Chapter 3
Climate Change: Updates on Recent Global and United States Temperature Anomalies and Impacts to Water, Forests, and Environmental Health

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Recent Changes to Global and United States Surface Temperatures

A number of critical improvements have been implemented to global surface air temperature datasets over the past few years, allowing for increased statistical reliability when determining surface temperature anomalies and trends. For example, the surface air temperature data in the Global Historical Climatology Network-Monthly (GHCNm) dataset, developed and maintained by the National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Information, was updated from Version 3.3.0 to Version 4.0 in October 2018 [57]. Previous improvements have been documented for past versions of GHCNm [77, 94], as well as the Extended Reconstructed Sea Surface Temperature (ERSST) dataset, most recently with Version 5 [41] that is combined with GHCNm to determine global land-ocean temperatures. GHCNm Version 4 includes data from approximately 26,000 surface stations, almost four times the number in the previous version. By including the additional surface stations, as well as estimates for missing base period (30-year) averages, NOAA has expanded the geographic coverage of surface temperature anomalies throughout the entire period of record (1880–present). Recent measurements show the continued rise in land surface temperatures, both globally and across the United States (Fig. 3.1 top-bottom, and Fig. 3.2), both of which show clear increasing trends since the 1970s. For global surface

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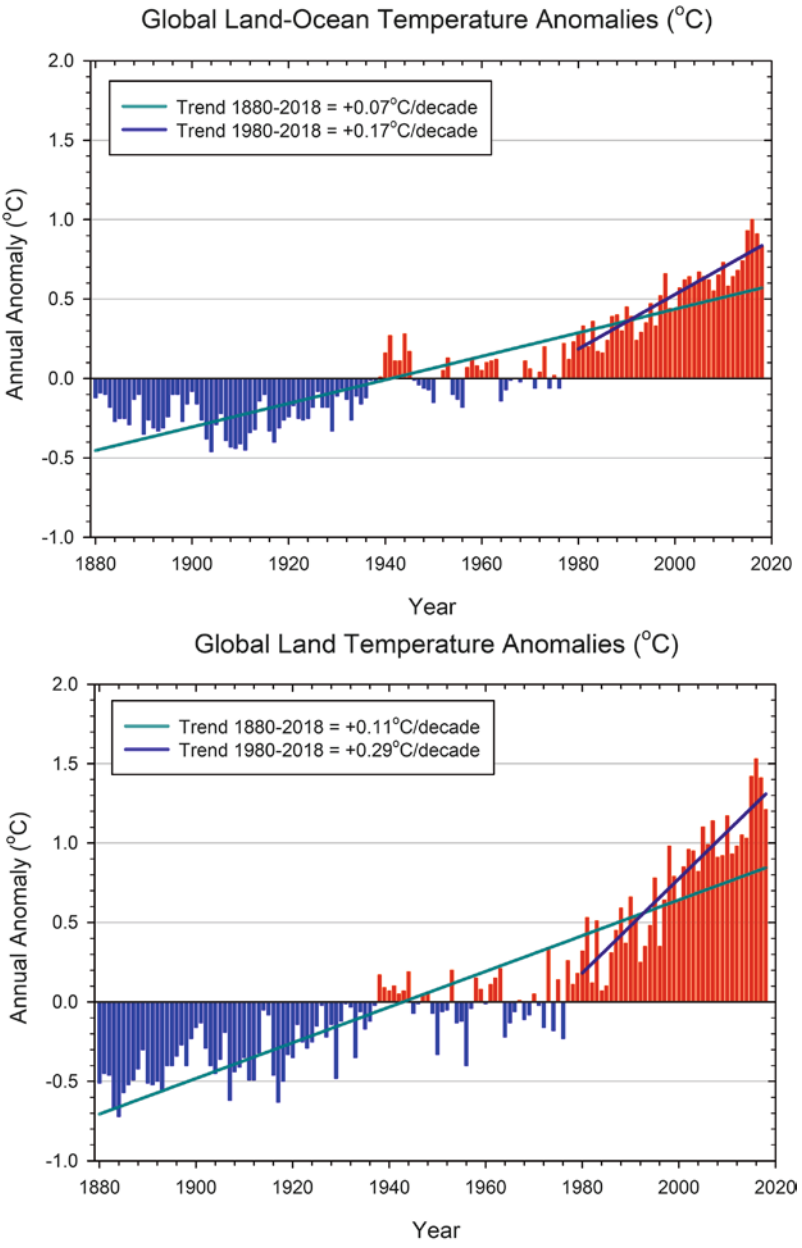

Fig. 3.1 (TOP) Combined land-ocean annual global surface temperature anomalies covering the period 1880–2018, relative to the 1901–2000 annual mean; (BOTTOM) Land-only annual global surface temperatures anomalies covering the period 1880–2018, relative to the 1901–2000 annual mean. Data for land surface temperatures are taken from NOAA's Global Historical Climatology Network-Monthly (GHCNm) dataset (Version 4; [57]), and data for ocean surface temperatures are from the Extended Reconstructed Sea Surface Temperature (ERSST) dataset (Version 5; [41])

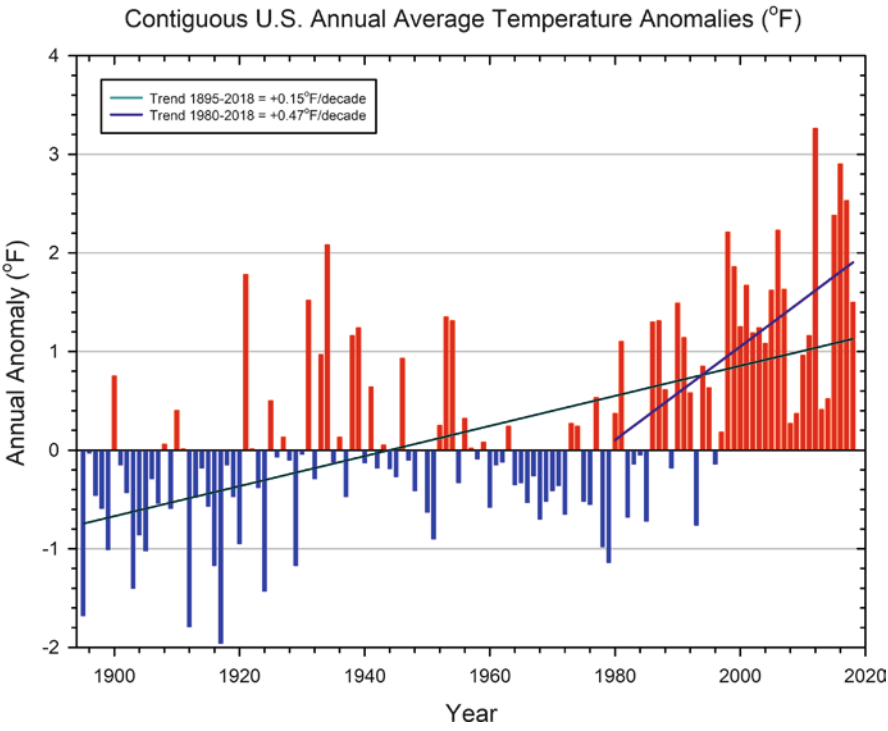

Fig. 3.2 Annual average surface temperatures (in °F) for the contiguous United States over the period 1895–2018, relative to the 1901–2000 mean. Data are from NOAA's Global Historical Climatology Network-Monthly (GHCNm) dataset (Version 4; [57])

temperatures, the observed trend over the century-scale, covering the period 1880–2018, is approximately +0.07 °C/decade. However, since 1980, the trend has increased significantly, and over the period 1980–2018 has risen to approximately +0.17 °C/decade. In addition, the observed surface temperatures for the contiguous United States have also increased steadily (Fig. 3.2) over the past several decades. Based on data covering the entire historical record from 1895 to 2018, the trend is just over +0.15 °F/decade, but, for the period 1980–2018, the trend has increased substantially to +0.47 °F/decade.

The observed increases in global surface temperatures has been larger over continental areas than oceans. As displayed spatially using gridded data in Fig. 3.3 (top-bottom), the observed trends over the 30-year period covering 1988–2017 exceeded +0.5 °C/decade across many Northern Hemisphere land areas, including most of North Africa, western parts of Asia, and higher latitudes of North America. The increased warming of global surface land temperatures is clearly shown when comparing the top 5 warmest and coolest years in the historical record. As shown in Table 3.1, the top 5 warmest years for global surface land temperatures have all occurred since 2015, with the top 5 coolest years all occurring in the late nineteenth and early twentieth centuries.

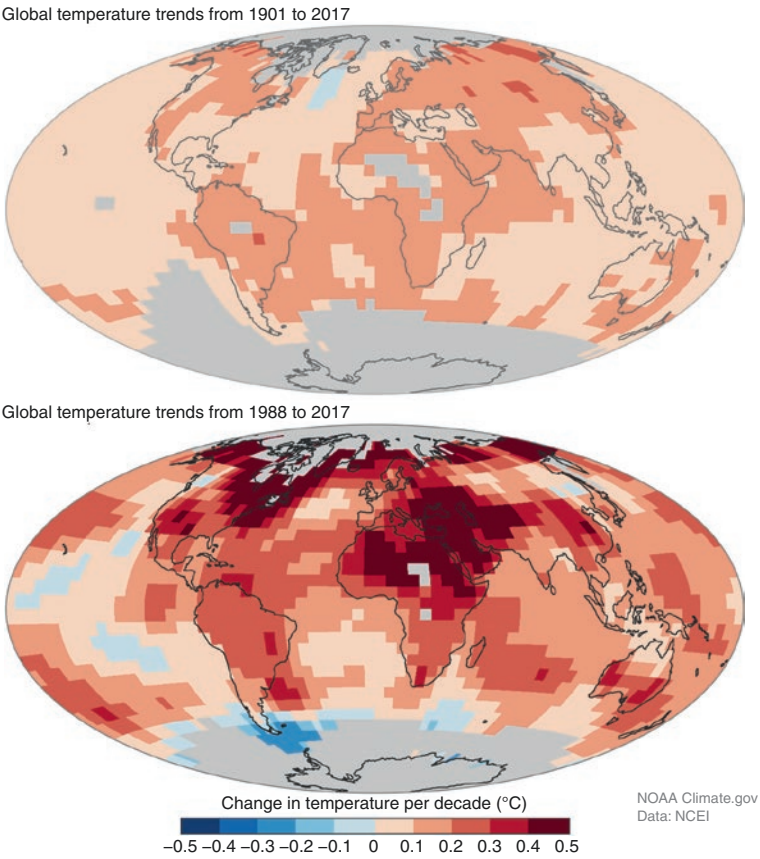

Fig. 3.3 (TOP) Observed trends (in ˚C/decade) of 5° × 5° gridded land and ocean annual global surface temperature anomalies covering the period 1901–2017, with anomalies relative to the 1901–2000 annual mean. (BOTTOM) Observed trends (in ˚C/decade) of 5°×°5° gridded land and ocean annual global surface temperature anomalies covering the period 1988–2017, with anomalies relative to the 1901–2000 annual mean. Data for land surface temperatures are taken from NOAA's Global Historical Climatology Network-Monthly (GHCNm) dataset (Version 4; [57]), and data for ocean surface temperatures are from the Extended Reconstructed Sea Surface Temperature (ERSST) dataset (Version 5; [41])

Climate Change Impacts on Water Resources and Water Quality

The impacts of climate change on the water cycle occur through changes in precipitation, stream and river flows, and water quality, and are felt across multiple sectors and regions [50]. Maintaining consistent, high-quality water resources is a primary concern for public and environmental health, and declining water supplies and degradation of water quality related to increasing surface air temperatures from climate change is of widespread concern. The environmental impacts of reduced water

Table 3.1 Top 5 warmest and coldest years for global surface air temperatures (land and ocean combined), based on data since 1880 (with annual temperature anomalies in °C relative to 1901–2000 mean). Data sources are the Global Historical Climatology Network-Monthly (GHCN-m) dataset for land temperatures and the Extended-Reconstructed Sea Surface Temperature Dataset (ERSST) for ocean surface temperatures, both developed and updated by NOAA

Warmest years	Coldest years
2016 (+1.55 °C)	1884 (−0.72 °C)
2019 (+1.51 °C)	1883 (−0.68 °C)
2015 (+1.43 °C)	1917 (−0.64 °C)
2017 (+1.42 °C)	1907 (−0.63 °C)
2018 (+1.23 °C)	1885 (−0.58 °C)

resources has been felt in regions around the world, with many drier regions having experienced increasing numbers and intensity of droughts, resulting in reductions in water supplies [84]. It is clear that the water supplies for many municipalities in the western United States are vulnerable to severe shortages [9], and this vulnerability increases in future climate simulations as surface temperatures increase [31]. Observed variations in river-flows indicate that the effects of increasing temperatures are dominated by fluctuations in precipitation [32, 37], although water management does have an effect where larger diversions, dams, and other water infrastructure play a role [50]. As shown by Brown et al. [16], water supplies across the contiguous United States are expected to decline in many areas due to the impacts of both population growth and climate change, specifically in the arid and semi-arid parts of the western United States (Fig. 3.4). Hydrologic model simulations of water supply and demand over the twenty-first century show that in the absence of further adaptation efforts, serious water shortages are likely in some regions. Specifically, those areas that currently experience water shortages are expected to experience increased water stress as surface air temperatures increase, while other areas will experience increasing streamflow related to increasing precipitation. For example, the observed runoff and streamflow at regional scales have declined during the last half-century in the northwestern United States [10], as well as in the Colorado River Basin [91], while streamflow is increasing in the Mississippi River Basin and the northeastern United States [95].

In addition, models of streamflow responses due to changes in climate show that many areas will see changes in the timing and magnitude of peak flows [39, 80]. For example, recent observations have shown a declining trend in annual runoff for the Colorado River Basin [97], the primary water supply for a vast area of the Southwest and Colorado Plateau. Significant changes have also been observed in the timing of winter-spring streamflows in river basins in eastern parts of North America [40]. Problems with water quality will also likely increase due to rising temperatures across stream and river systems, especially during severe drought events [68]. Lower and more persistent periods of low flows under drought conditions can worsen water quality [69]. The same is true for higher flows, which have increased due to extreme precipitation (flood) events [64]. The impacts of increasing

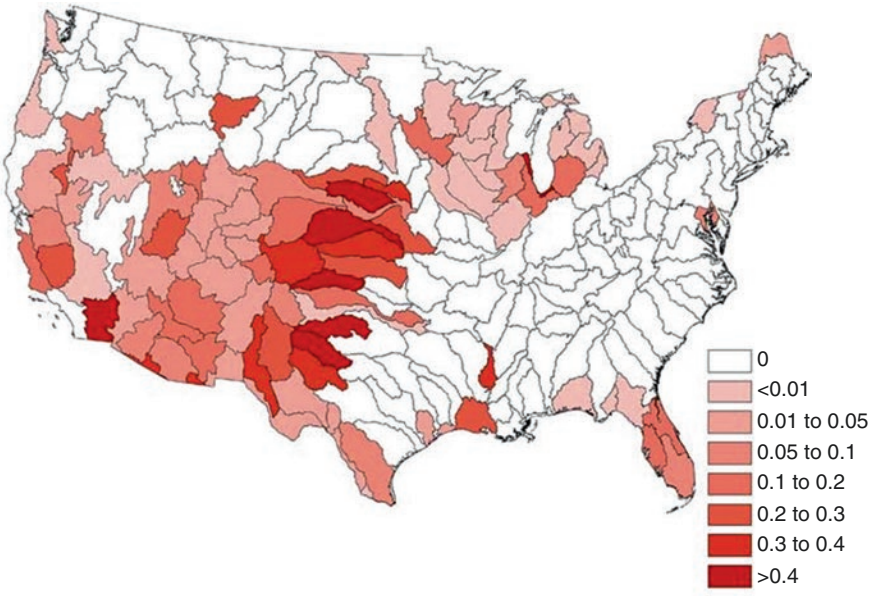

Fig. 3.4 Mean shortage frequency if relying only on renewable water supplies, determined using the mean of 14 future scenarios. The shortage frequency is shown by river basin for the period covering 2046–2070, which was determined using the mean of 14 future scenarios, which included the same number of both wet and dry future scenarios (originally from [16])

precipitation intensity, in conjunction with the effects of wildfires (see section "Wildfire", below) and widespread use of fertilizers, have been shown to increase sediment, nutrient, and contaminant loads in surface waters [55]. In addition, changing land cover, and increases in the frequency and magnitude of forest disturbances and floods will likely increase sediment loads in larger rivers [86, 88].

Significant rises in stream temperatures have been documented for some regions of the United States, which has implications for water quality and aquatic habitat. To address these concerns, the multi-agency NorWeST project combined stream temperature data from over 200,000,000 hourly temperature recordings at >20,000 unique stream monitoring sites across the entire western United States [42]. NorWeST uses observed data and numerical models to understand changes in stream and river temperatures, and current and potential impacts to aquatic habitat. They also utilized spatial statistical models to develop 36 historical and future climate scenarios at 1-km resolution for >1,000,000 km of streams, which are used comparatively with historical stream temperatures. Results from these simulations showed increasing water temperatures for all 36 scenarios. For many native fish species, cold headwater streams are needed for spawning and maintaining proper

habitat conditions, and rising stream temperatures pose a threat to survival of some species, especially those adapted to colder stream conditions.

The impacts of climate change on groundwater storage vary significantly, and are not well understood due to inconsistent monitoring of large aquifers and a lack of understanding the connection between surface and sub-surface flows [50]. However, it is clear that precipitation is the primary source of aquifer recharge in water-limited ecosystems [14, 31], and that changes in recharge rates are amplified relative to changes in total precipitation, especially in drier environments [36]. In many forested and mountainous areas, groundwater recharge is primarily generated by snowmelt infiltration, which puts groundwater dependent ecosystems at risk due to observed reductions in snowpacks across much of the western United States [98].

Expected increases in water demand under climate change are projected in regions of the United States where groundwater aquifers are the primary water supply source [15], specifically the Great Plains and parts of the Southwest and Southeast. Mining groundwater is commonly used in many regions to supplement surface water supplies, especially in semi-arid and arid climates, but such mining is unsustainable in the long-term [14] and may significantly deplete storage in aquifers if not properly managed and regulated.

Climate Change Impacts on Watershed Health

Ecosystems across the globe are responding to the impacts of warming temperatures and increasingly variable precipitation events in a variety of ways. In the United States, forested watersheds are experiencing increasing numbers of large fires, droughts and floods, insect outbreaks, major land-use changes, and other environmental impacts that are detrimental to their proper function (see section "Climate Change Impacts on Forests and Forest Health"). To improve understanding of the health and function of forested watersheds, the USDA Forest Service developed the Watershed Condition Framework (WCF) to help monitor and assess the condition of over 15,000 watersheds managed by the agency [65].

To measure and evaluate how well watersheds are functioning, the Watershed Condition Classification (WCC) system [66] was developed as the initial step of the WCF to integrate numerous drivers of watershed condition into a combined rating (Functioning Properly, Impaired Function, Functioning At-Risk). To assess the condition of watersheds, WCC utilizes 12 indicators, and 24 sub-attributes, to measure the complex function of watersheds due to their physical and biological environments. The 12 indicator/24 attribute model is broken into four categories: Aquatic Physical, Aquatic Biological, Terrestrial Physical, and Terrestrial Biological (weighted of 30%, 30%, 30%, and 10%, respectively).

The initial evaluation of watershed condition using the WCC was conducted in 2011, establishing baseline conditions for all HUC 6 (12-digit) watersheds on National Forest System lands in the United States. Additional evaluations were conducted over multiple years in 2015–2018 on watersheds that experienced substantial

disturbance or had large restoration projects completed. Figure 3.5 (left-right) shows both the initial WCC evaluation for watersheds in the western United States, along with those watersheds that changed their condition class (either improved or degraded) during subsequent evaluations. It is clear from the re-assessments that the vast majority of watersheds remained at the same condition class. However, of those that did have a change in their condition, the majority of those watersheds had a decline in their WCC rating and therefore a degradation of overall condition, especially those in the Southwest, where large fires and droughts have occurred.

To assess the condition of riparian zones, which have the highest biodiversity within forested and rangeland watersheds, the Western Riparian Threats Assessment was conducted in 2010 to provide an initial, coarse-scale assessment of historical, current, and future threats to streams and riparian areas in the western United States [83]. The effort supported the development of a strategic vision for the future of western wildland management that offers strategies for managing these important landscape elements and their watersheds, recognizing the need to balance sometimes conflicting interests and demands. Common indicators of stress in riparian ecosystems include reduced biodiversity, altered productivity, an increased prevalence of disease, shifts in species composition and "terrestrialization", reduced efficiency of nutrient cycling, and increased dominance of exotic and generalist species [58].

To develop this complex assessment, Theobold et al. [83] assessed threats to riparian ecosystems by examining their deviation from reference conditions in the

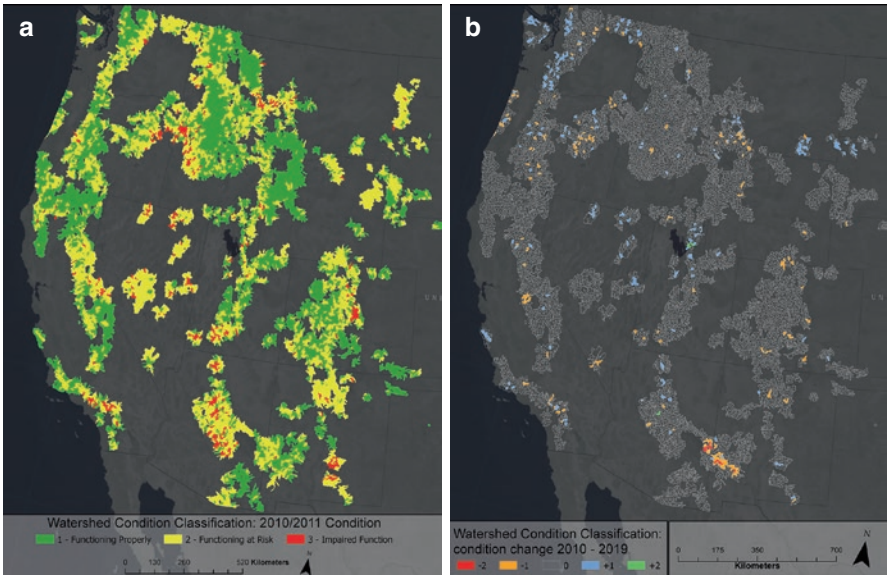

Fig. 3.5 (Left) Watershed Condition Classification (WCC) for the western United States, from initial condition assessments conducted on USDA Forest Service National Forest System lands in 2010–2011. (Right) The change in condition class for those watersheds reassessed in 2015–2018, with the observed change relative to the initial assessment in 2010–2011. (Source: data obtained from the USDA Forest Service's Watershed Condition Assessment and Tracking Tool)

physical processes that govern riparian pattern and process. These factors include the natural flow regime (and alterations to it), lateral connectivity to the landscape (and degree of anthropogenic confinement), and longitudinal connectivity. These were assessed using the most extensive geospatial information obtainable at the time, and used to model flow and sediment regimes at the 12 digit Hydrologic Unit Code (HUC) resolution. Comparisons of historical flow and sediment regimes to current and future regimes allowed for an assessment of threats to these systems as a result of human land uses and water development and the impacts of climate change on discharge and sediment yield from watersheds. Figure 3.6 is a map of the final threat assessment score on a scale of 0 to 100% (darker blue indicates a higher threat level). Based on this multi-parameter risk assessment, the riparian systems that are under the highest threat in the western United States include the central valley of California, the east slope of the Cascades in Washington, the Colorado River system, and the Southwest.

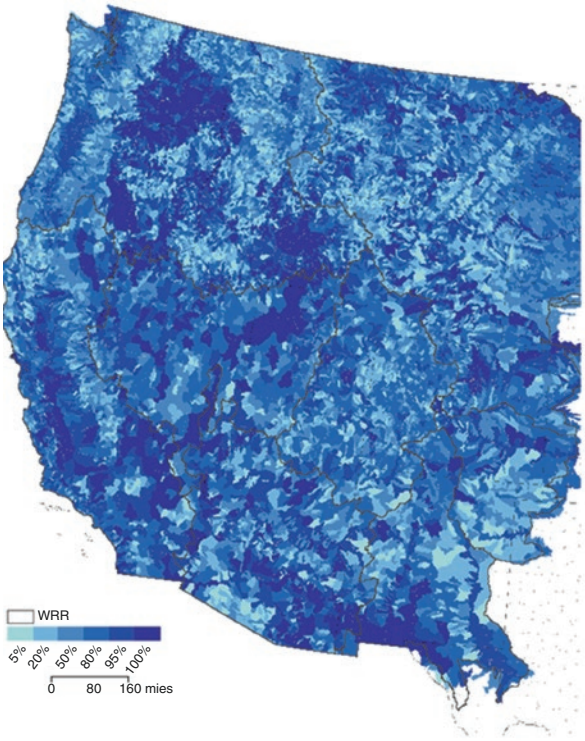

Fig. 3.6 Riparian threats score (scaled 0–100%) for reach catchment areas (~HUC12 scale) in the western United States, normalized by water resource region, with the highest threat levels to riparian zones represented by dark blue shading and the lowest threat levels by light blue shading. (From Theobald et al. 2010)

Climate Change Impacts on Forests and Forest Health

Forests cover ~42 million km^2 (~30%) of the earth's surface and are found in all regions at elevations and latitudes capable of sustaining tree growth, except where disturbances, whether natural or human-induced, are too frequent or too severe to enable establishment. Forests provide immeasurable ecological, economic, and social goods and services to both natural systems and humankind. These include, among others, purification of the air that we breathe; regulation of edaphic formation and water quantity and quality (see section "Climate Change Impacts on Watershed Health"); provision of fish and wildlife habitat, food, medicine, shelter, wood, and other forest products; provision of aesthetics, outdoor recreation and spiritual renewal; and regulation of climate through carbon storage and complex physical, chemical, and biological processes that affect planetary energetics [13]. In short, forests represent one of the earth's most important ecosystems, and are critical to the health, welfare, and survival of human societies across the globe.

Forests absorb the equivalent of ~2 billion tons of carbon dioxide (CO_2) each year [46] and are increasingly recognized for mitigation of atmospheric concentrations of CO_2 [20]. However, the sustainability of many forests is threatened by increases in the frequency and severity of disturbances exacerbated by climate change [5, 6, 25, 59, 86]. For example, a key finding of the recently-published Fourth National Climate Assessment is that "It is very likely that more frequent extreme weather events will increase the frequency and magnitude of severe ecological disturbances, driving rapid (months to years) and often persistent changes in forest structure and function across large landscapes" ([84], Table 3.2). Disturbances, such as wildfire and bark beetle epidemics, that cause large amounts of tree mortality may reverse the role of some forests from carbon sinks to carbon sources [7]. Alternatively, healthy forests assimilate, accumulate, and sequester large amounts of carbon from the atmosphere.

The effects of climate change on forests include both positive (e.g., increased growth through elevated water use efficiency and longer growing seasons) and negative impacts (e.g., increased frequency and severity of disturbances) with feedbacks that influence environmental health. Disturbances release growing space, alter nutrient cycling, and affect other key processes essential to the proper functioning of ecosystems [30]. For example, Schelhaas et al. [75] provided a quantitative overview of the role of natural disturbances in European forests, which they suggested was useful as a basis for modeling the future impacts of climate change by establishing a baseline. They reported storms were responsible for 53% of the net volume affected over a 40-year period, while biotic factors (e.g., bark beetle epidemics) contributed 16%. In managed forests, natural disturbance cycles have been altered by human interventions aimed at reducing the susceptibility of forests to disturbances. In some cases, these interventions have exacerbated the effects of other disturbances. For example, dry forests in portions of the western United States were once dominated by open and park-like stands of widely dispersed trees prior to Euro-American settlement. Frequent thinning of small-diameter and

Table 3.2 Key findings of the Fourth National Climate Assessment concerning the impacts of climate change on forests in the United States ([86], https://nca2018.globalchange.gov)

Ecological disturbances and forest health	It is very likely that more frequent extreme weather events will increase the frequency and magnitude of severe ecological disturbances, driving rapid (months to years) and often persistent changes in forest structure and function across large landscapes. It is also likely that other changes, resulting from gradual climate change and less severe disturbances, will alter forest productivity and health and the distribution and abundance of species at longer timescales (decades to centuries).
Ecosystem services	It is very likely that climate change will decrease the ability of many forest ecosystems to provide important ecosystem services to society. Tree growth and carbon storage are expected to decrease in most locations as a result of higher temperatures, more frequent drought, and increased disturbances. The onset and magnitude of climate change effects on water resources in forest ecosystems will vary, but are already occurring in some regions.
Adaptation	Forest management activities that increase the resilience of United States forests to climate change are being implemented, with a broad range of adaptation options for different resources, including applications in planning. The future pace of adaptation will depend on how effectively social, organizational, and economic conditions support implementation.

fire-intolerant tree species by low-intensity surface fires, and competitive exclusion of tree seedlings by understory grasses are believed to have maintained such conditions. Many of these forests are now denser, have more small trees and fewer large trees, and are dominated by more shade-tolerant and fire-intolerant tree species, primarily as a result of fire suppression activities and harvesting practices implemented in the twentieth century. These changes have led to heavy accumulations of forest fuels [92] that feed severe wildfires when natural or human-induced ignitions occur. Today, thinning and prescribed fire are commonly used to increase the resiliency of forests to wildfires, especially in the western United States (Fig. 3.7).

Climate has shaped the world's forests for millennia, and minor climatic shifts may have significant effects on community compositions [76]. A notable global assessment of forest health published in 2010 reported 88 unique episodes of tree mortality over the last 30 years [6]. Since then, numerous additional episodes have been identified. The common implicated causal factor in these examples is elevated temperatures and/or water stress, raising the concern that the world's forests are increasingly responding to ongoing warming and drying attributed to climate change. Reports of large tree mortality events occurring during "climate change-type droughts" (hotter, drier) are now common worldwide (e.g., [5, 6, 38, 89]) (Fig. 3.8).

Among other factors, the current distribution of trees results from climatic shifts dating back millions of years in addition to more recent recolonization of deglaciated lands [33]. These historical patterns perhaps foreshadow changes to current coniferous vegetation as climate change accelerates. For example, based on the best existing data for 130 tree species in North America and associated climate information, McKenney et al. [56] predicted that on average the geographic range for a

Fig. 3.7 Conditions of many seasonally dry forests in the western United States, especially those that once experienced low-to-moderate intensity fire regimes, leave them uncharacteristically susceptible to high-severity wildfire. Creating more fire-resilient stands generally requires treatment of surface and ladder fuels, reductions in crown density, and maintenance of large-diameter trees [1]. A combination of thinning (top) and prescribed burning (bottom) is commonly used. Most evidence suggests that these treatments are typically accomplished with few unintended consequences as most ecosystem components (e.g., carbon sequestration, soils, wildlife) exhibit subtle impacts or no measurable impacts [78]. Since increased wildfire activity is expected as a result of climate change and desired fuel treatment effects are transient, repeated applications of fuel reduction treatments are required to maintain resilient conditions. (Photo credits: top, C.J. Fettig, and bottom, S.R. McKelvey, USFS Pacific Southwest Research Station)

Fig. 3.8 Much of California experienced a "climate change-type drought" in 2012–2015, inciting a large tree mortality event in the central and southern Sierra Nevada. While droughts have had an important influence on this region for millennia, this drought was characterized by large precipitation deficits and abnormally high temperatures during both the wet and dry seasons [2, 90], and in some areas is thought to be the most severe in 1200 years [35]. In particular, 2014 is noted for the lowest Palmer Drought Severity Index recorded for 1895–2017, when instrumental records were widely available (www.ncdc.noaa.gov/cag/). The drought resulted in progressive canopy water stress of at least 888 million trees and severe canopy water stress of at least 58 million trees [8], substantial mortality of dominant and co-dominant trees, and impacts to many ecological goods and services [23]. Much of the tree mortality was attributed to western pine beetle (*Dendroctonus brevicomis*), a native species that readily colonizes drought-stressed ponderosa pine (*Pinus ponderosa*) [22], but other tree and shrub species were affected by other contributing factors [27]. Stephens et al. [79] concluded that a greater potential for "mass fires" exists in future decades as a result of the amount, size, and continuity of dry combustible woody fuels, which could produce large, severe, and uncontrollable wildfires. Climate change will further amplify evapotranspiration and moisture overdrafts, likely increasing levels of tree mortality in the Sierra Nevada during droughts by ~15–20% per °C increase in temperature [34]. (Photo credit: C.J. Fettig, USFS Pacific Southwest Research Station)

given tree species will decrease by 12% and shift northward 700 km during the twenty-first century. Under a scenario where survival only occurs in areas where anticipated climatic conditions overlap with current climatic conditions, niches for tree survival decrease by 58% and shift northward 330 km. In terms of tree species, there will be winners (e.g., ponderosa pine, *Pinus ponderosa*) and losers (e.g., Engelmann spruce, *Picea engelmanni*) [72]. The fate of any tree species will depend on genetic variation, phenotypic variation, fecundity and dispersal mechanisms, and their resistance and resilience to a multitude of disturbances. A number of recent improvements have been made in our understanding of the effects of climate change on forest disturbances. Below we highlight four examples focusing on impacts to coniferous forests in western North America.

Forest Insects

Insects have adapted multiple thermally dependent phenological strategies to survive and persist in harsh environments, including development rates and thermal thresholds, diapause (a dormant physiological state entered to survive harsh conditions and increase cohort synchrony) and cold-hardening (increased cold tolerance through acclimation and metabolic processes). These traits, in addition to interactions with host trees and community associates, determine species- and location-specific responses to climate change (Fig. 3.9). Overall, climate change is thought to increase levels of tree mortality attributed to insects (e.g., for bark beetles, [11]; for defoliators, [18]), but there are important exceptions to this trend, especially among defoliators (e.g., larch budworm (*Zeiraphera diniana*), [17]). Bark beetles are commonly recognized as a primary disturbance agent in coniferous forests. Frequently referred to as "aggressive" bark beetles, several species can kill healthy trees and have the capacity to cause landscape-scale tree mortality. In western North America, recent decades have seen elevated levels of tree mortality attributed to bark beetle epidemics in spruce forests of south-central Alaska and the Rocky Mountains, lodgepole pine (*P. contorta*) forests of western Canada and the Rocky Mountains, pinyon-juniper woodlands of the southwestern United States, and ponderosa pine forests of Arizona, California, Oregon, and South Dakota, among others [26]. Because bark beetles, like all insects, are highly sensitive to thermal conditions conducive to population survival and growth, and water stress can influence host tree vigor, epidemics have been correlated with recent shifts in temperature [67] and precipitation [47] attributed to climate change. Bentz et al. [11] predicted increases in thermal regimes conducive to population success for two economically important species in North America, spruce beetle (*Dendroctonus rufipennis*) and mountain pine beetle (*D. ponderosae*), although there was considerable spatial and temporal variability in their predictions. They suggested a northward and upward in elevation movement of temperature suitability, and identified regions with a high potential for epidemics to occur in the twenty-first century. In Europe, warming temperatures are increasing the area of spruce habitat that supports two rather than one generation per year of European spruce beetle (*I. typographus*) [61], the most economically important species in Europe, and a higher number of sister broods [19], both of which benefit population growth [12].

Forest Diseases

As with forest insects, forest diseases caused by native and introduced pathogens are generally predicted to become more severe as a result of climate change [71, 82]. However, diseases caused by pathogens directly affected by climate (e.g.,

Fig. 3.9 In western North America, recent epidemics of mountain pine beetle (*Dendroctonus ponderosae*) have been severe and long-lasting. Since 2001, >27 million hectares of forest have been impacted. The species ranges throughout British Columbia and Alberta, Canada, most of the western United States, into northern Mexico, and colonizes several pine species [60]. Episodic outbreaks are a common occurrence, but the magnitude of recent events have exceeded the range of historic variability and have occurred in areas where mountain pine beetle epidemics were once rare or previously unrecorded (e.g., jack pine forests (*Pinus banksiana*) in Canada). Historically, the range of mountain pine beetle was restricted by climatic conditions unfavorable to brood development, but is expanding due to climate change and other factors. Scientists are concerned that mountain pine beetle could expand eastward across the boreal forest of Canada and into the eastern United States ([74], but see [11]). Others have speculated that under continued warming the loss of whitebark pine (*Pinus albicaulis*) (bottom), and the unique ecological services that this species provides, is imminent in many areas. The U.S. Fish and Wildlife Service announced in 2011 that it determined whitebark pine warranted protection under the Endangered Species Act, but that adding the species to the Federal List of Endangered and Threatened Wildlife and Plants was precluded by the need to address other listing actions of higher priority. In 2015, the listing priority of whitebark pine was downgraded due to declines in mountain pine beetle populations [21]. (Photo credits: top, C.J. Fettig, and bottom, C.J. Hayes, USFS Pacific Southwest Research Station)

needle blights) are predicted to have a reduced impact. These groups of pathogens may cause disease in healthy hosts if the pathogen's environmental requirements are met, many of which require moist conditions. Relatedly, following a detailed meta-analysis, Jactel et al. [43] concluded that the direct effects of drought on forest pathogens is mainly negative, as many require high humidity for spore dispersal and germination. Despite this, forest diseases caused by pathogens indirectly affected by climate (e.g., root diseases) are generally predicted to have increased impacts [82]. While the ability of these pathogens to spread and infect new hosts is affected by moisture, factors associated with climate change that stress their hosts are generally considered to be more important to host invasion.

Wildfire

Increases in the annual area burned by wildfires and cost of suppression efforts have been observed since the mid-1980s (Fig. 3.10). Wildfires have been episodic, occurring during warm years and strongly associated with changes in timing of spring snowmelt in the western United States, which, in turn, is sensitive to changes in temperature and precipitation [87]. At the same time, rapid increases in human habitation of the wildland-urban interface, especially in the western and southeastern United States, further exacerbates wildfire risks [53, 85]. By 2100, the annual area burned in the United States is projected to increase 2–6 fold from present due to climate change [51, 63]. As a result, concerns regarding air quality [73], human

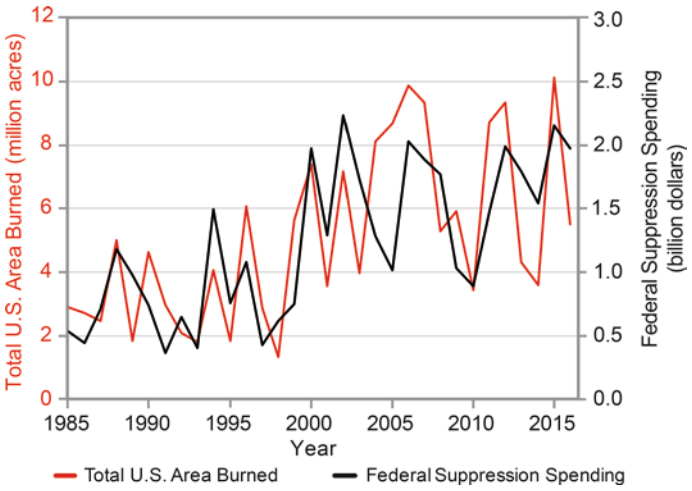

Fig. 3.10 Annual area burned by wildfire in the United States (1985–2016) and annual suppression costs (Consumer Price Index deflated, scaled to 2016 USD). (Source: USDA Forest Service, adapted from [86]). Wildfire-related concerns regarding air quality and human safety will become more important as a result of climate change

Fig. 3.11 A high-severity wildfire in a lodgepole pine (*Pinus contorta*) forest that was heavily impacted by mountain pine beetle (*Dendroctonus ponderosae*) a few years earlier. Dramatic changes are imposed on the forest fuel complex during and after a bark beetle epidemic. Associated anticipated changes in fire behavior include increased rates of fire spread and increased probabilities of torching, crowning, and spotting. As a result, fire fighters should expect increased difficulties with fire line construction and establishment of access, egress, and escape routes and safety zones [44, 45]. (Photo credit: C.J. Fettig, USFS Pacific Southwest Research Station)

safety, and protection of critical infrastructure will become increasingly important. As previously mentioned, bark beetles and wildfire are principal drivers of change in many North American forests, and both have increased in extent in recent years. As a result, these two disturbances are increasingly interacting on the landscape (Fig. 3.11).

Invasive Species

Finch et al. [29] provide an assessment of the effects of climate change on invasive species. They conclude that impacts are mediated primarily by direct effects on invaders, indirect effects that alter resource availability and interactions with other native and invasive species, and other factors such as human influences that alter the environment. Manipulative experiments, while uncommon, have shown that some invasive plants respond strongly to elevated CO_2. For example, growth of cheatgrass (*Bromus tectorum*), the notable invasive weed, is enhanced by elevated CO_2 [96] and increasing temperature [93], specifically during periods of high soil moisture. While desert plants like cheatgrass are likely to be among the most responsive to elevated CO_2 (i.e., due to increases in water use efficiency), similar relationships have been observed in many plants. While insects are not directly affected by

elevated CO_2, increasing temperatures caused by elevated CO_2 can positively affect growth rates, phenology, dispersal, and survival. Conversely, rising temperatures also have the potential to negatively affect invasive insects by disrupting their synchrony with hosts and altering their overwintering environments. As such, climate change is also likely to modify competitive interactions to produce communities that are more or less susceptible to colonization by new invaders or expansion by existing invaders [29]. Of particular importance, many disturbances exacerbated by climate change often result in releases of large amounts of growing space which may increase the performance of some invasive species (Fig. 3.12). For example, a recent meta-analysis of relevant literature concluded that wildfires enhance invasive plant composition and performance, but have no effect on native species compositions [3]. Today, many invaders first arrive in new regions as stowaways on cargo ships. Climate change is reducing the extent and thickness of sea ice resulting in increases in shipping efficiencies [52, 81], which will increase survival rates of stowaways and enhance the likelihood of establishment in new regions [70].

Rapid and broad-scale tree mortality can have long-term impacts not only on forest health but human health (e.g., [4, 62]), with feedbacks that further influence climate and land use [49, 54]. For example, the annual amount of pollution removed by trees and forests in the conterminous United States is estimated at 17.4 million tons with a human health value of $6.8 billion USD [62]. Most of these health benefits come from reductions in the incidences of human mortality (850 cases), acute

Fig. 3.12 Forest disturbances often result in releases of large amounts of growing space. One potential consequence is subsequent invasion by exotic plants, in this case Canada thistle (*Cirsium arvense*) and bull thistle (*Cirsium vulgare*) in a lodgepole pine (*Pinus contorta*) forest that experienced high levels of tree mortality (>70%) attributed to mountain pine beetle (*Dendroctonus ponderosae*). (Photo by J.B. Runyon, USFS Rocky Mountain Research Station)

respiratory symptoms (670,000), asthma exacerbation (430,000) and lost school days (200,000) [62]. On the other hand, most states in the western United States have at least 10% of their forested landscapes at risk (defined as without remediation, at least 25% of standing live basal area greater than 2.54 cm in diameter will be killed in the next 15 years) to forest insects and diseases epidemics [48], the impacts of many of which are exacerbated by climate change. Seven trees species endemic to the western United States are expected to suffer losses of ≥25% in the next 15 years [48]. To that end, the recent loss of whitebark pine (*P. albicaulis*) stands due to interactions among climate change, mountain pine beetle, and white pine blister rust underscores the need for a greater understanding of climate change effects on complex interactions important to ecosystem resiliency and stability (Fig. 3.9). Characterizing thresholds for systems beyond which such changes are irreversible is important.

There are tools available to restore forest health and to increase the resistance and resilience of forests to climate change and disturbances exacerbated by climate change (e.g., [24, 78]). Resource managers can intervene and mitigate some of the negative effects [28, 64] (Fig. 3.13), but this requires knowledge of the effects of climate change on forests, forest-related enterprises, and resource-dependent communities, and of institutional, social, and environmental factors that influence adaptive capacity. Healthy forests have a vital role to play in combating climate change and its influence on environmental health, and are critical to the welfare and sustainability of human societies.

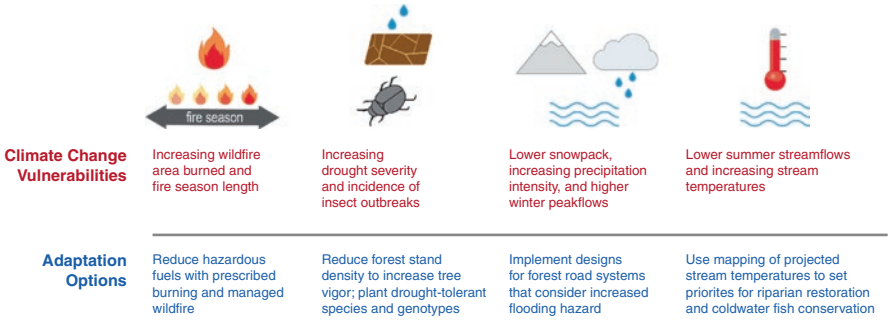

Fig. 3.13 In order to increase resistance and resilience to stressors and disturbances, adaptation practices have been developed in response to climate change vulnerabilities. Flexible approaches that promote learning and sharing among interested parties can help accelerate implementation. (Source: adapted from [86])

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