25 Southwest

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25 Southwest

Low water levels in Lake Mead

Key Message 1

Water Resources

Water for people and nature in the Southwest has declined during droughts, due in part to human-caused climate change. Intensifying droughts and occasional large floods, combined with critical water demands from a growing population, deteriorating infrastructure, and groundwater depletion, suggest the need for flexible water management techniques that address changing risks over time, balancing declining supplies with greater demands.

Key Message 2

Ecosystems and Ecosystem Services

The integrity of Southwest forests and other ecosystems and their ability to provide natural habitat, clean water, and economic livelihoods have declined as a result of recent droughts and wildfire due in part to human-caused climate change. Greenhouse gas emissions reductions, fire management, and other actions can help reduce future vulnerabilities of ecosystems and human well-being.

Key Message 3

The Coast

Many coastal resources in the Southwest have been affected by sea level rise, ocean warming, and reduced ocean oxygen—all impacts of human-caused climate change—and ocean acidification resulting from human emissions of carbon dioxide. Homes and other coastal infrastructure, marine flora and fauna, and people who depend on coastal resources face increased risks under continued climate change.

Key Message 4

Indigenous Peoples

Traditional foods, natural resource-based livelihoods, cultural resources, and spiritual well-being of Indigenous peoples in the Southwest are increasingly affected by drought, wildfire, and changing ocean conditions. Because future changes would further disrupt the ecosystems on which Indigenous peoples depend, tribes are implementing adaptation measures and emissions reduction actions.

Key Message 5

Energy

The ability of hydropower and fossil fuel electricity generation to meet growing energy use in the Southwest is decreasing as a result of drought and rising temperatures. Many renewable energy sources offer increased electricity reliability, lower water intensity of energy generation, reduced greenhouse gas emissions, and new economic opportunities.

Key Message 6

Food

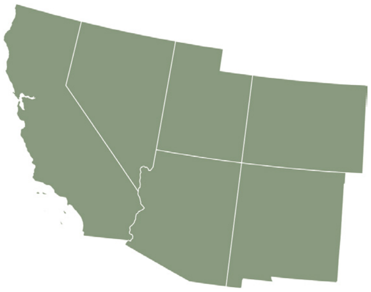
Food production in the Southwest is vulnerable to water shortages. Increased drought, heat waves, and reduction of winter chill hours can harm crops and livestock; exacerbate competition for water among agriculture, energy generation, and municipal uses; and increase future food insecurity.

Key Message 7

Human Health

Heat-associated deaths and illnesses, vulnerabilities to chronic disease, and other health risks to people in the Southwest result from increases in extreme heat, poor air quality, and conditions that foster pathogen growth and spread. Improving public health systems, community infrastructure, and personal health can reduce serious health risks under future climate change.

Executive Summary



The Southwest region encompasses diverse ecosystems, cultures, and economies, reflecting a broad range of climate conditions, including the hottest and driest climate in the United States. Water for people and nature in the Southwest region has declined during droughts, due in part to human-caused climate change. Higher temperatures intensified the recent severe drought in California and are amplifying drought in the Colorado River Basin. Since 2000, Lake Mead on the Colorado River has fallen 130 feet (40 m) and lost 60% of its volume, a result of the ongoing Colorado River Basin drought and continued water withdrawals by cities and agriculture.

The reduction of water volume in both Lake Powell and Lake Mead increases the risk of water shortages across much of the Southwest. Local water utilities, the governments of seven U.S. states, and the federal governments of the United States and Mexico have voluntarily developed and implemented solutions to minimize the possibility of water shortages for cities, farms, and ecosystems. In response to the recent California drought, the state implemented a water conservation plan in 2014 that set allocations for water utilities and major users and banned wasteful practices. As a result, the people of the state reduced water use 25% from 2014 to 2017.

Exposure to hotter temperatures and heat waves already leads to heat-associated deaths in Arizona and California. Mortality risk during a heat wave is amplified on days with high levels of ground-level ozone or particulate air pollution. Given the proportion of the U.S. population in the Southwest region, a disproportionate number of West Nile virus, plague, hantavirus pulmonary syndrome, and Valley fever cases occur in the region.

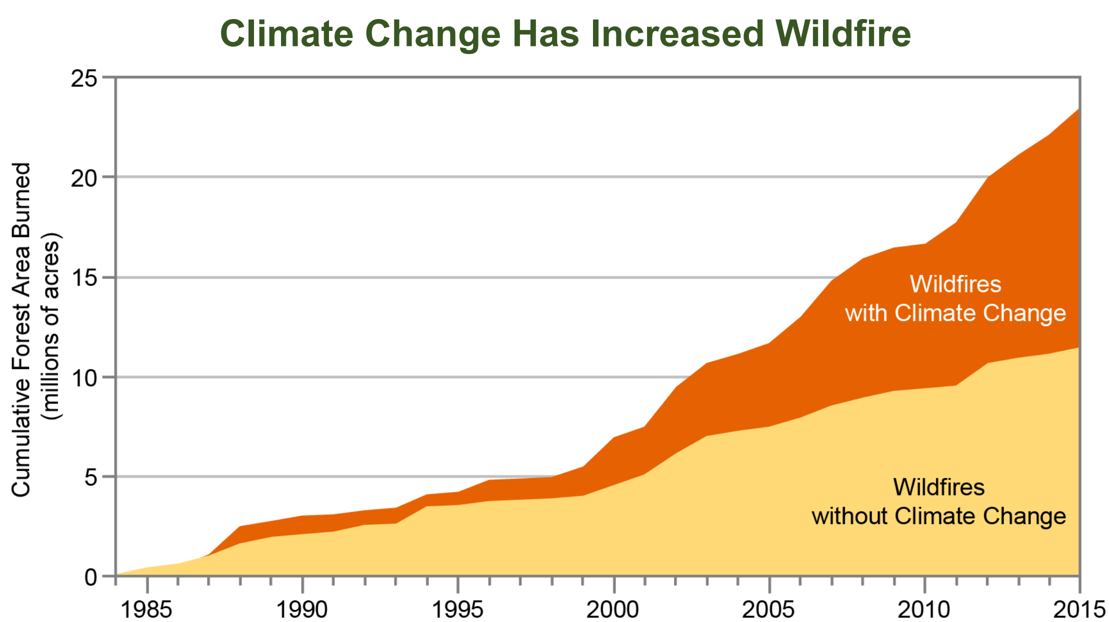
Analyses estimated that the area burned by wildfire across the western United States from 1984 to 2015 was twice what would have burned had climate change not occurred. Wildfires around Los Angeles from 1990 to 2009 caused $3.1 billion in damages (unadjusted for inflation). Tree death in mid-elevation conifer forests doubled from 1955 to 2007 due, in part, to climate change. Allowing naturally ignited fires to burn in wilderness areas and preemptively setting low-severity prescribed burns in areas of unnatural fuel accumulations can reduce the risk of high-severity fires under climate change. Reducing greenhouse gas emissions globally can also reduce ecological vulnerabilities.

At the Golden Gate Bridge in San Francisco, sea level rose 9 inches (22 cm) between 1854 and 2016. Climate change caused most of this rise by melting of land ice and thermal expansion of ocean water. Local governments on the California coast are using projections of sea level rise to develop plans to reduce future risks. Ocean water acidity off the coast of California increased 25% to 40% (decreases of 0.10 to 0.15 pH units) from the preindustrial era (circa 1750) to 2014 due to increasing concentrations of atmospheric carbon dioxide from human activities. The marine heat wave along the Pacific Coast from 2014 to 2016 occurred due to a combination of natural factors and climate change. The event led to the mass stranding of sick and starving birds and sea lions, and shifts of red crabs and tuna into the region. The ecosystem disruptions contributed to closures of commercially important fisheries.

Agricultural irrigation accounts for approximately three-quarters of water use in the Southwest region, which grows half of the fruits, vegetables, and nuts and most of the wine grapes, strawberries, and lettuce for the United States. Increasing heat stress during specific phases of the plant life cycle can increase crop failures.

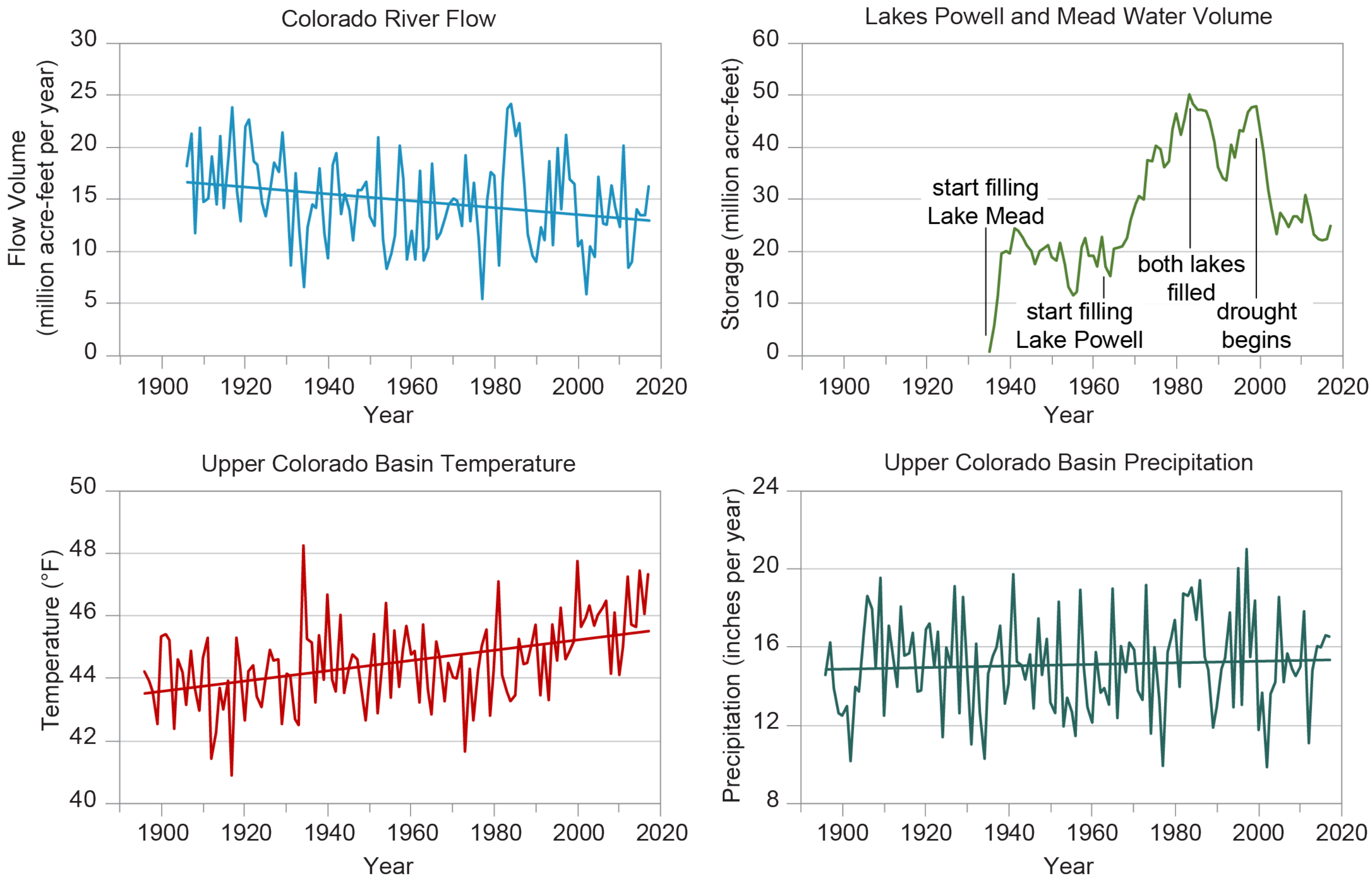
Drought and increasing heat intensify the arid conditions of reservations where the United States restricted some tribal nations in the Southwest region to the driest portions of their traditional homelands. In response to climate change, Indigenous peoples in the region are developing new adaptation and mitigation actions.

The severe drought in California, intensified by climate change, reduced hydroelectric generation two-thirds from 2011 to 2015. The efficiency of all water-cooled electric power plants that burn fuel depends on the temperature of the external cooling water, so climate change could reduce energy efficiency up to 15% across the Southwest by 2050. Solar, wind, and other renewable energy sources, except biofuels, emit less carbon and require less water than fossil fuel energy. Economic conditions and technological innovations have lowered renewable energy costs and increased renewable energy generation in the Southwest.



The cumulative forest area burned by wildfires has greatly increased between 1984 and 2015, with analyses estimating that the area burned by wildfire across the western United States over that period was twice what would have burned had climate change not occurred. *From Figure 25.4 (Source: adapted from Abatzoglou and Williams 2016).*

Severe Drought Reduces Water Supplies in the Southwest



Since 2000, drought that was intensified by long-term trends of higher temperatures due to climate change has reduced the flow in the Colorado River (top left), which in turn has reduced the combined contents of Lakes Powell and Mead to the lowest level since both lakes were first filled (top right). In the Upper Colorado River Basin that feeds the reservoirs, temperatures have increased (bottom left), which increases plant water use and evaporation, reducing lake inflows and contents. Although annual precipitation (bottom right) has been variable without a long-term trend, there has been a recent decline in precipitation that exacerbates the drought. Combined with increased Lower Basin water consumption that began in the 1990s, these trends explain the recently reduced reservoir contents. Straight lines indicate trends for temperature, precipitation, and river flow. The trends for temperature and river flow are statistically significant. *From Figure 25.3 (Sources: Colorado State University and CICS-NC. Temperature and precipitation data from: PRISM Climate Group, Oregon State University,* http://prism.oregonstate.edu*, accessed 20 June 2018).*

Background

The Southwest region encompasses diverse ecosystems, cultures, and economies, reflecting a broad range of climate conditions, including the hottest and driest climate in the United States. Arizona, California, Colorado, New Mexico, Nevada, and Utah occupy one-fifth of U.S. land area, extending across globally unique ecosystems from the Sonoran Desert to the Sierra Nevada to the Pacific Coast. The region is home to 60 million people, with 9 out of 10 living in urban areas and the total population growing 30% faster than the national average.[1] The Nation depends on the region for more than half of its specialty crops such as fruits, nuts, and vegetables.[2] The Southwest also drives the U.S. technology sector, with more than 80% of the country's technology capitalization located in California.[3]

Ecosystems in the Southwest gradually transform from deserts and grasslands in hotter and lower elevations in the south to forests and alpine meadows in cooler, higher elevations in the north. Natural and human-caused wildfire shapes the forests and shrublands that cover one-quarter and one-half of the region, respectively.[4] To conserve habitat for plants and wildlife and supply clean water, timber, recreation, and other services for people, the U.S. Government manages national parks and other public lands covering half of the Southwest region.[5] Climate change is altering ecosystems and their services through major vegetation shifts[213] and increases in the area burned by wildfire.[7]

The California coast extends 3,400 miles (5,500 km),[8] with 200,000 people living 3 feet (0.9 m) or less above sea level.[9] The seaports of Long Beach and Oakland, several international airports, many homes, and high-value infrastructure lie along the coast. In addition, much of the Sacramento–San Joaquin River Delta is near sea level. California has the most valuable ocean-based economy in the country, employing over half a million people and generating $20 billion in wages and $42 billion in economic production in 2014.[10] Coastal wetlands buffer against storms, protect water quality, provide habitat for plants and wildlife, and supply nutrients to fisheries. Sea level rise, storm surges, ocean warming, and ocean acidification are altering the coastal shoreline and ecosystems.

Water resources can be scarce because of the arid conditions of much of the Southwest and the large water demands of agriculture, energy, and cities. Winter snowpack in the Rocky Mountains, Sierra Nevada, and other mountain ranges provides a major portion of the surface water on which the region depends. Spring snowmelt flows into the Colorado, Rio Grande, Sacramento, and other major rivers, where dams capture the flow in reservoirs and canals and pipelines transport the water long distances. Complex water laws govern allocation among states, tribes, cities, ecosystems, energy generators, farms, and fisheries, and between the United States and Mexico. Water supplies change with year-to-year variability in precipitation and water use, but increased evapotranspiration due to higher temperatures reduces the effectiveness of precipitation in replenishing soil moisture and surface water.[11,12,13,14]

Agricultural irrigation accounts for nearly three-quarters of water use in the Southwest region,[15,16] which grows half of the fruits, vegetables, and nuts[2] and most of the wine grapes, strawberries, and lettuce[17] for the United States. Consequently, drought and competing water demands in this region pose a major risk for agriculture and food security in the country. Through production and trade networks, impacts to regional crop production can propagate nationally and internationally (see Ch. 16: International, KM 1)[18]

Parts of the Southwest reach the hottest temperatures on Earth, with the world record high of 134°F (57°C) recorded in Death Valley National Park, California[19] and daily maximum temperatures across much of the region regularly exceeding 98°F (35°C) during summer.[20] Greenhouse gases emitted from human activities have increased global average temperature since 1880[21] and caused detectable warming in the western United States since 1901.[22] The average annual temperature of the Southwest increased 1.6°F (0.9°C) between 1901 and 2016 (Figure 25.1).[23] Moreover, the region recorded more warm nights and fewer cold nights between 1990 and 2016),[24] including an increase of 4.1°F (2.3°C) for the coldest day of the year. Parts of the Southwest recorded the highest temperatures since 1895, in 2012,[25] 2014,[26] 2015,[27] 2016,[28] and 2017.[29]

Extreme heat episodes in much of the region disproportionately threaten the health and well-being of individuals and populations who are especially vulnerable (Ch. 14: Human Health, KM 1).[30] Vulnerability arises from numerous factors individually or in combination, including physical susceptibility (for example, young children and older adults), excessive exposure to heat (such as during heat waves), and socioeconomic factors that influence susceptibility and exposure (for example, hot and poorly ventilated homes or lack of access to public emergency cooling centers).[31,32,33] Communicable diseases, ground-level ozone air pollution, dust storms, and allergens can combine with temperature and precipitation extremes to generate multiple disease burdens (an indicator of the impact of a health problem).

Episodes of extreme heat can affect transportation by reducing the ability of commercial airlines to gain sufficient lift for takeoff at major regional airports (Ch. 12: Transportation, KM 1).[34]

Temperature Has Increased Across the Southwest

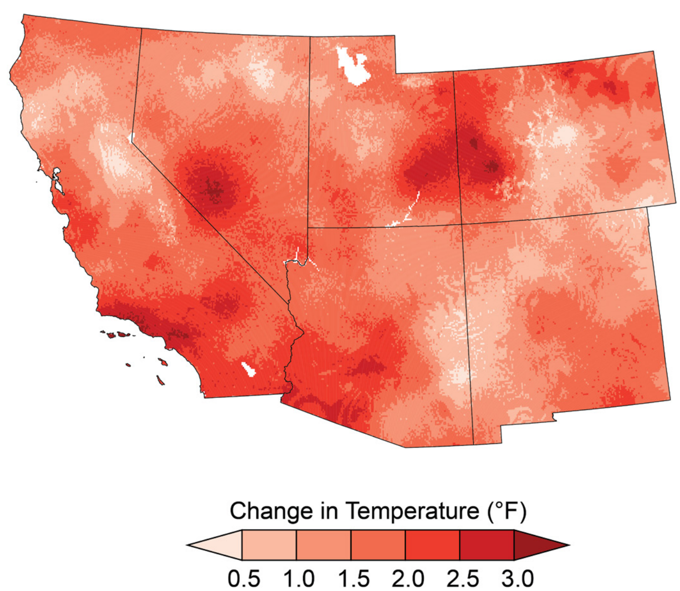


Figure 25.1: Temperatures increased across almost all of the Southwest region from 1901 to 2016, with the greatest increases in southern California and western Colorado.[23] This map shows the difference between 1986–2016 average temperature and 1901–1960 average temperature.[23] Source: adapted from Vose et al. 2017.[23]

Native Americans are among the most at risk from climate change, often experiencing the worst effects because of higher exposure, higher sensitivity, and lower adaptive capacity for historical, socioeconomic, and ecological reasons. With one and a half million Native Americans,[35] 182 federally recognized tribes,[36] and many state-recognized and other non-federally recognized tribes, the Southwest has the largest population of Indigenous peoples in the country. Over the last five centuries, many Indigenous peoples in the Southwest have either been forcibly restricted to lands with limited water and resources[37,38,39] or struggled to get their federally reserved water rights recognized by other users.[40] Climate change exacerbates this historical legacy because the sovereign lands on which many Indigenous peoples live are becoming increasingly dry.

Further, climate change affects traditional plant and animal species, sacred places, traditional building materials, and other material cultural heritage. The physical, mental, emotional, and spiritual health and overall well-being of Indigenous peoples rely on these vulnerable species and materials for their livelihoods, subsistence, cultural practices, ceremonies, and traditions.[41,42,43,44]

In parts of the region, hotter temperatures have already contributed to reductions of seasonal maximum snowpack and its water content over the past 30–65 years,[45,46,47,48,49] partially attributed to human-caused climate change.[45,46,48,49] Increased temperatures most strongly affect snowpack water content, snowmelt timing, and the fraction of precipitation falling as snow.[48,50,51,52,53,54]

The increase in heat and reduction of snow under climate change have amplified recent hydrological droughts (severe shortages of water) in California,[14,55,56,57,58] the Colorado River Basin,[12,13,59]and the Rio Grande.[45,60] Snow droughts can arise from a lack of precipitation (dry snow drought), temperatures that are too warm for snow (warm snow drought), or a combination of the two.[48,51]

Periods of low precipitation from natural variations in the climate system are the primary cause of major hydrological droughts in the Southwest region,[61,62,63,64,65,66,67,68] with increasing temperatures from climate change amplifying recent hydrological droughts, particularly in California and the upper Colorado River Basin.[12,13,14,56,57,59]

Under the higher scenario (RCP8.5), climate models project an 8.6°F (4.8°C) increase in Southwest regional annual average temperature by 2100.[23] Southern parts of the region could get up to 45 more days each year with maximum temperatures of 90°F (32°C) or higher.[23] Projected hotter temperatures increase probabilities of decadal to multi-decadal megadroughts,[61,62,69,70] which are persistent droughts lasting longer than a decade,[69] even when precipitation increases. Under the higher scenario (RCP8.5), much of the mountain area in California with winters currently dominated by snow would begin to receive more precipitation as rain and then only rain by 2050.[71] Colder and higher areas in the intermountain West would also receive more rain in the fall and spring but continue to receive snow in the winter at the highest elevations.[71]

Increases in temperature would also contribute to aridification (a potentially permanent change to a drier environment) in much of the Southwest, through increased evapotranspiration,[69,70,72,73] lower soil moisture,[74] reduced snow cover,[71,75,76,77] earlier and slower snowmelt,[75] and changes in the timing and efficiency of snowmelt and runoff.[50,54,75,76,78,79] Some research indicates increasing frequency of dry high-pressure weather systems associated with changes in Northern Hemisphere atmospheric circulation.[80,81] These changes would tend to increase the duration and severity of droughts[67,74] and generate an overall drier regional climate.[69,70,72]

Climate models project an increase in the frequency of heavy downpours, especially through atmospheric rivers,[74,82] which are narrow bands of highly concentrated storms that move in from the Pacific Ocean. A series of strong atmospheric rivers caused extreme flooding in California in 2016 and 2017. Under the higher scenario (RCP8.5), models project increases in the frequency and intensity of atmospheric rivers.[83,84,85,86] Climate models also project an increase in daily extreme summer precipitation in the Southwest region, based on projected increases in water vapor resulting from higher temperatures.[20,87,88] Projections of summer total precipitation are uncertain, with average projected totals not differing substantially from what would be expected due to natural variations in climate.[88]

The Southwest generates one-eighth of U.S. energy, with hydropower, solar, wind, and other renewable sources supplying one-fifth of regional energy generation.[89] By installing so much renewable energy, the Southwest has lowered its per capita and per dollar greenhouse gas emissions below the U.S. average.[90] Climate change can, however, decrease hydropower and fossil fuel energy generation.[91] California has enacted mandatory greenhouse gas emissions reductions,[92] and Arizona, California, Colorado, Nevada, and New Mexico have passed renewable portfolio standards to reduce fossil fuel dependence and greenhouse gas emissions.[93]

What Is New in the Fourth National Climate Assessment

This chapter builds on assessments of climate change in the Southwest region from the three previous U.S. National Climate Assessments.[94,95,96] Each assessment has consistently identified drought, water shortages, and loss of ecosystem integrity as major challenges that the Southwest confronts under climate change. This chapter further examines interconnections among water, ecosystems, the coast, food, and human health and adds new Key Messages concerning energy and Indigenous peoples.

Since the last assessment, published field research has provided even stronger detection of hydrological drought, tree death, wildfire increases, sea level rise, and warming, oxygen loss, and acidification of the ocean that have been statistically different from natural variation, with much of the attribution pointing to human-caused climate change. In addition, new research has provided published information on future vulnerabilities and risks from climate change, including floods, food insecurity, effects on the natural and cultural resources that sustain Indigenous peoples, illnesses due to the combination of heat with air pollution, harm to mental health, post-wildfire effects on ecosystems and infrastructure, and reductions of hydropower and fossil fuel electricity generation.

This chapter highlights many of the increasing number of actions that local governments and organizations have been taking in response to historical impacts of climate change and to reduce future risks (Figure 25.2). Some examples include voluntary water conservation and management in California and the Colorado River Basin, restoring cultural fire management in California, and rooftop solar policies in California, Colorado, and Nevada. Many state and local governments have issued climate change assessments and action plans.

Actions Responding to Climate Change Impacts and Vulnerabilities

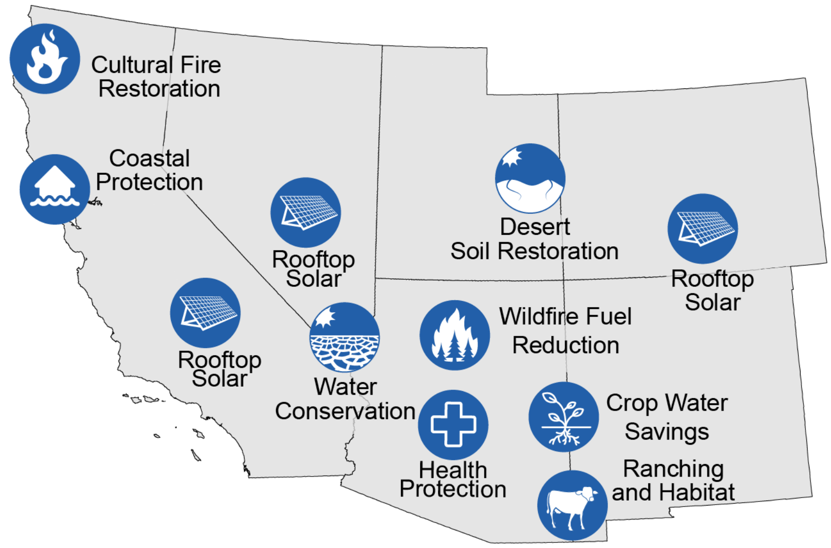


Figure 25.2: These examples illustrate actions that people, communities, and governments are taking in response to past impacts of climate change and future vulnerabilities. **Coastal protection**: In response to sea level rise and storm surge in San Francisco Bay, federal, state, and local agencies, supported by voter-approved funds, are restoring coastal habitats and levees to protect cities from flooding. **Crop water savings**: The risk of reduced food production increases as climate change intensifies drought. In the Gila River Basin, local government agencies have lined 15 miles (24 km) of irrigation canals to reduce seepage from the canals, saving enough water to irrigate approximately 8,500 acres (3,400 hectares) of alfalfa and other crops each year. **Cultural fire restoration**: Reintroduction of cultural burning by the Yurok Tribe in northern California reduces wildfire risks and protects public and tribal trust resources. **Desert soil restoration**: In Utah, transplanting native and drought-resistant microbial communities improves soil fertility and guards against erosion. **Health protection**: To reduce heat-associated injury and deaths on Arizona trails, the City of Phoenix and Arizona tourism organizations developed a campaign "Take a Hike. Do it Right." Signs at trailheads and on websites remind hikers to bring water, stay hydrated, and stay aware of environmental conditions. **Ranching and habitat**: The Malpai Borderlands Group in Arizona and New Mexico integrates native plant and wildlife conservation into private ranching. **Rooftop solar**: The state governments of California, Colorado, and Nevada have enacted policies that support rooftop solar on homes, which reduces greenhouse gas emissions, improves reliability of the electricity generation system, and creates local small businesses and new jobs. **Water conservation**: Drought in the Colorado River Basin has reduced the volume of water in both Lake Mead and Lake Powell by over half. The United States, Mexico, and state governments have mobilized users to conserve water, keeping the lake above a critical level. **Wildfire fuel reduction**: In response to severe wildfires, the City of Flagstaff, Arizona, enacted a bond to fund reduction of fire fuels in forests around the town. Source: National Park Service.

Key Message 1

Water Resources

Water for people and nature in the Southwest has declined during droughts, due in part to human-caused climate change. Intensifying droughts and occasional large floods, combined with critical water demands from a growing population, deteriorating infrastructure, and groundwater depletion suggest the need for flexible water management techniques that address changing risks over time, balancing declining supplies with greater demands.

Higher temperatures intensified the recent severe drought in California and are amplifying drought in the Colorado River Basin. In California, the higher temperatures intensified the 2011–2016 drought,[14,56,97,98,99] which had been initiated by years of low precipitation,[57,58] causing water shortages to ecosystems, cities, farms, and energy generators. In addition, above-freezing temperatures through the winter of 2014–2015 led to the lowest snowpack in California (referred to as a warm snow drought) on record.[47,55,98,100] Through increased temperature, climate change may have accounted for one-tenth to one-fifth of the reduced soil moisture from 2012 to 2014 during the recent California drought.[14] In the ongoing Colorado River Basin drought, high temperatures due mainly to climate change have contributed to lower runoff[12,59] and to 17%–50% of the record-setting streamflow reductions between 2000 and 2014 (Figure 25.3).[13] In the Rio Grande, higher temperatures have been linked to declining runoff efficiency[60] and reductions in snowpack.[45]

Increased temperatures, especially the earlier occurrence of spring warmth,[101] have significantly altered the water cycle in the Southwest region. These changes include decreases in snowpack and its water content,[46,47,48,49,102] earlier peak of snow-fed streamflow,[103] and increases in the proportion of rain to snow.[49,103] These changes, attributed mainly to climate change,[49,103] exacerbate hydrological drought.

With continued greenhouse gas emissions, higher temperatures would cause more frequent and severe droughts in the Southwest.[11,56,62,65,80] This would also lead to drier future conditions for the region.[70,74] Higher temperatures sharply increase the risk of megadroughts—dry periods lasting 10 years or more.[61,62,65] Under the higher scenario (RCP8.5), models project annual declines of river flow in southern basins (the Rio Grande and the lower Colorado River) and either no change or modest increases in northern basins (northern California and the upper Colorado River).[78,104,105,106,107] Snowpack supplies a major portion of water in the Southwest, but with continued emissions, models project substantial reductions in snowpack, less snow and more rain, shorter snowfall seasons, earlier runoff,[55,71,78,79,108,109] and warmer late-season stream temperatures.[110] Fewer days with precipitation would lead to increased year-to-year variability.[111,112,113] Substantial increases in precipitation would be needed to overcome temperature-induced decreases in river flow.[13] The combination of reduced river flows in California and the Colorado River Basin and increasing population in southern California, which imports most of its water, would increase the probability of future water shortages.[114]

In response to the recent California drought, the state government implemented a water conservation plan in 2014 that set allocations for water utilities and major users and banned wasteful practices such as watering during or after a rainfall, hosing off sidewalks, and irrigating ornamental turf on public street medians.[115] As a result, the people of the state reduced water use 25% from 2014 to 2017, when abundant rains allowed the state to lift many restrictions while continuing to promote water conservation as a way of life.[116]

The Southern Nevada Water Authority used similar measures to reduce water use per person 38% from 2002 to 2016.[117] Water utilities in the Colorado Front Range also used similar conservation practices to reduce water use more than 20% in the early 2000s.[118] While many southwestern cities have reduced total and per-person water use since the 1990s despite growing populations,[119] ongoing drought has increased competition for reliable water supplies in many locations. In parts of Colorado, Nevada, and Utah, population growth has prompted proposals for new water diversions and transfers from agriculture. While desalination of seawater and brackish water has been proposed as a partial solution to water scarcity, its high energy requirement creates greenhouse gas emissions and its capital costs are high.[15]

Atmospheric rivers, which have caused many large floods in California,[120] may increase in severity and frequency under climate change.[82,83,107,121,122,123,124] In the winter of 2016–2017, a series of strong atmospheric rivers generated high runoff in northern California and filled reservoirs. At Oroville

Dam, high flows eroded the structurally flawed emergency spillway, caused costly damage, and led to the preventive evacuation of people living downstream. In addition to the immediate threat to human life and property, this incident revealed two water supply risks. First, summer water supplies are reduced when protective flood control releases of water from reservoirs are necessary in the spring.[108] Second, several studies have concluded that deteriorating dams, spillways, and other infrastructure require substantial maintenance and repair.[125,126] In U.S.–Mexico border cities with chronic urban storm water and pollutant runoff problems[127] and populations vulnerable to flooding,[127,128] projected increases in heavy precipitation[88] would increase risks of floods.

Wet periods present a water resource opportunity because increased infiltration from the surface into the ground recharges groundwater aquifers. Groundwater was critical for farmers during the California drought, especially for fruit and nut trees and grapevines.[129,130,131] Overdraft of groundwater, however, caused land subsidence (sinking), which can permanently reduce groundwater storage capacity and damage infrastructure as the ground deforms.[132]

In light of projected future changes in the hydrologic cycle, water resource planners and scientists are testing new techniques to combine results from multiple climate and hydrology models, downscale climate model output to finer geographic scales, calculate changing water demands, and use forecasts for flood control.[133,134,135,136] Integrating data from satellites, climate and hydrology models, and field observations remains difficult with existing water management tools, methods, and legal requirements.

Box 25.1: Collaborative Management of Colorado River Water

Since 2000, Lake Mead on the Colorado River has fallen 130 feet (40 m) and lost 60% of its volume,[137,138,139] a result of the ongoing Colorado River Basin drought and continued water withdrawals by cities and agriculture (Figure 25.3). This is the lowest level since the filling of the reservoir in 1936.[139] The reduction of Lake Mead increases the risk of water shortages across much of the Southwest and reduces energy generation at the Hoover Dam hydroelectric plant at the reservoir outlet. Local water utilities, the governments of seven U.S. states, and the federal governments of the United States and Mexico have voluntarily developed and implemented solutions to minimize the possibility of water shortages for cities, farms, and ecosystems. The parties have taken four key actions:

Hydrological drought in Lake Mead, Nevada, on March 10, 2014. Photo credit: U.S. Bureau of Reclamation.

1. Arizona, California, and Nevada agreed in 2007, with Mexico joining in 2012, to allow users to store water in Lake Mead for later years, rather than being forced to use it immediately or lose their rights.[140]

2. The United States and Mexico agreed in 2014 to release water for eight weeks to re-water the Colorado River Delta in Mexico in order to improve wildlife habitat and to conduct research on environmental restoration.[141]

Box 25.1: Collaborative Management of Colorado River Water, *continued*

3. The water agencies of Denver, Las Vegas, Los Angeles, and Phoenix and the U.S. Bureau of Reclamation in 2015 set up the Colorado River System Conservation Pilot Program, a fund for local water conservation projects. A second phase extended conservation projects to all of the Colorado River Basin.

4. Mexico agreed in 2017 to absorb a share of water shortages if Lake Mead fell below a specific elevation. The agreement continues Mexico's right to bank unused water in Lake Mead for future use. With financial and other U.S. assistance, Mexico will pursue water conservation projects and environmental restoration within the Colorado River Delta.

Currently, stakeholders are engaged in drought contingency planning for multiple climate futures, implementing management strategies that make sense for the range of climate futures, and preserving options when possible.[142]

Severe Drought Reduces Water Supplies in the Southwest

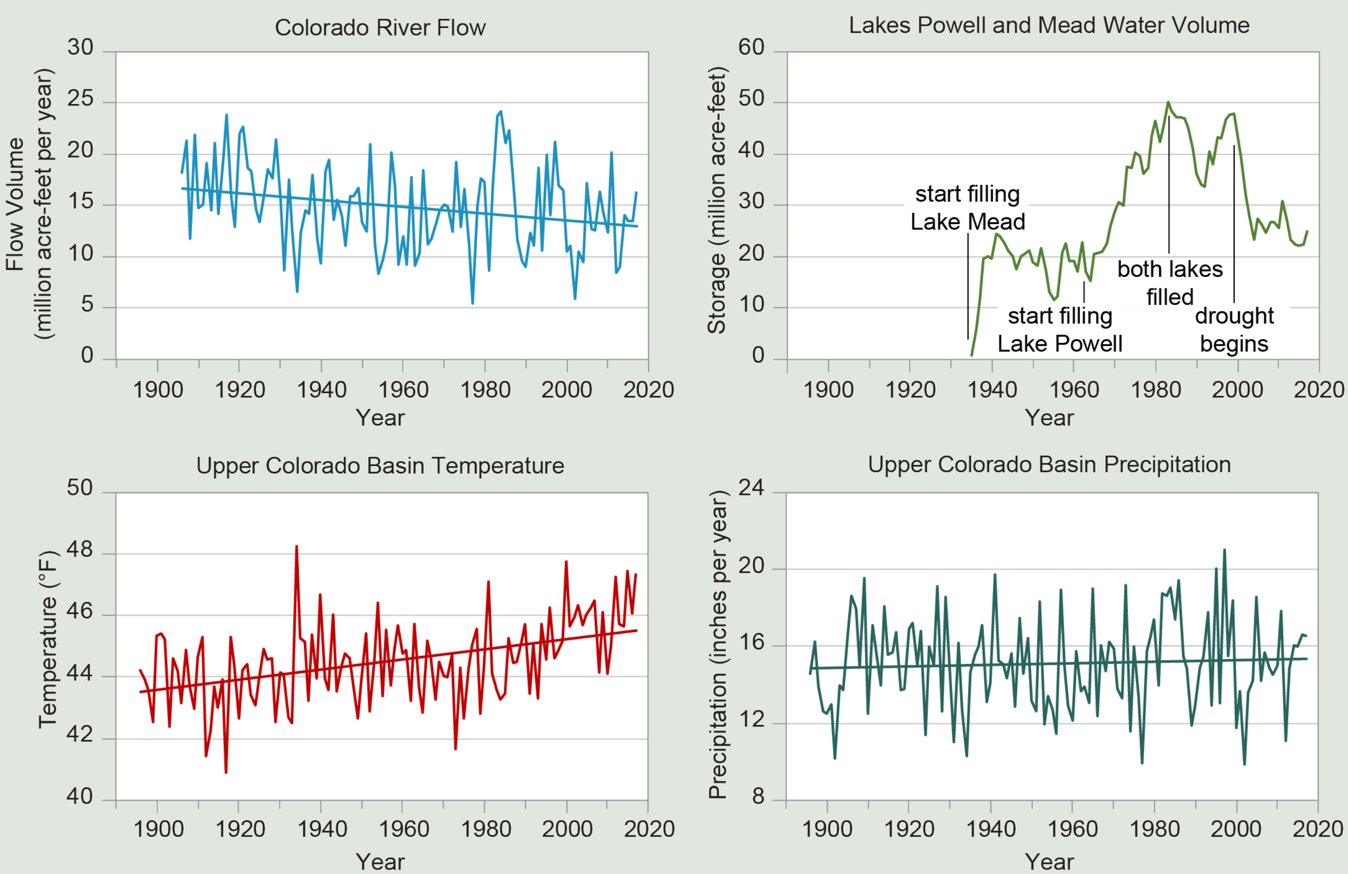


Figure 25.3: Since 2000, drought that was intensified by long-term trends of higher temperatures due to climate change has reduced the flow in the Colorado River (top left), which in turn has reduced the combined contents of Lakes Powell and Mead to the lowest level since both lakes were first filled (top right). In the Upper Colorado River Basin that feeds the reservoirs, temperatures have increased (bottom left), which increases plant water use and evaporation, reducing lake inflows and contents. Although annual precipitation (bottom right) has been variable without a long-term trend, there has been a recent decline in precipitation that exacerbates the drought. Combined with increased Lower Basin water consumption that began in the 1990s, these trends explain the recently reduced reservoir contents. Straight lines indicate trends for temperature, precipitation, and river flow. The trends for temperature and river flow are statistically significant. Sources: Colorado State University and CICS-NC. Temperature and precipitation data from: PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu, accessed 20 June 2018.

Key Message 2

Ecosystems and Ecosystem Services

The integrity of Southwest forests and other ecosystems and their ability to provide natural habitat, clean water, and economic livelihoods have declined as a result of recent droughts and wildfire due in part to human-caused climate change. Greenhouse gas emissions reductions, fire management, and other actions can help reduce future vulnerabilities of ecosystems and human well-being.

The forests and other ecosystems of the Southwest region that provide natural habitat and essential resources for people have declined in fundamental ways due in part to climate change. Vast numbers of trees have died across Southwest forests and woodlands,[143,144,145,146] disproportionately affecting larger trees.[147] Tree death in mid-elevation conifer forests doubled from 1955 to 2007 due in part to climate change.[146] Field measurements showed that changes attributable, in part, to climate change, including increases in temperature, wildfire,[7] and bark beetle infestations,[148,149] outweighed non-climate factors such as fire exclusion or competition for light.[146]

Wildfire is a natural part of many ecosystems in the Southwest, facilitating germination of new seedlings and killing pests. Although many ecosystems require fire, excessive wildfire can permanently alter ecosystem integrity.[150,151] Climate change has led to an increase in the area burned by wildfire in the western United States.[7,152] Analyses estimate that the area burned by wildfire from 1984 to 2015 was twice what would have burned had climate change not occurred (Figure 25.4).[7] Furthermore, the area burned from 1916 to 2003 was more closely related to climate factors than to fire suppression, local fire management, or other non-climate factors.[152]

Climate change has driven the wildfire increase,[7,153] particularly by drying forests and making them more susceptible to burning.[154,155] Specifically, increased temperatures have intensified drought in California,[14] contributed to drought in the Colorado River Basin,[12,13]

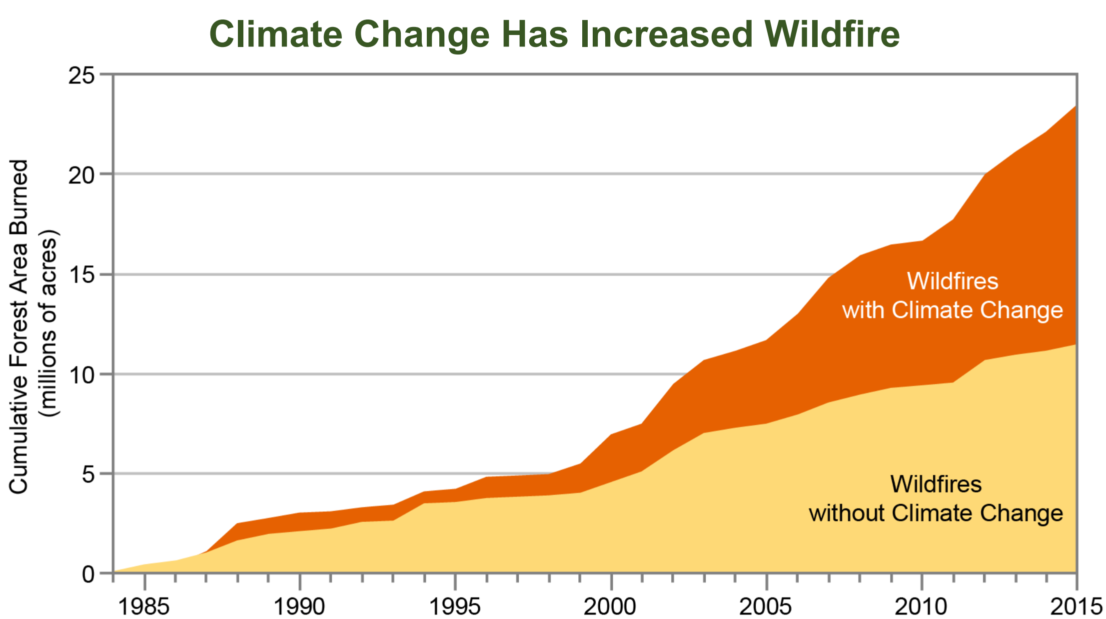


Figure 25.4: The cumulative forest area burned by wildfires has greatly increased between 1984 and 2015, with analyses estimating that the area burned by wildfire across the western United States over that period was twice what would have burned had climate change not occurred. Source: adapted from Abatzoglou and Williams 2016.[7]

reduced snowpack,[46,49,156] and caused spring-like temperatures to occur earlier in the year.[101] In addition, historical fire suppression policies have caused unnatural accumulations of understory trees and coarse woody debris in many lower-elevation forest types, fueling more intense and extensive wildfires.[150,157]

Wildfire can threaten people and homes,[159] particularly as building expands in fire-prone areas. Wildfires around Los Angeles from 1990 to 2009 caused $3.1 billion in damages (unadjusted for inflation).[159] Respiratory illnesses and life disruptions from the Station Fire north of Los Angeles in 2009 cost an estimated $84 per person per day (in 2009 dollars).[160] In addition, wildfires degraded drinking water upstream of Albuquerque with sediment, acidity, and nitrates[161,162] and in Fort Collins, Colorado, with sediment and precursors of cancer-causing trihalomethane, necessitating a multi-month switch to alternative municipal water supplies.[163,164]

Ecosystems can naturally slow climate change by storing carbon, but recent wildfires have made California ecosystems and Southwest forests net carbon emitters (they are releasing more carbon to the atmosphere than they are storing).[6,144,165] Wildfire has also exacerbated the spread of invasive plant species and damaged habitat. For example, repeated wildfire in sagebrush in Nevada and Utah has caused extensive invasions of cheatgrass, reducing habitat for the endangered sage-grouse.[64,166]

Post-wildfire erosion damages ecosystems by denuding hillsides, such as occurred in Valles Caldera National Preserve in New Mexico when the 2011 Las Conchas Fire generated the biggest local erosion event in 1,000 years.[167] In New Mexico, consecutive large wildfires degraded habitat and reduced abundance of six out of seven native coldwater fishes and some native insects, although nonnative fishes were less affected.[168]

With continued greenhouse gas emissions, models project more wildfire across the Southwest region.[169,170,171,172,173] Under higher emissions (SRES A2)[174] (see the Scenario Products section of App. 3), fire frequency could increase 25%,[172] and the frequency of very large fires (greater than 5,000 hectares) could triple.[169] The Santa Ana winds and other very dry seasonal winds increase fire risk in California[175] and Mexico.[176] Under higher emissions (SRES A2), sediment flows after fires would double in one-third of western U.S. watersheds modeled,[177] with the sediment potentially damaging ecosystems, homes, roads, and rail lines (Ch. 12: Transportation; Ch. 17: Complex Systems). Under the higher scenario (RCP8.5), cumulative firefighting costs for the Southwest could total $13 billion from 2006 to 2099 (in 2015 dollars, discounted at 3%).[178]

Reducing greenhouse gas emissions can reduce ecological vulnerabilities to wildfire.[179] For example, under a higher emissions scenario (SRES A2), climate change could triple burned area (in a 30-year period) in the Sierra Nevada by 2100, while under a lower emissions scenario (SRES B1[174]), fire would only slightly increase.[173]

Allowing naturally ignited fires to burn in wilderness and preemptively setting low-severity prescribed burns in areas of unnatural fuel accumulations can reduce the risk of high-severity fires under climate change.[180,181,182,183,184] These actions can naturally reduce or slow climate change because long-term storage of carbon in large trees can outweigh short-term emissions.[185,186] Proactive use of fire in Yosemite, Sequoia, and Kings Canyon National Parks has improved the resilience of giant sequoias and other trees to severe fires and protected their stores of carbon.[187,188,190,191]

Climate change has also contributed to increased forest pest infestations, another major cause of tree death in Southwest forests and woodlands (Ch. 17: Complex Systems, Box 17.4). Bark beetle infestations killed 7% of western U.S. forest area from 1979 to 2012,[148,149] driven by winter warming due to climate change[103,192] and by drought.[193] Tree death from bark beetles in Colorado increased organic matter in local streams, elevating precursors of cancer-causing trihalomethane in local water treatment plants[194] to levels that exceed the maximum contaminant levels for drinking water specified by the U.S. Environmental Protection Agency.[195] Without greenhouse gas emissions reductions, further increases in heat and drought could kill many more trees,[143,196,197] especially affecting piñon pine,[198] whitebark pine,[199] and tall old-growth trees.[200] Drought hastens tree mortality over a wide range of temperatures.[201] On the Colorado Plateau in Utah, five years of hotter temperatures in experiments killed microbial biocrusts, which conserve soil fertility and protect soils from erosion.[202,203,204] In addition, grasslands[205,206] and desert plants[207,208] are vulnerable to increased plant death.

Field research in Southwest ecosystems has detected geographic shifts (Ch. 7: Ecosystems) of both plant and animal species, partly attributable to climate change. In Yosemite National Park, forest shifted into subalpine meadows from 1880 to 2002,[209] and small mammals shifted 1,600 feet (500 m) upslope from 1914 to 2006,[210] with climate change outweighing other factors as the cause.[209,210] Across the United States, including the Southwest, birds shifted northward between 0.1 and 0.5 miles (0.2 to 0.8 km) per year from 1975 to 2004, and analyses attribute the shift to climate change.[211,212]

Continued climate change would cause north-south or upslope shifts of biomes (major vegetation types) in the Southwest as vegetation follows cooler temperatures.[213] Areas highly vulnerable to such biome shifts include the Arizona Sky Islands[214] and the Sierra Nevada.[215] Potential shifts of suitable habitat for individual species include the shifting of Joshua tree habitat out of much of Joshua Tree National Park,[207,216] American pika habitat shifting off of mountain tops,[217,218] and upslope or northward shifts of numerous birds and reptiles across the Southwest.[219,220,221] Climate change may also cause shifts in the timing of plant and animal life events (phenology), including flower blooming, plant leafing, and breeding time of birds and other animals.[222,223,224] The arrival of migrating broad-tailed hummingbirds in Colorado advanced five days between 1975 and 2011.[225] Plant species that provide essential food (nectar) for the hummingbirds also shifted in phenology (Ch. 7: Ecosystems), but much more than the birds, potentially jeopardizing breeding success.

To prepare for potential future ecological changes, U.S. federal agencies have begun to integrate climate change science into resource management planning in the Southwest. For example, the U.S. National Park Service has developed park plans with specific actions for managing resources under climate change.[226] On private lands, planning that integrates native plants and wildlife into working landscapes such as farms, orchards, and ranches can promote conservation outside of protected areas and provide valued ecosystem services,

The 2013 Rim Fire in California burned more than 257,000 acres, the second largest wildfire in the Sierra Nevada and the third largest fire in California since 1932. Photo credit: Mike McMillan, U.S. Forest Service.

as demonstrated for rangelands by the Malpai Borderlands Group in Arizona and New Mexico.[227,228] In response to severe wildfires, the City of Flagstaff, Arizona, enacted a bond to provide funds to thin forest around the town perimeter.[229,230] Ecosystem restoration provides an opportunity to integrate climate change considerations into natural resource management.[231] Desert research scientists have developed the ability to grow microbial biocrusts and are testing whether translocating biocrusts that are adapted to thrive at higher temperatures can restore the soil-stabilizing, nutrient-fixing, and other services that these organisms provide in many Southwest desert ecosystems.[232,233,234] Finally, conservation of forests, especially coast redwoods, which have the highest carbon densities of any ecosystem in the world,[235] can slow or reduce climate change by naturally removing carbon from the atmosphere.[6]

Key Message 3

The Coast

Many coastal resources in the Southwest have been affected by sea level rise, ocean warming, and reduced ocean oxygen—all impacts of human-caused climate change—and ocean acidification resulting from human emissions of carbon dioxide. Homes and other coastal infrastructure, marine flora and fauna, and people who depend on coastal resources face increased risks under continued climate change.

At the Golden Gate Bridge in San Francisco, sea level rose 9 inches (22 cm) between 1854 and 2016 (Figure 25.5),[236] and in San Diego, sea level rose 9.5 inches (24 cm) from 1906 to 2016.[237] Tidal gauges around the world show increases in sea level,[238,239] and analyses show that climate change caused most of this rise by melting of land ice and thermal expansion of ocean water.[21,240,241] Non-climate-related land level changes influence relative sea level change. For example, between Cape Mendocino, California, and the Oregon border, lifting of the land at the San Andreas Fault has caused a drop in relative sea level between 1933 and 2016. Past earthquakes in the northern California coastal zone have abruptly lowered the shoreline and raised relative sea level.[242]

Under the higher scenario (RCP8.5), continued climate change could raise sea level near San Francisco by 30 inches (76 cm) by 2100, with a range of 19–41 inches (49–104 cm).[242] Currently, 200,000 people in California live in areas 3 feet (0.9 m) or less above sea level.[9] Projections of sea level rise show that this population lives in areas at risk of inundation by 2100.[9] Storm surges and high tides on top of sea level rise would exacerbate flooding.[242] In Redwood City, one-fifth of houses and one-quarter of roads are at risk of flooding under the higher scenario (RCP8.5) by 2100.[243] Sea level rise and storm surge could completely erode two-thirds of southern California beaches by 2100[244] and cause saltwater infiltration that would spoil groundwater at Stinson Beach in Marin County, California.[245] Major seaports in Long Beach and Oakland and the international airports of San Francisco, Oakland, and San Diego are vulnerable. Projected sea level rise and storm surges could cause as much as $5 billion (2015 dollars, undiscounted) in damage to property along the California coast from 2000 to 2100 under the higher scenario (RCP8.5).[178] In Point Reyes National Seashore, sea level rise threatens to inundate habitat for the endangered western snowy plover, harbor seals,[246] and northern elephant seals,[247] as well as archaeological Indigenous sites.

Governments and private landowners along the California coast have built seawalls, revetments, and other structures to protect against sea level rise and storm surge, armoring 10% of the coastline.[248] Because hard structures often alter natural water flows and increase coastal erosion, many parties are now exploring how to restore dunes, reefs, wetlands, and other natural features to protect the coast by breaking wave energy, to increase wildlife habitat, and to preserve public access to the coast.[249]

Local governments on the California coast are using projections of sea level rise to develop plans to reduce future risks. The City of San Francisco[250] is implementing a plan that limits building in low-lying areas, constructs terraced wetlands at India Basin to facilitate upland migration of marsh habitat, and protects San Francisco International Airport with berms and seawalls along the 8-mile (13 km) shoreline. Golden Gate National Recreation Area has produced a detailed spatial analysis of the vulnerability of the marsh, paths, and buildings at Crissy Field to sea level rise and storm surges and has developed adaptation options, including moving infrastructure and establishing protective wetlands on inundated land.[251] In 2016, residents of the nine counties of the San Francisco Bay passed Measure AA, which provides funding for wetlands restoration to naturally reduce risks of flooding and inundation due to sea level rise and storm surge.

Ocean waters off the California coast and around the world warmed 0.6° to 0.8°F (0.3° to 0.5°C) from 1971 to 2010,[252] mainly due to human-caused climate change.[21] Over the past century, sea surface temperatures in the northeast Pacific Ocean (including those off the coast of California) also experienced large year-to-year and decade-to-decade variations in response to changes in wind and weather patterns that altered the exchange of heat between the ocean and atmosphere and within the upper ocean,[253] but showed overall warming from 1920 to 2016 (Figure. 25.6).

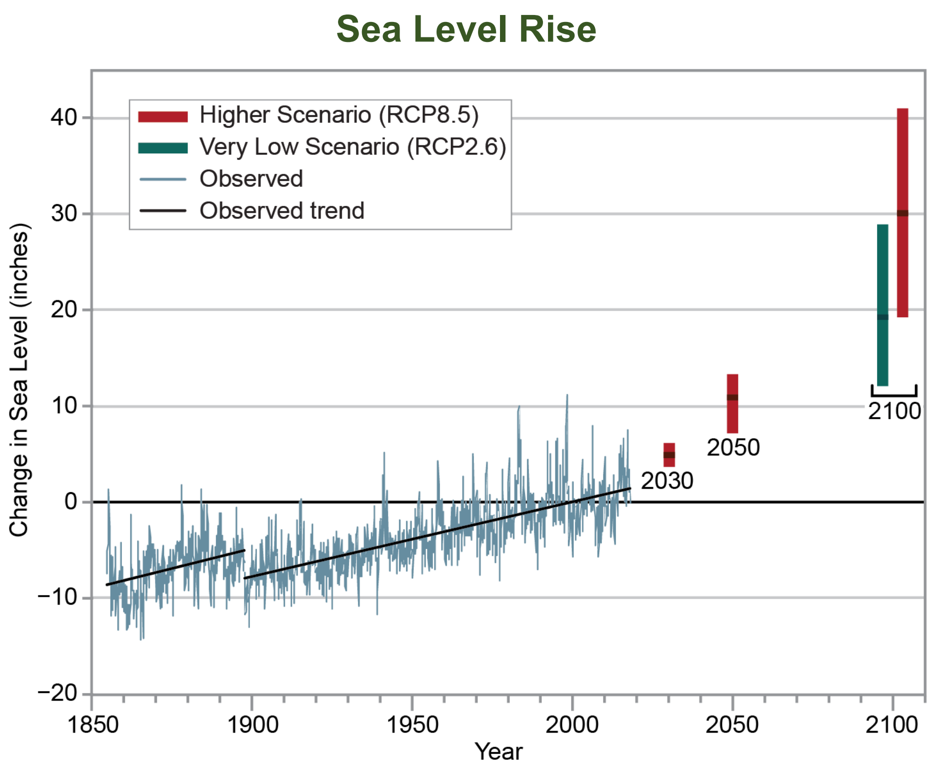


Figure 25.5: Sea level rise increases risks to infrastructure. At the Golden Gate Bridge in San Francisco, California, the tidal gauge with the longest time series in the Western Hemisphere shows that sea level has risen nearly 9 inches (22 cm) since 1854 (blue line).[236,295] In 1897, the tidal gauge was moved, which caused a slight shift downward of the numerical level but no change in the long-term trend (trends indicated by the black lines). The bars show models projections of sea levels under a higher scenario (RCP8.5; red) and a very low scenario (RCP2.6; green).[242] The change in sea level is shown relative to the 1991–2009 average. Source: National Park Service.

Ocean Temperature Increase

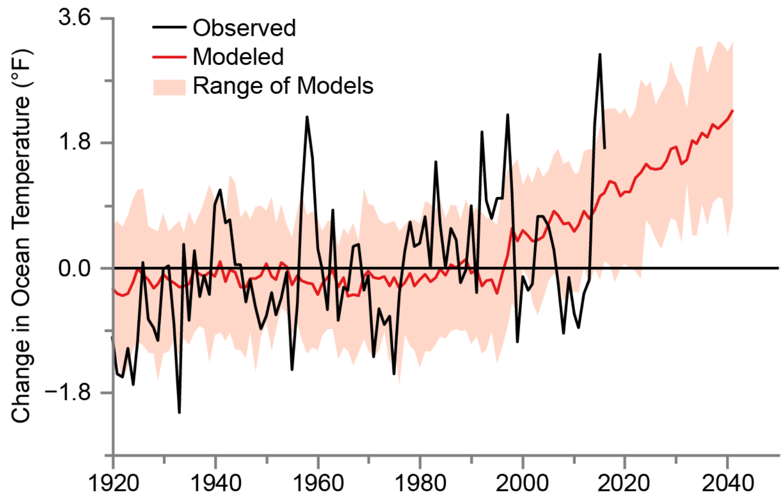


Figure 25.6 Ocean warming increases risks to fisheries and shellfish. The graph shows observed ocean temperatures of the California Current from measurements (black line); modeled temperatures, extended into the future under the higher scenario (RCP8.5; red line); and the range of 10% to 90% of the 28 models used (pink).[254,296,297] Sources: National Park Service and NOAA.

The marine heat wave along the Pacific Coast from 2014 to 2016 occurred due to a combination of natural factors and climate change.[254] The event led to the mass stranding of sick or starving birds and sea lions and shifts in pelagic (open water) red crabs and tuna into the region.[255] The ecosystem disruptions contributed to closures of commercially important fisheries and substantial reductions in California salmon catches in 2016 and 2017.[256,257,258] Ocean warming also contributed to an increase in harmful blooms of algae along the Pacific Coast.[259,260,261,262] These harmful algal blooms have produced domoic acid, which can kill people who eat tainted shellfish[261,263] and kill California sea lions.[261,264,265] Harmful algal blooms and shellfish contamination in the record warm year of 2015 delayed the commercially important Dungeness crab fishery, which contributed to a substantially reduced catch. Shifts in the timing of Dungeness and rock crab fisheries into whale migration season in 2016 contributed to increases in whale entanglements in fishing gear.[266]

Continued climate change could warm California Current waters 4°–7°F (2°–4°C) above the 1980–2005 average by 2100 (Figure 25.6).[267] This could contribute to more harmful algal blooms,[259,261] deaths of birds and sea lions, closures of fisheries, and economic loss to sectors dependent upon coastal marine resources. Under higher emissions (SRES A2), 28 fish species, including coho salmon and steelhead, could shift northward more than 180 miles (300 km) by 2050 due to higher sea surface temperatures.[268] Marine heat waves may also increase in frequency, possibly causing local disappearance of some fish and economic losses.[269]

Observed ocean water acidity off the coast of California increased 25% to 40% (decreases of about 0.10 to 0.15 pH units) from the preindustrial era (circa 1750) to the early 2000s[270,271] due to increasing emissions of carbon dioxide from human activities.[21,272] Modeling studies show that human-caused changes in ocean acidity have increased beyond what would be expected from natural variations in the early-to-mid-20th century.[273] Along the California coast, during some episodes of naturally acidic spring/summer upwelling of deeper ocean water, ocean acidity has quadrupled (a decrease of 0.7 pH units) to some of the most acidic values in the world.[274] Increased ocean acidity along California's coast has dissolved shells of some small planktonic sea snails (pteropods), exceeding their adaptive capacity, which was developed from evolution in natural acidic upwellings.[275,276,277] In contrast, nearshore kelp forests in the northern Channel Islands off the California coast experienced few acidic events compared to local mainland sites in one three-year study.[278]

Higher carbon emissions (SRES A2) could increase the acidity of California coastal waters 40% (a decrease of 0.15 pH units) above 1995 levels by 2050.[270] In addition to damaging marine ecosystems, ocean acidification increases risks of economic losses in the shellfish industry. One ecosystem modeling study suggests negative effects of projected ocean acidification on California's state-managed crab, shrimp, mussel, clam, and oyster fisheries, but an increase in the urchin fishery.[279] Warming of ocean waters has reduced oxygen concentrations in the California Current System by 20% from 1980 to 2012.[280,281] Dissolved oxygen variations in waters far offshore affect oxygen concentrations in the California Current System nearshore.[280,282] This deoxygenation contributed to an expansion of Humboldt squid, a species that thrives in deoxygenated water, in the northeastern Pacific Ocean in the late 1990s.[283,284] Invading Humboldt squid prey on hake and other fish that are commercially important to coastal fishing communities.[283]

Climate change may reduce ocean oxygen in Pacific Ocean waters to levels lower than any naturally occurring levels as early as 2030[285] or 2050.[273] Reduced oxygen could decrease rockfish habitat off southern California by 20% to 50%.[286] Further deoxygenation may harm bottom-dwelling marine life, shrink open-water habitat for hake and other economically important species,[287] and increase the number of invasions by squid. Tracking the variability of ocean waters and fish populations and adjusting catch quotas accordingly can reduce pressures on fisheries stressed by climate change,[288] actions that have been identified as parts of the National Oceanic and Atmospheric Administration's (NOAA) Fisheries Climate Science Strategy.[289]

With continued climate change, risks would cascade from one area to another. For example, projected warmer winter temperatures in the Sierra Nevada would increase winter runoff, reduce spring and summer freshwater inflows into San Francisco Bay, and increase salinity in the Bay 3 to 5 grams per kilogram of water by 2100.[290,291,292] Also, sea level rise and storm surge would compound effects inland of river and stream flooding, putting houses and roads at risk of inundation and damage.[293,294]

Key Message 4

Indigenous Peoples

Traditional foods, natural resource-based livelihoods, cultural resources, and spiritual well-being of Indigenous peoples in the Southwest are increasingly affected by drought, wildfire, and changing ocean conditions. Because future changes would further disrupt the ecosystems on which Indigenous peoples depend, tribes are implementing adaptation measures and emissions reduction actions.

Droughts in the Southwest have contributed to declines in traditional Indigenous staple foods, including acorns, corn, and pine nuts.[298,299,300] Drought and increasing heat intensify the arid conditions of reservations where the United States restricted some tribal nations in the Southwest region to the driest portions of their traditional homelands.[301] Navajo elders tell of the increasingly arid conditions over the last half of the 20th century that contributed to declines in culturally significant crops, the flow of specific water springs and seeps, and wildlife populations, such as eagles.[44,302] Projected reductions in water supply reliability,[13,114] coupled with water agreements that involve selling or leasing tribal water to neighboring communities, could place tribal water supplies at risk during severe shortages. As water supplies decrease and water demand increases, tribes are at risk of finding themselves committed to providing purchased water to other entities, resulting in situations in which, in the words of one elder, "water sold must be delivered, regardless of the condition of the selling reservation. In this worst-case scenario, the Community will have to breach its contracts for the survival of its people."[303]

In addition to drought, wildfires affect traditional resources, including fish, wildlife, and plants, such as tanoaks and beargrass, upon which some Southwest tribes rely for food and cultural uses.[304,305,306] Continued climate change would reduce populations of some fish, wildlife, and plants that serve as traditional foods, medicines, and livelihood and cultural resources.[298,307,308] Reduced availability of traditional foods often contributes to poorer nutrition and an increase in diabetes and heart disease.[298,309] Reductions in runoff would, for example, increase the salinity of Pyramid Lake in Nevada, reducing fish biodiversity and affecting the cui-ui fish, the primary cultural resource of the Pyramid Lake Paiute Tribe.[310] Tribes in the Southwest that depend on livestock are at risk of climate-related degradation of rangelands.[44,311,312] Many California tribes, including the Miwok, Paiute, Western Mono, and Yurok, among others, are concerned about the loss of acorns—a nutritious traditional food, medicine, and basketry component[313,314]—due to sudden oak death, which can increase with changes in humidity and temperature.[44,312,315] Changes in plant and animal ranges (Ch. 7: Ecosystems, KM 1) can also affect mental and spiritual health, disrupting cultural connections to disappearing plant and animal relatives and to place-based identity and practices.[42,316]

Changes in marine ecosystems affect resources for Indigenous peoples (Ch. 15: Tribes). Ocean warming affects salmon and other fish on which Pacific Coast tribes rely for subsistence, livelihoods, and cultural identity.[307,317,318,319,320] Ocean warming and acidification, as well as sea level rise, increase risks to shellfish beds (which reduces access for traditional harvesting),[298] pathogens that cause shellfish poisoning,[307,311] and damage to shellfish populations, which can cause cascading effects in food and ecological systems upon which some tribes depend.[298,321]

Although Indigenous peoples have adapted to climate variations in the past, historical intergenerational trauma, extractive infrastructure, and socioeconomic and political pressures[322,323] reduce their adaptive capacity to current and future climate change (Ch 15: Tribes, KM 1 and 3).[324] Still, in response to climate change, Indigenous peoples in the Southwest are developing new adaptation and mitigation actions based on a cultural model focused on relationships between humans and nonhumans.[313,325,326] Traditional ecological knowledge of specific plants and habitats can enable Indigenous peoples to provide early detection of invasive species and support to ecological restoration.[327] Some tribes, such as the Tesuque Pueblo of New Mexico, use their knowledge to reintegrate traditional foods into their diets. Other tribes, such as the Karuk Tribe,[304] North Fork Mono,[313] and Mountain Maidu[328] use traditional ecological knowledge to guide natural resource management. The Yurok Tribe, Gila River Indian Community, and Tohono O'odham Nation, among others, are developing climate adaptation plans, often in partnership with universities and other research institutions (Ch. 15: Tribes, KM 3 and Figure 15.1).

Many Indigenous peoples in the Southwest region have traditionally used fire as a tool central to cultural and spiritual practices. They use fire to protect and enhance species used for basket weaving, medicines, and traditional foods.[306,313,328,329,330,331,332] This cultural use of fire offers an important tool for adaptation and mitigation, as traditional burning reduces fuel accumulations that can lead to high-severity wildfires (see Case Study "Cultural Fire and Climate Resilience" and Figure 25.7).[331,333]

Case Study: Cultural Fire and Climate Resilience

Indigenous peoples in the Southwest have traditionally used fire as a tool central to social, cultural, and spiritual practices. They use fire to increase ecosystem resilience, reduce fuel loads, manage crops, and protect species used for basket weaving, medicines, and traditional foods.[306,313,328,329,330,331,332] Tribal entities are restoring cultural burning practices and management principles that guide the use of fire on the landscape to reduce wildfire risks and protect public and tribal trust resources.[331,333] For example, Yurok tribal members have formed the Cultural Fire Management Council (CFMC), in partnership with the Nature Conservancy Fire Learning Network, Firestorm Inc., Yurok Forestry/Wildland Fire, Northern California Indian Development Council, and the U.S. Department of Agriculture (USDA) Forest Service, to bring fire back to the landscape for ecosystem restoration.[334] The collaboration builds capacity and trains Yurok and local fire crews through the Prescribed Fire Training Exchange. "Restoration of the land means restoration of the people," said CFMC President Margo Robbins, "Returning fire to the land enables us to continue the traditions of our ancestors."[334]

Cultural Fire on Yurok Reservation

Figure 25.7: Andy Lamebear, a Yurok Wildland Fire Department firefighter and Yurok tribal member, ignites a cultural burn on the Yurok Reservation. The tribe uses low- to medium- intensity fires to enhance the production of plant-based medicines, traditional basket materials, native fruits, and forage for wildlife. Cultural burning also reduces risks of catastrophic wildfire. Photo courtesy of the Yurok Tribe.

Key Message 5

Energy

The ability of hydropower and fossil fuel electricity generation to meet growing energy use in the Southwest is decreasing as a result of drought and rising temperatures. Many renewable energy sources offer increased electricity reliability, lower water intensity of energy generation, reduced greenhouse gas emissions, and new economic opportunities.

Hydroelectric generation depends on sufficient water supplies. The severe drought in California, intensified by climate change,[14,56] reduced hydroelectric generation by two-thirds from 2011 to 2015.[335] Drought in the Colorado River Basin[13,59] caused river runoff, on which hydroelectric generation depends,[12,336,337] to decline. By 2016, Lake Mead, which stores water for drinking, agriculture, and the Hoover Dam hydroelectric plant, had fallen by half (Box 25.1 and Figure 25.3). Although the Bureau of Reclamation maintained constant electricity generation at Hoover Dam throughout the drought, this decline potentially reduces maximum generation capacity.

In California, utilities increased fossil fuel generation of electricity to compensate for the drought-driven decline in hydroelectricity, increasing state carbon dioxide emissions in the first year of the drought (2011 to 2012) by 1.8 million tons of carbon, the equivalent of emissions from roughly 1 million cars.[338,339] A drop in the price of natural gas also contributed to the increase, although the shift from hydroelectric to fossil fuels cost California an estimated $2.0 billion (in 2015 dollars).[340] Other southwestern states also shifted some generation from hydropower to fossil fuels.[89]

Under a higher scenario (RCP8.5), declines in snowpack and runoff in the Colorado River and Rio Grande Basins and a shift of spring runoff to earlier in the year[105] would reduce hydroelectric power potential in the region by up to 15% by 2050.[91] Under a very low scenario (RCP2.6), hydroelectric generation may remain unchanged, demonstrating the positive benefits of emissions reductions.[91] With increased precipitation, hydroelectric potential could increase,[342] except in cases of reservoir spillage to protect dams in extreme storms.[343]

The efficiency of water-cooled electric power plants that burn fuel depends on the temperature of the external cooling water, so climate change could reduce energy efficiency up to 15% across the Southwest region by 2050.[91] Since higher temperatures also increase electric resistance in transmission lines, electricity losses in many transmission lines across the Southwest could reach 5% by 2080 under a lower scenario (RCP4.5) and 7% under a higher scenario (RCP8.5).[344] Under the higher scenario (RCP8.5), water demand by thermoelectric plants in the Southwest is projected to increase 8% by 2100.[345] In a 10-year drought, summer electric generating potential in the Southwest could fall 3% to 9% under higher emissions (SRES A2) or 1% to 7% under lower emissions (SRES B1; Figure 25.8).[346]

Any increase in water requirements for energy generation from fossil fuels would coincide with reduced water supply reliability from projected decreases in snowpack[46,77] and earlier snowmelt.[75,347] Increased agricultural water demands under higher temperatures could affect the seasonal demand for hydropower electricity.[105] The water consumption, pollution, and greenhouse gas emissions of hydraulic fracturing (fracking) make that source of fuel even less adaptive under climate change.[348] Substantial energy and carbon emissions are embedded in the pumping, treatment, and transport of water, so renewable-powered water systems are less energy and carbon intense than ones powered by fossil fuels.[349]

Economic conditions and technological innovations have lowered renewable energy costs and increased renewable energy generation in the Southwest. For example, wind energy generation in California rose by half from 2011 to 2015, and solar energy generation increased by 15 times.[335]

Solar, wind, and other renewable energy sources, except biofuels, emit less carbon and require less water than fossil fuel energy. By cutting carbon emissions, renewable energy can reduce future impacts of climate change on nature and human well-being.[30,350,351,352] After the first year of the drought, when natural gas burning increased to compensate for a loss of hydroelectric energy, solar and wind energy sources in California increased enough to displace 15% of fossil fuel burning for electricity from 2012 to 2017, thereby reducing state greenhouse gas emissions by 6%.[335] Increased electricity generation by renewable sources can cut water needs up to 90% in the Southwest, depending on the fraction of production derived from fossil fuels.[353,354] Under a higher scenario (RCP8.5), conversion of two-thirds of fossil fuel plants to renewables would reduce water demand by half.[345]

State energy policies are facilitating the switch to renewable energy. Arizona, California, Colorado, Nevada, and New Mexico have enacted renewable energy portfolio standards.[93] California has set the highest standard: 50% of energy generation from renewable sources by 2030. In 2017, renewable energy sources supplied 32% of California energy generation.[355] By 2013, these standards had averted 26 trillion watt-hours of fossil fuel generation in the Southwest and 3% of carbon emissions nationally and had produced $5 billion in health benefits from reduced air pollution (in 2013 dollars; $5.2 billion in 2015 dollars).[356] Potential future benefits of existing renewable portfolio standards include carbon emission reductions of 6% nationally and health benefits of $560 billion (in 2013 dollars; $577 billion in 2015 dollars) from 2015 to 2050.[357]

Electricity Generation Capacity at Risk Under Continued Climate Change

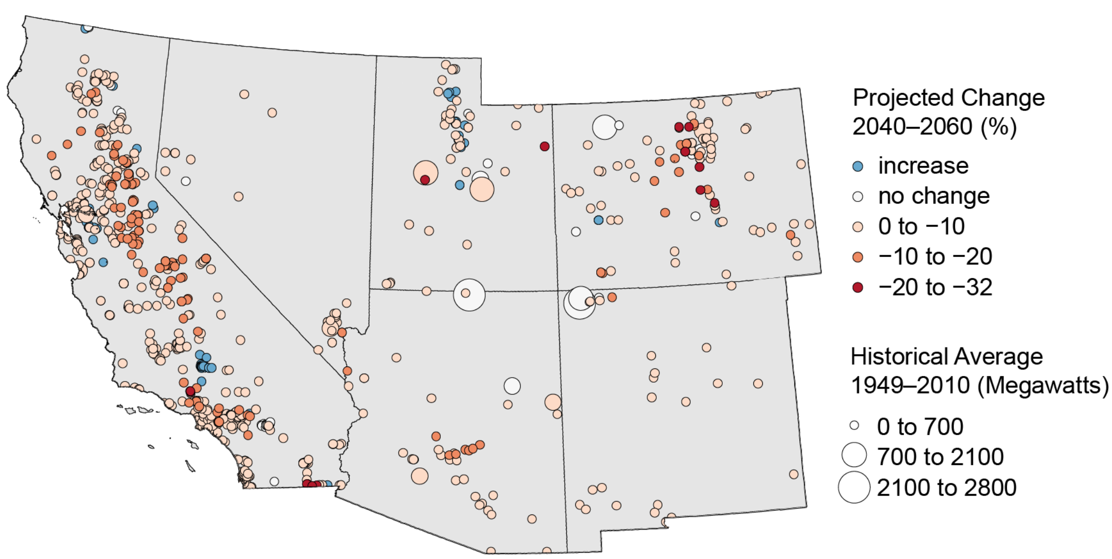


Figure 25.8: Under a higher emissions scenario (SRES A2[174]), heat-induced reduction of energy efficiency and reduced water flows would reduce summer energy generation capacity across the Southwest region. These projected reductions would increase risks of electricity shortages. The map shows projected changes for the period 2040–2060 compared to the period 1949–2010. Source: adapted from Bartos and Chester 2015.[346] Reprinted by permission from Macmillan Publishers Ltd.

Distributed solar energy systems place individual solar panels on roofs, on parking lot canopies, and other built places. The high number of sunny days in the Southwest and the great extent of existing rooftops and parking lots create a high potential for distributed solar generation, which could provide two-thirds of electricity use in California.[358] Distributed solar uses land that has already been urbanized and is close to energy users, reducing the need for transmission lines and transmission line electricity losses. Compared to industrial centralized solar power systems, distributed solar causes less death and disruption to wildlife that are already vulnerable to climate change, such as birds and endangered desert tortoises.[359] California, Colorado, and Nevada have enacted policies that support rooftop solar on homes, in particular net metering, in which customers sell their excess solar electricity to the grid.[360] Distributed wind energy systems can provide similar benefits.

Arizona, California, Colorado, Nevada, and New Mexico have enacted energy efficiency standards for utilities. California and New Mexico have also enacted policies that decouple utility profits from electricity sales.[361] White or reflective roofs, known as cool roofs, increase energy efficiency of buildings. Under a higher scenario (RCP8.5), cool roofs would reduce urban heat islands in Los Angeles and San Diego 2°–4°F (1°–2°C) by 2050 and decrease energy use and the use of air conditioning.[362] Urban tree planting in Phoenix that would increase tree cover from 10% to 25% would provide daytime cooling of up to 2°C in local neighborhoods.[363]

Newer technologies now allow generating plants to use nontraditional water sources, including saline groundwater, recycled water from landscaping, and municipal and industrial wastewater. For example, the Palo Verde Nuclear Generating Station in Arizona uses municipal wastewater.[361] Other plants in the region use extremely water-efficient hybrid wet–dry cooling technology. For instance, the Afton Generating Station in New Mexico is a natural gas combined-cycle plant that uses hybrid cooling to reduce water intensity by 60% compared to conventionally cooled plants.[361]

Electric cars can reduce fossil fuel use and greenhouse gas emissions compared to gasoline-powered vehicles. The relative greenhouse gas emissions from electric and gasoline vehicles depend on how the electricity is generated.[364,365] If the electricity is produced from renewable sources, then the operating emissions for electric vehicles are near zero, although the manufacturing of the vehicle emitted greenhouse gases. Conversely, if the electricity is produced completely from fossil fuel, the emissions from the electric vehicle are higher because of the limit of energy efficiency of large power plants and transmission line losses. Because sunlight, wind, and other renewable resources are intermittent and sometimes not available at times of demand, charging at night and improvements in battery technology would facilitate renewable energy generation.

Key Message 6

Food

Food production in the Southwest is vulnerable to water shortages. Increased drought, heat waves, and reduction of winter chill hours can harm crops and livestock; exacerbate competition for water among agriculture, energy generation, and municipal uses; and increase future food insecurity.

Climate change has altered factors fundamental to food production and rural livelihoods in the Southwest, particularly the shortage of water caused by droughts in California[14,56] and the Colorado River Basin.[13] The California drought led to losses of more than 10,000 jobs and the fallowing of 540,000 acres (220,000 hectares), at a cost of $900 million in gross crop revenue in 2015.[130] Increased temperatures in the Southwest also affected agricultural productivity from 1981 to 2010.[366]

Food production depends on reliable surface and groundwater supplies, which decline from droughts and reductions in snowpack and soil moisture.[67] Irrigated agriculture and livestock water use accounted for approximately three-quarters of total water use in the Southwest in 2010, excluding Colorado, which has wide-ranging dryland wheat production.[16,367,368] In the recent California drought, domestic wells dried out in some rural communities, but increased groundwater pumping from deeper wells prevented some agricultural revenue losses.[369] Falling groundwater tables increase pumping costs and require drilling to deepen wells.[130] Drought-related agricultural changes, stricter drilling regulations, and rapid aquifer depletion have already led to a decline in irrigation in parts of the region. According to climate projections for lower and higher emissions scenarios (RCP4.5 and RCP8.5), future changes in climate would reduce aquifer recharge in the southern part of the region by 10%–20%,[370] removing some of the secondary water source responsible for buffering effects of severe drought. In the Gila River Basin of New Mexico, farmers shift to groundwater pumping when surface water supplies are reduced, despite associated increases in production costs.[371] Under continued climate change, increased drought risk[13] and higher aridity[70] could expose some agricultural operations in the Southwest to less reliable surface and groundwater supplies (Ch. 10: Ag & Rural, KM 1).

Under continued climate change, higher temperatures would shift plant hardiness zones northward and upslope (Figure 25.9). These changes would affect individual crops differently depending on optimal crop temperature thresholds. Some crops, including corn[372] and rice,[373] are already near optimal thresholds in the Southwest. Increasing heat stress during specific phases of the plant life cycle can increase crop failures, with elevated temperatures associated with failure of warm-season vegetable crops and reduced yields or quality in other crops.[374] While crops grown in some areas might not be viable under hotter conditions, crops such as olives, cotton, kiwi, and oranges may replace them.[375] In parts of the Southwest region, increasing temperatures would prompt geographic shifts in crop production, potentially displacing existing growers and affecting rural communities.[376] Wine grape quality can be particularly influenced by elevated temperatures.[377] Increased levels of ozone and carbon dioxide near the surface, combined with increases in temperature, can decrease food quality and nutritive values of fruit and vegetable crops.[378,379]

Because many fruit and nut trees require a certain period of cold temperatures in the winter, decreased winter chill hours under continued climate change would reduce crop yields, though the magnitude may vary considerably.[380] In Yolo County, California, reduced winter chill may make conditions too hot for walnut cultivation by 2100.[381] California almond acreage has nearly doubled over the last two decades due to high foreign demand and the favorable Mediterranean climate. California now produces over 80% of world almond supply.[382] Since almonds also have a relatively high water requirement, both water and adequate cool winter temperatures will be important factors to maintain California tree nut production under climate change.

Projected Shift in Agricultural Zones

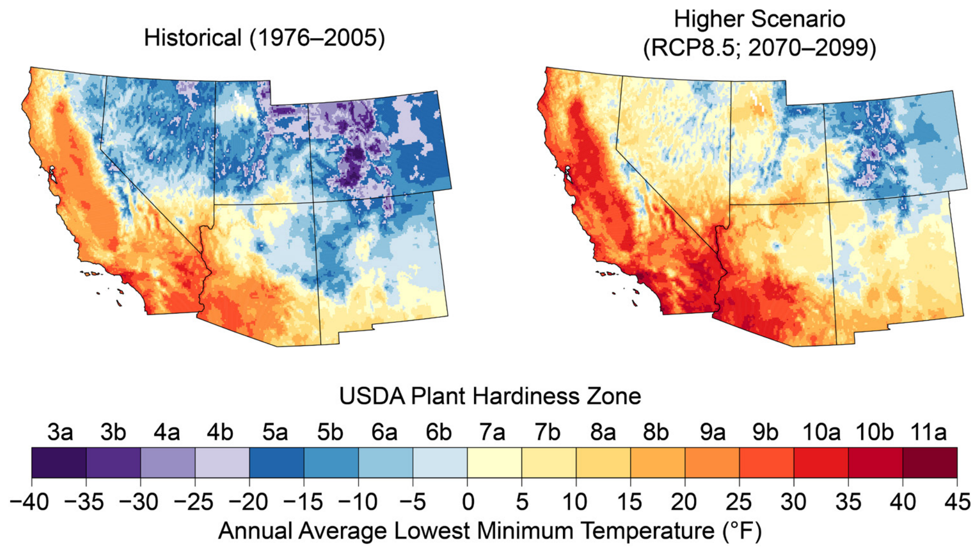


Figure 25.9: The U.S. Department of Agriculture plant hardiness zones indicate the cold temperature requirements of crops. Increases in temperature under the higher scenario (RCP8.5), would shift these zones northward and upslope, from the period 1976—2005 (left, modeled historical) compared to projections for 2070—2099 (right, average of 32 general circulation models). Sources: NOAA NCEI and CICS-NC.

Climate-related vulnerabilities of the Southwest region's livestock industry include reduced long-term livestock grazing capacity, reduced feed supply, increased heat stress (Ch. 10: Ag & Rural, KM 3), and reduced forage quality.[383] Water-intensive forage crops are especially vulnerable to water shortages.[15] Although livestock production systems persist in highly variable conditions, projected high temperatures may decrease production of rangeland vegetation and livestock forage.[384] In response to drought (1999–2004), 75% of Utah ranch operations reported major reductions in water supply, forage, and cattle productivity.[385] Only 14% felt they were adequately prepared for the drought, which may be reflected in the high use of federal relief programs.

One potential adaptation of agriculture to drought is water banking, the storage of excess surface water in groundwater aquifers.[386,387] For example, streamflows from the Sierra Nevada in high-precipitation years could provide substantial groundwater recharge in the California Central Valley.[388] Additional options include expanding surface reservoir storage or relying upon groundwater pumping, although this further depletes limited groundwater stores.[389]

Flexible livestock management strategies, such as stocking rates, grazing management practices, employing livestock bred for arid environments, erosion control, and identification of alternate forage supplies can help reduce vulnerability in an increasingly arid and variable climate.[390,391] Criollo cattle appear well-suited for the arid Southwest because they are more heat tolerant and adaptive than traditional breeds.[392]

In urban areas across the Southwest, such as Tucson, Arizona, and Sacramento, California, community food banks that grow food in community gardens can help maintain food security in a drier and more variable climate. Urban gardens and local food organizations provide fresh produce, foster community education, and support networks of local growers. These organizations build food systems capacity, which helps to mitigate impacts of urban heat, reduces food transportation costs and emissions, and supports provision of fresh local food to low-income urban dwellers.

Additional emerging issues that increase risks to food production include invasive nonnative or alien insect pests (introduced into the region intentionally or unintentionally) that are more adapted to hotter temperatures.[393] Global trade and efficient transportation also increase risks of invasion by alien insect pests. A mismatch in timing between plant flowering and the arrival of insect pollinators would reduce crop production and pollinator survival.[393] In addition, some subsistence foods, such as fish, upon which some Indigenous and other subsistence and urban communities depend,[309,394,395,396,397] and spiritually, socially, and culturally important tribal traditional foods[298] would be vulnerable in a drier and more variable climate (Key Message 4).

Key Message 7

Human Health

Heat-associated deaths and illnesses, vulnerabilities to chronic disease, and other health risks to people in the Southwest result from increases in extreme heat, poor air quality, and conditions that foster pathogen growth and spread. Improving public health systems, community infrastructure, and personal health can reduce serious health risks under future climate change.

Exposure to hotter temperatures and heat waves has led to heat-associated deaths and illnesses in Arizona and California.[398,399,400,401,402,403] In the unprecedented 2006 California heat wave, which affected much of the state and part of Nevada, extremely high temperatures occurred day and night for more than two weeks.[404] Compared to non-heat wave summer days, it is estimated that the event led to an additional 600 deaths, 16,000 emergency room visits, 1,100 hospitalizations in California,[399,405,406] and economic costs of $5.4 billion (in 2008 dollars).[405] Parts of the Southwest region experienced record-breaking heat in five of the six years from 2012 to 2017.[25,26,27,28,29] Assessments of the health impacts associated with record high temperatures in parts of the Southwest since 2010 are not yet available in the scientific literature.

Under continued climate change, projected increases in hot days and extreme heat events in the Southwest (Figure 25.10)[23,24,404,407] will increase the risk of heat-associated deaths.[30] Under the higher scenario (RCP8.5), the Southwest would experience the highest increase in annual premature deaths due to extreme heat in the country, with an estimated 850 additional deaths per year and an economic loss of $11 billion (in 2015 dollars) by 2050.[178] Under a lower scenario (RCP4.5), deaths and costs would be reduced by half compared to the higher scenario (RCP8.5).[178] By 2090, deaths and economic losses would more than double from 2050 under all emissions scenarios.[178] Heat and other environmental exposures particularly affect outdoor workers.[178] Under the higher scenario (RCP8.5), extreme heat in the Southwest (Figure 25.10) would also lead to high labor losses, including losses of high-risk labor hours of up to 6.5% for some counties by 2090 and of $23 billion per year in regionwide wages (in 2015 dollars).[178] It is projected that the lower scenario (RCP4.5) would reduce those wage losses by half.[178]

The risk of illness or death associated with extreme temperatures can be reduced through targeted public health and clinical interventions.[30,32] The main factors that put individuals and populations at increased risk in a heat wave are age (children and older adults are most at risk), hydration status, and presence of a chronic disease such as obesity, cardiovascular or respiratory disease, or psychiatric illness.[400,408,409,410,411,412,413,414,415] Psychosocial stresses and socioeconomic conditions, such as hot and poorly ventilated homes or lack of access to public emergency cooling centers can elevate these risks.[31,33,416]

Without adoption and implementation of strategies to minimize exposures to extended periods of extreme heat, the public health impacts of future heat waves may be as serious as those observed in California in 2006. The technological and behavioral adaptations to heat developed by populations in the Southwest are based on the observed historical range of nighttime minimum temperatures.[404] Projected increases in minimum temperatures and decreases in the number of cool nights[23] may diminish the efficacy of these adaptations.

Climate change and variability can also increase communicable and chronic disease burdens.[417,418,419] While infectious diseases like plague and hantavirus pulmonary syndrome disproportionately affect the Southwest region,[158] new research to support estimating future climate-associated risk for these diseases is sparse.[420] Therefore, this assessment focuses on recent developments in the understanding of heat, air quality, mosquito-borne diseases, and Valley fever and vulnerabilities that influence them.

In addition to extreme heat, the environmental conditions of greatest concern for human health are ground-level ozone air pollution, dust storms, particulate air pollution (such as from wildfires and dust storms), aeroallergens (airborne substances that trigger allergic reactions), and low water quality and availability.[30,178] In addition, alternating episodes of drought and extreme precipitation coupled with increasing temperatures promote the growth and transmission of pathogens.[30,421] The risk of onset or exacerbation of respiratory and cardiovascular disease is associated with a single or a combined exposure to ground-level ozone pollution, particulate air pollution, respiratory allergens, and extreme heat. Ground-level ozone is produced by chemical reactions of combustion-related chemicals (for example, from vehicles or wildfires) in a reaction that is dependent on ultraviolet radiation (that is, from the sun) and amplified by higher temperatures. Once formed, ozone can travel great distances and persist in high concentrations overnight in rural areas. Among many health impacts, ozone can promote or aggravate asthma and respiratory allergies.[422,423,424,425]

Projected Increases in Extreme Heat

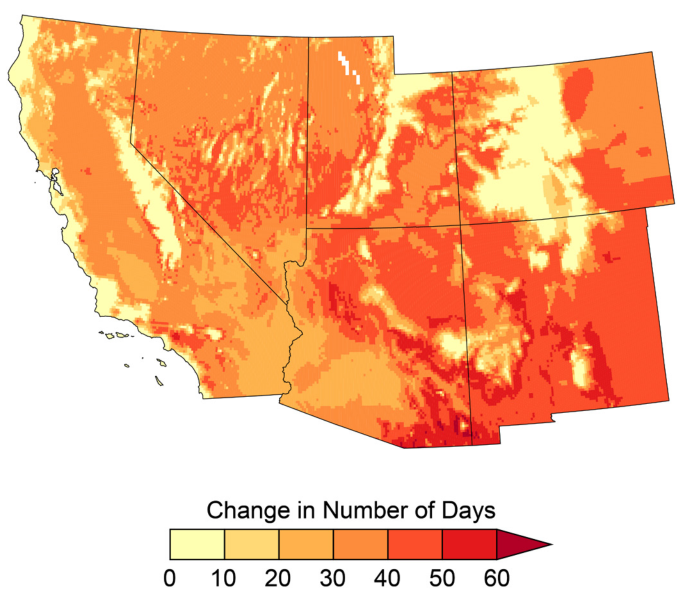


Figure 25.10: Under the higher scenario (RCP8.5), extreme heat would increase across the Southwest, shown here as the increase in the average number of days per year when the temperature exceeds 90°F (32°C) by the period 2036–2065, compared to the period 1976–2005.[23] Heat waves increase the exposure of people to heat stroke and other illnesses that could cause death.[30] Source: adapted from Vose et al. 2017.[23]

Elevated levels of CO_2 in conjunction with higher temperatures can increase the amount and potency of aeroallergens (Ch. 14: Human Health, KM 1). These conditions may also lead to new cases or exacerbation of allergy and asthma.[426,427,428,429] Mortality risk during a heat wave is amplified on days with high levels of ground-level ozone or particulate air pollution, with the greatest mortality due to cardiovascular causes.[430]

Severe dust storms in the Southwest contribute to respiratory and cardiovascular disease.[431,432] The association between Valley fever, a soilborne fungal respiratory infection of the Southwest, and warmer temperatures and soil dryness varies across the region and by time of year.[189,433,434] The connection between climate change, dust storm frequency and severity, and future public health effects in the region is complex and remains an emerging area of research.[435,436,437,438,439] Heat extremes, warming, and changes in precipitation will also influence the distribution and occurrence of vector-borne diseases like West Nile virus[440,441,442,443] and may lead to the emergence of new disease (Ch. 14: Human Health, KM 1).[30] Without proactive interventions and policies that address the biological, exposure, and socioeconomic factors that influence individual and population vulnerability, adverse health impacts may increase (Ch. 14: Human Health, KM 2). Those increases may disproportionately affect people with the lowest incomes, which hinders adaptive capacity (Ch. 14: Human Health, KM 1).[416,444]

Climate-related hazards such as heat waves, flooding, wildfires, or large disease outbreaks require emergency responses. Prolonged droughts can affect drinking water availability, reduce water quality,[445] and send more people seeking medical treatment.[446,447] The increased burden of disease can outpace the resources and adaptive capacity of public health and clinical infrastructures. The region may not be prepared to absorb the additional patient load that could accompany climate change,[448] but integrating risk reduction strategies into emergency response plans and recognizing and addressing vulnerability factors can appreciably reduce risks of future adverse health consequences (Ch. 14: Human Health, KM 3). This approach is embodied in the Centers for Disease Control and Prevention's (CDC) Building Resilience Against Climate Effects framework for adaptation planning.[449] Adaptation planning is already yielding health protection benefits.[450]

Local government agencies are preparing for extreme events by developing and updating emergency response plans and improving public warning and response systems. In 2014, California updated its Contingency Plan for Excessive Heat Emergencies,[451] Arizona released its Heat Emergency Response Plan,[452] and Salt Lake City, San Francisco, and Sonoma County were recognized in the first cohort of U.S. Department of Energy Climate Action Champions. Integrated and participatory planning for extreme heat,[453] such as the Capital Region Climate Readiness Collaborative in Sacramento, California, can help overcome institutional and governance barriers to implementing adaptation actions (Ch. 28: Adaptation).[454]

Policies and interventions related to one health factor can positively affect other factors and yield co-benefits[455,456,457,458,459] For example, research shows that heat-associated deaths and illnesses are preventable[460] and that healthier individuals are less susceptible to adverse effects of extreme heat exposure. Obesity, which affects about 30% of adults and 15% of school-age children and teens nationwide, increases the risk for many chronic diseases, such as asthma and diabetes, and increases the risk for serious heat-related adverse health outcomes.[32,461,462,463] Access to healthcare, social isolation, housing quality, and neighborhood poverty are also key risk factors for heat-related health impacts.[31,33,412]

Urban design strategies to address these risk factors include increasing walkability and bicycle safety and maintaining and planting trees and green space.[464] These strategies can achieve multiple health benefits, including increasing physical activity, thereby helping residents maintain a healthy weight,[465,466] reducing the urban heat island effect,[467] and reducing exposure to harmful air pollutants from vehicles. Reducing the urban heat island effect also reduces energy demand and risks of power outages, which can contribute to health risks, such as patients losing access to electricity-dependent medical devices.

Climate change may weigh heavily on mental health in the general population and those already struggling with mental health disorders.[468,469,470,471,472] One impact of rising temperatures, especially in combination with environmental and socioeconomic stresses, is violence towards others and towards self.[473,474,475] Slow-moving disasters, such as drought, may affect mental health over many years.[470] Studies of chronic stress indicate a potentially diminished ability to cope with subsequent exposures to stress.[476,477,478]

Populations under chronic social and economic stresses in urban and rural areas possess lower psychological, physical, and economic resilience (Ch. 10: Ag & Rural, KM 3). Communities that rely especially on well-functioning natural and agricultural systems in specific locations may be especially vulnerable to mental health effects when those systems fail. In the Southwest, the loss of stability and certainty in natural systems may affect physical, mental, and spiritual health of Indigenous peoples with close ties to the land.[42,316] For example, extended drought raises concerns about maintaining Navajo Nation water-based ceremonies essential for spiritual health, livelihoods, cultural values, and overall well-being.[301]

Acknowledgments

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Traceable Accounts

Process Description

The authors examined the scientific literature in their areas of expertise. The team placed the highest weight on scientific articles published in refereed peer-reviewed journals. Other sources included published books, government technical reports, and, for data, government websites. The U.S. Global Change Research Program issued a public call for technical input and provided the authors with the submissions. The University of Arizona Center for Climate Adaptation Science and Solutions organized the Southwest Regional Stakeholder Engagement Workshop on January 28, 2017, with over 70 participants at the main location in Tucson, AZ, and dozens of participants in Albuquerque, NM, Boulder, CO, Davis, CA, Los Angeles, CA, Reno, NV, and Salt Lake City, UT, all connected by video. Participants included scientists and managers. The author team met the following day for their only meeting in person. Subsequently, authors held discussions in regular teleconferences. Many chapter authors met at the all-author meeting March 26–28, 2018, in Bethesda, MD.

Key Message 1

Water Resources

Water for people and nature in the Southwest has declined during droughts, due in part to human-caused climate change (*very high confidence*). Intensifying droughts (*very high confidence*) and occasional large floods (*medium confidence*), combined with critical water demands from a growing population, deteriorating infrastructure, and groundwater depletion, suggest the need for flexible water management techniques that address changing risks over time (*high confidence*), balancing declining supplies with greater demands.

Description of evidence base

Research has found that hotter temperatures can make hydrologic droughts more severe. The unprecedented droughts in the Colorado River Basin and California showed that increased temperatures from climate change intensified the severity of the drought.[13,14,56,59] Climate change, more than natural cycles, has reduced snowpack.[46,49] Models project more drought under climate change,[13,56,62] snowpack and streamflow decline in parts of the Southwest, and decreasing surface water supply reliability for cities, agriculture, and ecosystems.[479]

Major uncertainties

Projecting future streamflow and hydrologic characteristics in a basin contains many uncertainties. These differences arise because of uncertainty in temperature and precipitation projections due to differences among global climate models (GCMs), uncertainty in regional downscaling, uncertainty in hydrological modeling, and differences in emissions, aerosols, and other forcing factors. Another important uncertainty is differences in the hemispheric and regional-scale atmospheric circulation patterns produced by different GCMs, which generate different levels of snow loss in different model simulations. A key uncertainty is the wide range in projections of future precipitation across the Southwest;[105] some projections of higher-than-average precipitation in the northern parts of the Southwest could roughly offset declines in warm-season runoff associated with warming.[105]

Detection is the finding of statistically significant changes different from natural cycles. Attribution is the analysis of the relative contribution of different causes and whether greenhouse gas emissions from human sources outweigh other factors. Attribution of extreme events, such as the recent California drought to climate change, is an area of emerging science. On the one hand, Seager et al. (2015)[58] concluded that the California drought was primarily driven by natural precipitation variability. Sea surface temperature anomalies helped set up the high-pressure ridge over California that blocked moisture from moving inland. On the other hand, Diffenbaugh et al. (2015),[56] Williams et al. (2015),[14] and Berg and Hall (2017)[55] concluded that high temperatures from climate change drove record-setting surface soil moisture deficits that made the drought more severe than it would have been without climate change. Storage of increased precipitation in soils may partially offset increased evaporation, possibly making drought less likely.[480]

In addition to the uncertainties in regional climate and hydrology projections and attribution studies, other uncertainties include potential changes in water management strategies and responses to accommodate the new changing baseline. Additionally, external uncertainties can impact water use in the region via legal, economic, and institutional options for augmenting existing supplies, adding underground storage and recovery infrastructure, and fostering further water conservation, changes in unresolved water rights, and changes to local, state, tribal, regional and national policies related to the balance of agricultural, ecosystem, and urban water use.

Description of confidence and likelihood

The *very high confidence* in historical droughts derives from the detection and attribution analyses of temperature increases, snow decreases, and soil moisture decreases that have documented hydrologic droughts in California and the Colorado River Basin due to anthropogenic climate change and the conclusions of the *Climate Science Special Report* (CSSR), Volume I of the Fourth National Climate Assessment.[74] The *very high confidence* in drought projections derives from the multitude of analyses projecting drought in the Southwest under a range of emissions scenarios and the conclusions of the CSSR.[74] Only *medium confidence* is found for flood projections due to lack of consensus in the model projections of precipitation. Increasingly arid conditions and the potential for increased water use by people lead to an assessment of *high confidence* in the need for new ways to address increasing risks of water scarcity. The actual frequency and duration of water supply disruptions will depend on the preparation of water resource managers with drought and flood plans, the flexibility of water resource managers to implement or change those plans in response to altered circumstances,[481] the availability of funding to make infrastructure more resilient, and the magnitude and frequency of climate extremes.

Key Message 2

Ecosystems and Ecosystem Services

The integrity of Southwest forests and other ecosystems and their ability to provide natural habitat, clean water, and economic livelihoods have declined as a result of recent droughts and wildfire due in part to human-caused climate change (*high confidence*). Greenhouse gas emissions reductions, fire management, and other actions can help reduce future vulnerabilities of ecosystems and human well-being (*high confidence*).

Description of evidence base

Scientific research in the Southwest has provided many cases of detection and attribution of historical climate change impacts. Detection is the finding of statistically significant changes different from natural cycles. Attribution is the analysis of the relative contribution of different causes and whether greenhouse gas emissions from human sources outweigh other factors. Published field research has detected ecological changes in the Southwest and attributed much of the causes of the changes to climate change. Wildfire across the western United States doubled from 1984 to 2015, compared to what would have burned without climate change, based on analyses of eight fuel aridity metrics calculated from observed data, historical observed temperature, and historical modeled temperature from global climate models.[7] The increased heat has intensified droughts in the Southwest,[13,14] reduced snowpack,[49,156] and advanced spring warmth.[101] These changes have dried forests,[154,155] driving the wildfire increase.[7,153] Tree death across the western United States doubled from 1955 to 2007[146] likely due to increased heat,[21] wildfire,[7] and bark beetle infestations,[148,149] all of which are mainly attributable to climate change[7,148,149] more than to other factors such as fire exclusion or competition for light and water.[146] In the Yosemite National Park biome shift,[209] the research analyzed the relative contributions of temperature, precipitation, and the Pacific Decadal Oscillation. The researchers found that "Minimum temperature was the main effect related to accelerating annual branch growth in krummholz whitebark pine and initiation of pine invasion into formerly persistent snowfield openings." In the Yosemite National Park small mammal range shift,[210] the locations of the monitoring sites allowed relative isolation of climate change factors. Moritz et al. (2008)[210] state, "The transect spans YNP [Yosemite National Park], a protected landscape since 1890, and allowed us to examine long-term responses to climate change without confounding effects of land-use change, although at low to mid-elevations there has been localized vegetation change relating to seral dynamics, climate change, or both."

Cutting emissions through energy conservation and renewable energy can reduce ecological vulnerabilities. Under high emissions, projected climate change could triple burned area in the Sierra Nevada, but under low emissions, fire could increase just slightly.[173] Projections of biome shifts[213,215] and wildlife range shifts[217,218,219,220,221] consistently show lower vulnerabilities with lower emissions. Extensive research on, and practice of, fire management show that allowing naturally ignited fires to burn in wilderness and using low-severity prescribed burns can reduce fuels and the risk of high-severity fires under climate change.[181,182,183] Proactive use of fire in Yosemite, Sequoia, and Kings Canyon National Parks has improved the resilience of giant sequoias and other trees to severe fires.[187,188,190,191] Numerous research results have identified climate change refugia for plants and animals.[207,482,483]

Major uncertainties

Because climate model projections often diverge on whether precipitation may increase or decrease, two broad types of fire futures[152] could be 1) dry-fire future—hotter and drier climate, increased fire frequency, fire limited by vegetation, potential biome change of forest to grassland after a fire due to low natural regeneration, and high carbon emissions; or 2) intense-fire future—hotter and wetter climate, more vegetation, increased fire frequency and intensity, fire limited by climate, and higher carbon emissions. These two broad categories each encompass a range of fire conditions. On the ground, gradients of temperature, precipitation, and climate water deficit (difference between precipitation and actual evapotranspiration) generate gradients of fire regimes. Because climate change, vegetation, and ignitions vary across the landscape, potential fire frequency shows high spatial variability. Therefore, future fire types could appear in patches across the landscape, with different fire future types manifesting themselves in adjacent forest patches. Changes in aridity may shift some plant and animal species ranges downslope to favorable combinations of available moisture and suitable temperature, rather than upslope.[484] Plants and animals may respond to changing climate, and have been shown to do so, through range shifts, phenology shifts, biological evolution, or local extirpation. Thus, no single expected response pattern exists.[224]

Description of confidence and likelihood

Field evidence provides *high confidence* that human-caused climate change has increased wildfire, tree death, and species range shifts. Projections consistently indicate that continued climate change under higher emissions could increase the future vulnerability of ecosystems, but that reducing emissions and increasing fire management would reduce the vulnerability, providing *high confidence* in positive benefits of these actions.

Key Message 3

The Coast

Many coastal resources in the Southwest have been affected by sea level rise, ocean warming, and reduced ocean oxygen—all impacts of human-caused climate change (*high confidence*)—and ocean acidification resulting from human emissions of carbon dioxide (*high confidence*). Homes and other coastal infrastructure, marine flora and fauna, and people who depend on coastal resources face increased risks under continued climate change (*high confidence*).

Description of evidence base

At the Golden Gate Bridge, San Francisco, sea level rose 9 ± 0.4 inches (22 ± 1 cm) from 1854 to 2016,[236] and at San Diego, 9 ± 0.8 inches (24 ± 2 cm) from 1906 to 2016.[237] Analyses of these gauges and hundreds around the world show a statistically significant increase in global mean sea level[238,239] due to melting of land ice and expansion of warming water caused by climate change.[21,240] Measurements of sea surface temperatures from buoys off the California coast and around the world, combined with remote sensing data, have found warming of the top 75 m of ocean water at a rate of 2 ± 0.4°F (1.1 ± 0.2°C) per century from 1971 to 2010,[252] caused by climate change.[21] Measurements and modeling of ocean acidity found an increase of acidity in the Pacific Ocean off San Diego of 25% to 40% (0.1 to 0.15 pH units) since 1750,[485] caused by the increase of carbon dioxide in the atmosphere from cars, power plants, deforestation, and other human activities.[21] Measurements along the California coast have found ocean acidity during the core upwelling season (April to October) increasing by as much as four times (0.7 pH units) to some of the most acidic values in the world.[274] Griggs et al. (2017)[242] project a median sea level rise of 19 inches (49 cm) and a range of 12–29 inches (30–73 cm; 67% probability) for the very low scenario (RCP2.6) and a median of 30 inches (76 cm) and a range of 19–41 inches (49–104 cm; 67% probability) for the higher scenario (RCP8.5) by the end of the century. On a similar timescale, Sweet et al. (2017)[241] provide one map showing sea level rise projections for San Francisco, which shows a 39–47 inch (1–1.2 m) rise for the Intermediate scenario (approximately RCP8.5); the range for all of their scenarios is 0.3–2.5 m. Jevrejeva et al. (2016)[486] project a sea level rise of 73 cm and a range of 12–74 inches (37–187 cm; 5% probability) for the higher scenario (RCP8.5) by 2100.

Major uncertainties

Catastrophic rapid loss of Antarctic and Greenland ice sheets could increase sea level more rapidly. Sea level rise at individual locations depends on the form of the seafloor (bathymetry) and other local conditions. Climate change impacts compound overfishing and make fish populations more vulnerable. Potential economic changes in California's coastal and marine-based economies are subject to many different environmental and socioeconomic factors.

The full complexity of ecological responses to ocean acidification in combination with other stresses in California marine waters is currently unknown. Food supply for marine species,[487] natural variation in resilience,[488,489] and other environmental factors can affect the sensitivity of organisms to acidic conditions.

Description of confidence and likelihood

Field measurements at numerous locations have detected sea level rise, ocean warming, ocean acidification, and ocean hypoxia. Multiple model-based analyses have attributed these changes to human-caused climate change, giving *high confidence* to these impacts of climate change.

Key Message 4

Indigenous Peoples

Traditional foods, natural resource-based livelihoods, cultural resources, and spiritual well-being of Indigenous peoples in the Southwest are increasingly affected by drought, wildfire, and changing ocean conditions (*very likely, high confidence*). Because future changes would further disrupt the ecosystems on which Indigenous peoples depend (*likely, high confidence*), tribes are implementing adaptation measures and emissions reduction actions (*very likely, very high confidence*).

Description of evidence base

Abundant evidence and strong agreement among sources exist regarding current impacts of climate change in the region. Impacts of climate change on the food sources, natural resources-based livelihoods, cultural resources and practices, and spiritual health and well-being of Southwest Indigenous peoples are supported, in part, by evidence of regional temperature increases,[23,24] drought,[14,56,58,480] declines in snow,[46,49,156] and streamflow,[11,13,60,110] which have affected ecological processes, such as tree death,[146] fire occurrence,[7,152] and species ranges.[211]

Impacts specific to Indigenous peoples include: 1) declining surface soil moisture, higher temperatures, and evaporation converge with oak trees' decreased resilience,[285] diminished acorn production, and fire and pest threat to reduce the availability and quality of acorns for tribal food consumption and cultural purposes;[306] and 2) declining vegetation, higher temperatures, diminished snow, and soil desiccation have caused dust storms and more mobile dunes on some Navajo and Hopi lands, resulting in damaged infrastructure and grazing lands and loss of valued native plant habitat.[44,301,490] Evidence and agreement among evidence exist on the effects of climate-related environmental changes on culturally important foods,[318,319] practices, and mental and spiritual health.[42]

Multiple projections of climate and hydrological changes show potential future change and disruption to the ecosystems on which Indigenous peoples depend for their natural resources-based livelihoods, health, cultural practices, and traditions. These include projections of increased temperatures and heat extremes;[24] longer, more severe, and more frequent drought;[13,65] expanded forest mortality;[197,198] increased wildfire;[172] and ocean temperature increases, ocean acidification, and inundation of coastal areas.[242,273]

Evidence of specific future disruptions to traditional food sources from forests and oceans mostly relies upon inferences, based on projections of changing seasonality and associated phenological or ecosystem responses[298,307] or potential changes to biophysical factors, such as salinity of freshwater lakes, and associated impacts to culturally important fish species.[310]

Abundant evidence exists of autonomous adaptation strategies, projects, and actions, rooted in traditional environmental knowledge and practices or integration of diverse knowledge systems to inform ecological management to support adaptation and ecosystem resilience.[490,491,492,493]

In response to the current and future projected climate changes and ecosystem disruptions, a number of tribes in the Southwest are planning and implementing energy efficient and renewable energy projects.[327,361,494,495] These include installation of or planning for photovoltaic systems,[361] solar arrays, biofuels, microgrids, utility-scale wind, biogas, geothermal heating and cooling systems,[327] increased building insulation,[495] and carbon offsets.[334] Several Southwest tribes, such as the Ramona Band of Cahuilla and the Santa Ynez Band of Chumash Indians, have established or are in the process of establishing energy independence.[495] A well-recognized example is that of the Blue Lake Rancheria Tribe, in California, which was named a Climate Action Champion in 2015–2016 for implementing innovative climate actions, such as an all-of-the-above renewable strategy of transportation, residential, and municipal renewable energy projects, which includes a biogas project. A number of these projects (Ch. 15: Tribes, Figure 15.1) aim to simultaneously meet mitigation and adaptation objectives, such as the Yurok Tribe and the Round Valley Indian Tribe, which have developed carbon offset projects under California's cap-and-trade program to support tribally led restoration and stewardship.[496]

Several tribes in the Southwest are developing climate change adaptation plans to address the current climate-related impacts and prepare for future projected climate changes. The Santa Ynez Band of Chumash Indians, which is working towards an integrated energy and climate action plan, the Yurok Tribe, the Gila River Indian Community, and the Tohono O'odham Nation are among the first tribes in the region to develop climate adaptation and resilience plans, which reflects a nationwide gap or need for further tribal adaptation plan development. Lack of capacity and funds has hindered progress in moving from planning to implementation, which is similar to the situation for U.S. cities.[497]

Major uncertainties

Uncertainties in the climate and hydrologic drivers of regional changes affecting Indigenous peoples in the Southwest include 1) differences in projections from multiple GCMs and associated uncertainties related to regional downscaling methods, 2) the way snow is treated in regional modeling,[498] 3) variability in projections of extreme precipitation, and, in particular, 4) uncertainties in summer and fall precipitation projections for the region.[88] Additional uncertainties exist in sea level rise projections[242] and, for the California coast, ocean process model projections of acidification, deoxygenation, and warming coastal zone temperatures.[499] For the most part, Native lands lack instrumental monitoring for weather and climate, which is a barrier for long-term climate-related planning.[493]

Complexities arising from the multiple factors affecting ecosystem processes, including tree mortality and fire, often preclude formal detection and attribution studies. Much evidence and agreement among evidence exist regarding the role of hotter temperatures in fire and tree mortality.[7,146] Detection and attribution studies seldom focus explicitly on tribal lands.

Other uncertainties relate to estimating future vulnerabilities and impacts, which depend, in part, on adjudication of unresolved water rights and the potential development of local, state, regional, tribal, and national policies that may promote or inhibit the development and deployment of adaptation and mitigation strategies.

Description of confidence and likelihood

The documented human-caused increase in temperature is a key driver of regional impacts to snow, soil moisture, forests, and wildfire, which affect Indigenous peoples, other frontline communities, and all of civil society. Case study evidence, using Indigenous and Western scientific observations, oral histories, traditional knowledge and wisdom (e.g., Ferguson et al. 2016[493]), suggests that climate change is affecting the health, livelihoods, natural and cultural resources, practices, and spiritual well-being of Indigenous communities and peoples in the Southwest (e.g., Redsteer et al. 2011, 2013; Wotkyns 2011; Cozzetto et al. 2013; Gautam et al. 2013; Navajo Nation Department of Fish and Wildlife 2013; Nania and Cozzetto et al. 2014; Sloan and Hostler 2014; Redsteer and Fordham 2017[44,302,305,307,310,311,490,500,501]). Abundant evidence gives *high confidence* that hotter temperatures, tree mortality, and increased wildfire and drought, due to climate change, would disrupt the ecosystems on which Indigenous people depend; the likelihood of these impacts affecting individual tribes will depend in large part on the non-climatic stresses (such as historical legacies and resource management practices) interacting with the climatic stresses. *Very high confidence* exists that tribes are developing adaptation measures and emissions reductions to address current and future climate change, based on abundant ongoing initiatives and associated documentation.

Key Message 5

Energy

The ability of hydropower and fossil fuel electricity generation to meet growing energy use in the Southwest is decreasing as a result of drought and rising temperatures (*very likely, very high confidence*). Many renewable energy sources offer increased electricity reliability, lower water intensity of energy generation, reduced greenhouse gas emissions, and new economic opportunities (*likely, high confidence*).

Description of evidence base

Numerous studies link Southwest hydrologic drought with a decline in renewable hydroelectricity generation in the region. Hydroelectric generation depends on runoff to fill reservoirs to maximize generation capacity.[336,337] During the California drought, which was intensified by climate change,[14,56] hydroelectric generation in California fell from 43 trillion watt-hours (TWh) in 2011 before the drought to 14 TWh in 2015 during the drought.[335] Climate change also reduced the snowpack[46,47,48,49] and river runoff on which hydroelectric generation depends.[336,337]

Similarly, low reservoir levels in Lake Mead—which is formed by damming the Colorado River—driven by reduced Colorado River runoff[13,59] can reduce the efficiency and production levels of hydropower at Hoover Dam.

Fossil fuel generation efficiency depends on the temperature and availability of the external cooling water. Warming could reduce energy efficiency up to 15% across the Southwest by 2100.[91] Higher temperatures also increase electric resistance in transmission lines, causing transmission losses of 7% under higher emissions.[344] Replacing fossil fuel generation with solar power renewables reduces greenhouse gas emissions and water use per unit of electricity generated.[90] This supports the assertion that increasing solar energy generation in the Southwest could meet the energy demand no longer being met by hydropower and fossil fuel as well as the expected increase in energy use in the future.

Solar energy production is also an economic opportunity for the region. The energy potential for renewable energy is estimated to range from one-third to over ten times 2013 generation levels from all sources.[502] The lower range assumes capacity requirements remain at 2013 levels,[502] but recent data show an upward trend in Southwest energy use.[89]

The high potential for solar energy projects in the Southwest and the extent of federally owned land in the Southwest (well over half the total surface area for the six-state region) prompted the Bureau of Land Management (BLM) and the U.S. Department of Energy to conduct a programmatic environmental impact analysis of a new Solar Energy Program to further support utility-scale solar energy development on BLM-administered lands.[502,503] This potential capacity, combined with the increasingly competitive cost of solar and wind,[504] presents economic opportunities for the region and an opportunity to reduce overall greenhouse gas emissions.

Solar and renewable energy jobs are increasing. The solar workforce increased 25% in 2016, while wind employment increased 32%.[505] Jobs in low-carbon-emission generation systems, including renewables, nuclear, and advanced low-emission natural gas, comprise 45% of all the jobs in the electric power generation and fuels technologies.[505] Growing Southwest energy use, competitive prices for renewables, and the renewable energy potential of the Southwest favor the replacement of fossil-fuel-generated energy by renewable solar and wind energy.

Major uncertainties

Climate model projections of the future diverge on whether precipitation may increase or decrease for much of the region, so hydroelectric power changes may exhibit spatial variation. The amount of runoff is a key factor driving the generation potential for hydroelectric power. A key uncertainty is how much hydroelectricity generation will decline. Some projections of higher-than-average precipitation in the northern parts of the Southwest could roughly offset declines in warm-season runoff associated with warming.[105]

Energy demand in the Southwest is increasing, but the rate of growth is uncertain.[506] Changes in energy market prices cause future uncertainty in the future mix of energy sources for the Southwest.[502] The low cost of natural gas and the competitive cost of solar and wind renewables make it somewhat certain the proportion of the energy generated from these sources will continue to increase and offset reductions in traditional fossil-fuel-generated energy, reducing overall greenhouse gas emissions.[504] Renewable energy job growth potential is also uncertain and depends on the factors mentioned above.[505]

Additionally, daily to multiyear variation in coastal cloud cover affects solar electricity generation potential along the California coast.[507,508,509,510]

Description of confidence and likelihood

Hydrological drought in California reduced hydroelectric generation[335] and fossil fuel electricity generation efficiencies. Drought and rising temperatures under climate change can reduce the ability of hydropower and fossil fuel electricity generation to meet growing energy use in the Southwest (*very likely*, *very high confidence*). Renewable solar and wind energy offers increased electricity reliability, lower water intensity for energy generation, reduced greenhouse gas emissions, and new economic opportunities (*likely*, *high confidence*).

Key Message 6

Food

Food production in the Southwest is vulnerable to water shortages (*medium confidence*). Increased drought, heat waves, and reduction of winter chill hours can harm crops (*medium confidence*) and livestock (*high confidence*); exacerbate competition for water among agriculture, energy generation, and municipal uses (*medium confidence*); and increase future food insecurity (*medium confidence*).

Description of evidence base

Climate change has altered climate factors fundamental to food production and rural livelihoods in the Southwest. Abundant evidence and good agreement in evidence exist regarding regionally increasing temperatures, reduced soil moisture, and effects on regional snowpack and surface water sources.[13,23,67,74,79] The heat of climate change has intensified severe droughts in California[14,56] and the Colorado River Basin.[13] Hotter temperatures and aridity in the Southwest affected agricultural productivity from 1981 to 2010.[366]

Elevated temperatures can be associated with failure of some crops, such as warm-season vegetable crops, and reduced yields and/or quality in others.[374] Temperatures in California, Nevada, and Arizona are already at the upper threshold for corn[372] and rice.[373] While crops grown in some areas might not be viable under hotter conditions, other crops such as olives, cotton, kiwi, and oranges may replace them.[375] In the Southwest, climate change may cause a northward shift in crop production, potentially displacing existing growers and affecting rural communities.[376] Quality of specialty crops, both nutritive and sensory, declines because of increased temperatures and other changes associated with a changing climate,[393,511] which is particularly important in a region producing a majority of the Nation's specialty crops. Decreases in winter chill hours may reduce fruit and tree nut yields, though the magnitude may vary considerably.[380,381]

High ambient temperatures associated with climate change could decrease production of rangeland vegetation across the Southwest,[384] reducing available forage for livestock. Ranching enterprises across the region have vastly different characteristics that will influence their adaptive capacities.[390]

Local-scale impacts can vary considerably across the region depending upon surface and groundwater availability. Drought causes altered water management, with heavy reliance on a limited groundwater to sustain regional food production.[130] Despite severe localized impacts, losses in total agricultural revenue are buffered by groundwater reliance to offset surface water shortage.[369] Parts of the Southwest have exhausted sustainable use of groundwater resources. When surface water supplies are reduced, farmers shift to increased groundwater pumping, even when pumping raises production costs[371]—declining groundwater tables significantly increase pumping costs and require drilling of deeper wells.[130] Continued climate change may reduce aquifer recharge in the southern part of the region 10%–20%.[370] Climate change is projected to cause longer and more severe drought periods that will intensify the uncertainty associated with Southwest water supply and demand. Water-intensive forage crops and the livestock industry are especially vulnerable to climate-related water shortages.[15]

Major uncertainties

The impacts of climate change on food production depend upon microclimatology and local-scale environmental, social, and economic resources. While the scientific community relies upon computer models and generalized information to project likely future conditions, unforeseen consequences of warming temperatures, such as those related to pests, pollinators, and pathogens, may be more detrimental than some of the well-documented projections, such as temperature impacts on reduced yields. The effects of increased precipitation supplying the deep root zone may somewhat offset the increase in temperature, so agricultural drought may be less frequent for trees and other crops dependent on deeper soil moisture.[480] Scientists are producing more drought- and heat-tolerant cultivars, which may be suitable to production in the projected warmer and more arid climate of the Southwest.

Since food security relies on complex national and international trade networks, how regional climate change may affect local food security is uncertain. Many adaptation options, such as using alternate breeds, crops, planting and harvest dates, and new (sometimes untested) chemicals, may work in certain situations but not others. Thus, predicting impacts to food production in a hotter/drier land is likely to vary by crop and location, necessitating flexibility and adaptive management. Of paramount uncertainty is the impact of water shortage on regional food production as other uses may outcompete producers for limited supplies.

Description of confidence and likelihood

Since the availability of affordable food around the world depends upon complex trade and transportation networks, the effects of climate change on Southwest food availability, production, and affordability remain highly complex and thereby uncertain and classified with *medium confidence*. While the viability of rural livelihoods is vulnerable to water shortages and other climate-related risks, rural livelihoods may be supplemented by other nonagricultural income, such as recreation and hunting. The viability of rural livelihoods is highly complex, and risk is, therefore, classified with *medium confidence*. Crop impacts related to hotter and drier conditions and reduced winter chill periods, caused by climate change, are classified with *medium confidence*. Not all crops are directly harmed by warming temperatures, and the simulation impacts of reduced chilling hours can produce a fairly wide range of results depending upon model assumptions. Hotter and drier conditions can directly harm livestock via reduced forage quantity and quality and exposure to higher temperatures, conferring a *high confidence* classification. Projections of future drought and water scarcity portend increased competition for water from other beneficial uses with *medium confidence*.

Key Message 7

Human Health

Heat-associated deaths and illnesses, vulnerabilities to chronic disease, and other health risks to people in the Southwest result from increases in extreme heat, poor air quality, and conditions that foster pathogen growth and spread (*high confidence*). Improving public health systems, community infrastructure, and personal health can reduce serious health risks under future climate change (*medium confidence*).

Description of evidence base

Strong evidence and good agreement among multiple sources and lines of evidence exist, indicating that the Southwest regional temperature may increase, snowpack may decline, soil moisture may decrease, and drought may be prolonged.[14,23,24,56,58,62,68,74,480]

Exposure to hotter temperatures and extreme heat events, partly a manifestation of human-caused climate change, already led to heat-associated deaths and illnesses in heat waves in Arizona and California in the early and mid-2000s.[398,399,400,401,402,406,444,450,512]

Good agreement exists among models that most of the Southwest may become more arid, due to the effect of increasing temperatures on snow, evaporation, and soil moisture.[58,65,70,80] Projections also indicate that flood-causing atmospheric rivers may become more moist, frequent, and intense[84,85,86] and that intense daily precipitation may increase in frequency.[88,513] Models project declines in future runoff of key Southwest rivers, such as the Colorado, due chiefly to the effects of increased temperature on soil moisture and snowpack.[13,71,110]

Strong evidence exists of the effects of extreme heat on public health in the region (e.g., Knowlton et al. 2009, Oleson et al. 2015, Wilhelmi et al. 2004[400,514,515]) and for reasonable projections of future deaths and costs of lost labor productivity due to enhanced future episodes of extreme heat. Factors that predict a person will be at increased risk include being confined to bed, not leaving home daily, and being unable to care for oneself;[516] various general indicators of being socially isolated (such as living alone, the presence of or frequency of social contacts, or being isolated linguistically);[516,517,518,519] and persons who are socioeconomically disadvantaged.[516,517,518,519] Dehydration in general and dehydration associated with medications (neurological and non-neurological) that impair thermoregulation or thirst regulation were also associated with elevated risk of mortality during the 2003 heat wave in France.[520] The role of prescription medications in altering the risk for heat-associated illness or death is of growing interest and concern.[521] This issue is more important as chronic diseases become more prevalent and more people take prescription drugs.

Given the proportion of the U.S. population in the Southwest, a disproportionate number of West Nile virus, plague, hantavirus pulmonary syndrome, and Valley fever cases occur in the region.[158,420] West Nile virus transmission is projected to shift to the north under climate change, and areas where the mosquitoes that carry this virus are present may see increased abundances.[441,442,443] The mosquito species that carry Zika and chikungunya are established in parts of the region, but mosquito-borne transmission has only been observed in Puerto Rico, the U.S. Virgin Islands, Florida, and Texas (Ch. 14: Human Health).

Overall, the Southwest is ill-prepared to absorb the additional patient load that would accompany climate change associated disasters.[448] The American College of Emergency Physicians assigned an overall emergency care grade of C or C+ to three of the six Southwest states, with the others receiving poorer grades, and four of the six states received an F grade for access to emergency care.[448]

Major uncertainties

Uncertainties in the climate and hydrologic drivers of regional changes affecting public health include 1) differences in projections from multiple GCMs and associated uncertainties related to regional downscaling methods, 2) variability in projections of extreme precipitation, 3) uncertainties in summer and fall precipitation projections for the region,[88] and 4) uncertainties in models that project occurrence and levels of climate-sensitive exposures that are known to impact public health, such as local and regional ozone air pollution, particulate air pollution (for example, increases from wildfire emissions or reductions from advancements in vehicle emissions control technology), or occurrence and exposure to toxins or pathogens.

Studies of non-fatal illnesses using healthcare services data can yield critical insights different from those one can derive from death data. Most studies of heat impacts on health have focused on deaths rather than nonfatal illnesses. This is primarily because hospitalization and emergency department data, compared with death certificate data, are not as available or uniform across locations, and when they are available it can be difficult to access them due to concerns for patient confidentiality. Ongoing enhancements to electronic medical records technology and adoption across the healthcare services sector will potentially address those limitations in the near future and will provide invaluable data resources to identify and adopt prevention strategies that reduce the vulnerability of patients and populations to the adverse effects of climate-sensitive exposures.

More recent work focusing on the more deadly neuroinvasive West Nile virus indicates that regionally, the central and southern parts of the country may experience increasing cost from this vector-borne disease in the future.[178,440] The lack of a statistical association between temperature and West Nile virus diagnoses in the Southwest may be because extreme temperatures in some locations rise above the survival thresholds for vectors, thereby reducing mosquito abundance[522,523] and disease transmission.[419] Additionally, because the data for diseases like Valley fever are limited to cases, rather than exposures, the link to climate change is not clear.[435,436]

While improvements to individual health and to clinical and community infrastructure are highly likely to 1) improve physical capacity to adapt to climate effects, 2) diminish the overall impacts on population health, and 3) increase societal capacity to respond quickly to dampen the effects of long-term and emergency responses,[446,447,524] other factors also influence adaptive capacity, adding considerable uncertainty. For example, many factors influence the observed number of West Nile virus cases including available habitat, human prevention and control efforts, and recent history of cases in a given area.[442,525,526,527]

Description of confidence and likelihood

Evaluation of confidence levels for the assessment of the type and magnitude of observed or projected public health and clinical impacts was based on the strength of evidence underlying the answers to three primary questions:

1. What characteristics of the region's historical climate and weather patterns translate directly (for example, extreme heat) or indirectly (for example, higher temperatures fostering ozone formation or the growth and spread of pathogens and vectors) to exposures associated with observed human health risks that are unique to or overrepresented in the Southwest?

2. Does recent historical evidence indicate that climate and weather patterns have changed, or do climate models project changes over the 21st century, thereby increasing the risk of human exposures and health impacts evaluated under question 1?

3. What are the determinants of individual and population vulnerability that increase or decrease the risk of an adverse health outcome or affect adaptive capacity? These include factors that affect a) biological susceptibility, b) physical environment and exposure characteristics, and c) social, behavioral, or economic factors.

To the extent possible, the evaluation recognized and accounted for the complex interconnections among these factors, the fact that their relative importance may differ across geographic and temporal scales, and the combined uncertainties of evidence from multiple disciplines (for example, health sciences, climatology, and social or behavioral sciences) that can vary substantially.

The information revealed by answering those questions, gives *high confidence* that extreme heat will be the dominant driver of exposures that pose the greatest health risks in the

Southwest—including direct effects of heat on individuals and indirect effects of heat on air pollution levels. Due to the uncertainties related to the frequency and intensity of human exposures and related to impacts on essential ecosystem services under projected climate change, the statement "Improving public health systems, community infrastructure, and personal health can reduce serious health risks under future climate change" is made with *medium confidence*. Nevertheless, clinical and public health policy effectiveness assessments show that such improvements can reduce the burden of disease and health risks associated with environmental exposures.

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