, and pathogens.

INTERIOR WEST (Chapter 6)

- High temperatures, low snowpack, and low water availability in summer will affect both people and ecosystems in the Interior West more frequently in the future.
- Planning for and adapting to the likelihood of increasing frequency and duration of droughts are needed to minimize negative effects on species, ecosystems, and ecosystem services, and to facilitate a transition to different climatic conditions in the future.
- The diversity of the Interior West’s climate, biogeography, and socioeconomics means that drought occurrence and effects will vary greatly from north to south and from year to year.
- The first, best, and often least costly means of increasing resilience to drought are to reduce existing stressors and improve the current condition (“health”) of ecosystems.
- Pre-emptive actions that create benefits for multiple resources are valuable, especially actions that increase the quantity and duration of water availability.
- Reconnecting floodplains with side channels and restoring populations of American beaver contribute to retaining water during the summer, benefit water supply for agriculture and municipal watersheds, maintain productivity of riparian areas, and maintain high-quality fish habitat.
- In dry forests, the effects of past fire exclusion can be addressed by reducing stand densities and hazardous fuels to increase resilience to drought and fire.
- In rangelands, management responses to altered fire regimes, overgrazing, and invasive species will help maintain productivity and benefit livestock grazing, native ungulates, and many other animal species.
- The organizational capacity of Federal agencies to respond effectively and quickly is key to successful management of current and future drought conditions.
- Best management practices for water and climate change vulnerability assessments provide scientific information as the basis for decision making, as well as options that can be implemented to reduce drought impacts.

GREAT PLAINS (CHAPTER 7)

- As the climate continues to warm in the future, weather in the Great Plains is expected to become increasingly variable, and drought is expected to occur more frequently.
- Rangeland management differs based on local conditions, but core principles remain, primarily restoration or maintenance of diverse native species that nurture belowground ecosystem health and facilitate a range of species tolerances to meet changing conditions, including drought.
- Protection of the soil resource will maintain water-holding capacity and support vegetation cover, thus attenuating drought effects.
- Wildfire and variable-intensity grazing are primary disturbances in rangelands and provide mechanisms to increase vegetation heterogeneity.
- Numerous strategies are available for livestock producers to prepare for drought and buffer economic volatility, ranging from conservative stocking to economic diversification.
- Although economic downturns provide disincentives to reducing stocking rates, delayed response to drought may degrade rangelands if high stocking levels are decoupled from forage production, resulting in long-term productivity declines, which makes retention of a core herd more challenging.
- Information about drought scale, severity, and forecasts improves decisions on how to balance short-term gains and losses against risk of damage to future productivity.
- Communication among livestock owners, grazing association boards, governmental agencies, and other stakeholders will help achieve favorable outcomes during drought years, facilitating a return to profitability and sustainability.
- Proactive practices increase management options and flexibility, and collaboration and positive relationships are crucial for planning processes before, during, and after drought.
- Successful practices can inform the next cycle of preparation for drought, a process that needs to become embedded in management of rangelands.

NORTHEAST AND MIDWEST (Chapter 8)

- Climate change projections suggest that the frequency and severity of drought will likely increase in this region in the future, especially under "worst case" climate change scenarios.

Prescribed fire in grasslands makes them more drought-resilient. (Photo by Catherine J. Hibbard, U.S. Fish and Wildlife Service)

- The potential response of different tree species and whole ecosystems to higher moisture stress is unclear, largely because of the historical lack of drought in the Northeast and Midwest.
- Based on climate change projections, future forest responses to drought could include mortality of sensitive species, shifts in forest composition toward more drought-tolerant species (including nonnative species), and potential migration of tree species into more suitable habitats outside of current geographic ranges.
- Such drought-related effects could affect many ecosystem services, including timber and nontimber products, water supply, carbon sequestration, wildlife habitat, and cultural benefits.
- Forest thinning may be an important management strategy to enhance resilience during drought, even in humid parts of the Northeast.
- Using silvicultural systems that promote high species diversity may enhance the sustainability of forest production under changing climate regimes.
- To promote the establishment of individuals that are more likely to survive and adapt to more frequent future drought, seeding and planting genotypes or species considered better adapted to soil moisture deficit is preferred over natural regeneration.
- Although the Northeast is currently relatively wet and not moisture-limited, forest managers are likely to face new challenges related to water availability.
- Although managing water resources is typically not the primary forest management objective, many best management practices for forests are designed to maintain water supply and quality.
- Efforts to prepare forests for uncertain future conditions are needed concurrently with measures to reduce the rate of climate change.

SOUTHEAST (Chapter 9)

- Despite projections that precipitation will increase throughout most of the Southeast, drought frequency and intensity are projected to increase throughout the 21st century
- Severe droughts increase the risk of high-severity wildfires that are costly to suppress; suppression costs are 25-percent higher than average during drought years.
- Projections of increased drought frequency and duration in many areas of the Southeast will present challenges for land managers to reduce the likelihood of wildfire occurrence and area burned.
- Management options to reduce fire risk in the Southeast have mostly focused on reducing fuel loads through frequent prescribed burning. Additional actions include reducing fuel loading through planting at lower densities, thinning natural stands and existing plantations, reducing live and down fuels mechanically with mastication treatments, and reducing live fuels with herbicide.
- Thinning or other silvicultural practices that improve pine vigor may help mitigate drought-related impacts by southern pine beetle and other bark beetles.
- Planting or regenerating more drought-tolerant species (e.g., longleaf pine instead of loblolly pine) could help reduce drought-related impacts.
- Restoration of longleaf pine and shortleaf pine ecosystems is a broad effort organized across the historical range of both ecosystems. Both longleaf pine and shortleaf pine provide numerous benefits for responding to current and future climate change, including resistance to wildfire, higher productivity during drought periods, and higher disease and pest resistance.
- Thinning can increase water availability for tree growth by reducing stand transpiration and canopy interception.
- As climate change intensifies the length and severity of droughts in the Southeast, wildlife managers in this region may need to adopt techniques used in the Western United States to provide water to stressed terrestrial wildlife.


Loblolly pine (*Pinus taeda*) in Alabama. (Photo by David Stephens, Bugwood.org)

NEXT STEPS

Information presented in this report demonstrates that much is known about how forests and rangelands respond to drought and about options available for responding to current and anticipated drought. However, long-term impacts are uncertain, suggesting a need for monitoring and ongoing learning to adjust management actions and goals over time. We contend that effective natural resource managers must be an intelligent component of the ecosystem who are able to learn and use information on trends and responses to disturbance, anticipating future conditions and developing robust management decisions over time. This is challenging because new drought regimes may create conditions that are different than those observed in the past. The ability to anticipate responses to drought, and to change course if anticipated drought effects do not occur, will be critical for effectively sustaining ecosystem services.

The following strategic actions will help to institutionalize awareness of drought effects and drought responses in forest and rangeland management:

Establish and maintain relationships with providers of drought information

Federal agencies such as the National Oceanic and Atmospheric Administration (National Integrated Drought Information System; https://www.drought.gov) provide data and maps on current and projected drought in the United States. State agencies, some universities, and other organizations provide data and maps at smaller spatial scales that may be more customized to local interests and needs. Although simply referencing drought data online is useful, establishing working

Sandbar willow (*Salix interior*) in Ohio. (Photo by T. Davis Sydnor, The Ohio State University, Bugwood.org)

relationships with data providers will ensure that the information is clearly understood and used appropriately in planning and management.

Include drought in collaborative efforts among agencies and stakeholders

Drought is generally so pervasive that it will affect multiple ownerships in any given region. Many resources overlap boundaries, including water and wildlife, as do large disturbances such as wildfire. Therefore, stakeholders and organizations engaged in resource management will be more effective in minimizing the impacts of drought if they work together to plan for and implement responses.

Revise best management practices as needed

Best management practices (BMPs) for water resources, vegetation, infrastructure, and other resource areas are part of the standard toolkit used by public land managers. This is particularly true in range management, for which BMPs have been developed by Federal agencies to specifically address drought impacts. Development of drought-informed BMPs across all resource areas will provide science-based options that can be referenced and applied in a timely way when drought occurs. In most cases, this will require fine tuning of existing practices, rather than a major change.

Implement drought in relevant planning processes

Public land management agencies organize their operations around various types of planning documents. For example, each national forest in the Forest Service has a land management plan (“forest plan”) that guides the administration of the forest and its management of natural resources; these plans are periodically revised and amended. Agencies also have vegetation management plans, restoration plans, road and infrastructure maintenance plans, and other types of documents that guide specific functions at various spatial and temporal scales. Including drought as a discrete component within these plans will ensure that drought impacts are recognized, response options are available, and response options can be implemented in a timely way.

Establish long-term monitoring of drought effects

Although the general effects of drought on water resources and vegetation are well known, they are not as well known for fisheries, wildlife, recreation, and other ecosystem services. Scientific data on specific conditions in any particular location are needed in order for land managers to document impacts and develop potential management responses. These data are needed over multiple years because some impacts may be cumulative or alternatively may dissipate if moisture availability improves. Long-term monitoring that identifies representative landscapes and employs robust data collection will ensure that drought impacts are accurately quantified. Monitoring drought impacts can generally be integrated within existing monitoring programs.

Share information on effectiveness of drought responses

Monitoring programs as described above need to include an evaluation of the short-term and long-term effectiveness of drought management options that have been implemented. This will guide future application of management responses for any particular location. In addition, sharing information about the effectiveness of drought management within and among agencies, Tribes, the private sector, and stakeholders will help to propagate effective, consistent practices across large landscapes. Shared learning regarding drought can be institutionalized through regional meetings, professional organizations, and online networking.

Vose, James M.; Peterson, David L.; Luce, Charles H.; Patel-Weynand, Toral., eds. 2019. Effects of drought on forests and rangelands in the United States: translating science into management responses. Gen. Tech. Rep. WO-98. Washington, DC: U.S. Department of Agriculture, Forest Service, Washington Office. 227 p. https://doi.org/10.2737/WO-GTR-98.

Most regions of the United States are projected to experience a higher frequency of severe droughts and longer dry periods as a result of a warming climate. Even if current drought regimes remain unchanged, higher temperatures will interact with drought to exacerbate moisture limitation and water stress. Observations of regional-scale drought impacts and expectations of more frequent and severe droughts prompted a recent state-of-science synthesis (Vose et al. 2016). The current volume builds on that synthesis and provides region-specific management options for increasing resilience to drought for Alaska and Pacific Northwest, California, Hawaiʻi and U.S-Affiliated Pacific Islands, Interior West, Central Plains, Midwest and Northeast, and Southern United States.

Ecological drought refers to the negative impacts of meteorological drought on ecosystem services, generally focused on observable changes (e.g., forest mortality, soil loss in rangelands), but less observable responses (e.g., lower plant productivity) can have observable changes and economic consequences over the long term. The magnitude of these impacts depends on the severity, duration, frequency, and spatial extent of drought events. A wide range of management options is available for minimizing the adverse impacts of drought when they occur, facilitating postdrought recovery, and creating ecosystem conditions that reduce negative impacts of future droughts. For forests, a common theme among regions is reducing water demand by managing stands at a lower density and favoring species that either require less water or can tolerate drought. Responses to hydrological drought include restoring riparian areas and wetlands to improve functionality, ensuring that aquatic habitats for fish and other organisms provide refugia and passage during low streamflow conditions, and carefully managing consumptive uses for livestock grazing, recreation, agriculture, and drinking water during droughts.

For drought management to be effective, timely implementation is needed across large spatial scales, facilitated by coordination among agencies and stakeholders. Optimal responses can be developed by integrating existing policies and practices with new information and by timely reporting of current conditions. The following strategic actions will help institutionalize awareness of drought effects and drought responses in public and private land management: (1) establish and maintain relationships with providers of drought information, (2) include drought in collaborative efforts among agencies and stakeholders, (3) revise best management practices as needed, (4) implement drought in relevant planning processes, (5) establish long-term monitoring of drought effects, and (6) share information on effectiveness of drought responses. If drought-informed practices are institutionalized as part of agency operations, then planning and management will be more effective, and "crisis management" in response to drought can be avoided.

Vose, J.M.; Clark, J.S.; Luce, C.H.; Patel-Weynand, T., eds. 2016. 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. 289 p.

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