

FOURTH
NATIONAL
CLIMATE
ASSESSMENT

CHAPTER
25:
SOUTHWEST

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 to address changing risks over time, balancing declining supplies with greater demands.

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CHAPTER 25 Southwest

Background

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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 shifts²¹³ 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 nuts² and most of the wine grapes, strawberries, and lettuce¹⁷ 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 1880²¹ 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

Figure 25.1: 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

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

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](#)

Figure 25.2: 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.

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.



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.

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 problems¹²⁷ and populations vulnerable to flooding,^{127, 128} projected increases in heavy precipitation⁸⁸ 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

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

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:

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

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

Figure 25.3: 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.



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.

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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](#)} 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}

Figure 25.4: Climate Change Has Increased Wildfire

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

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

The 2013 Rim Fire in California burned more than 257,000 acres, the second largest wildfire in the ...

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 California¹⁷⁵ 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, 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](#)}



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.

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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 Francisco²⁵⁰ 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).

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](#)}

Figure 25.5: Sea Level Rise

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.

Figure 25.6: 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.



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.

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 Maidu³²⁸ 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.



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.

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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 year¹⁰⁵ 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

Figure 25.8: Electricity Generation Capacity at Risk Under Continued Climate Change

Figure 25.8: Under a higher emissions scenario (SRES A2¹⁷⁴), 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. Sources: adapted from Bartos and Chester 2015.³⁴⁶ Reprinted by permission from Macmillan Publishers Ltd.

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

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.



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.

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 risk¹³ and higher aridity⁷⁰ could expose some agricultural operations in the Southwest to less reliable surface and groundwater supplies (Ch. 10: Ag & Rural, KM 1).

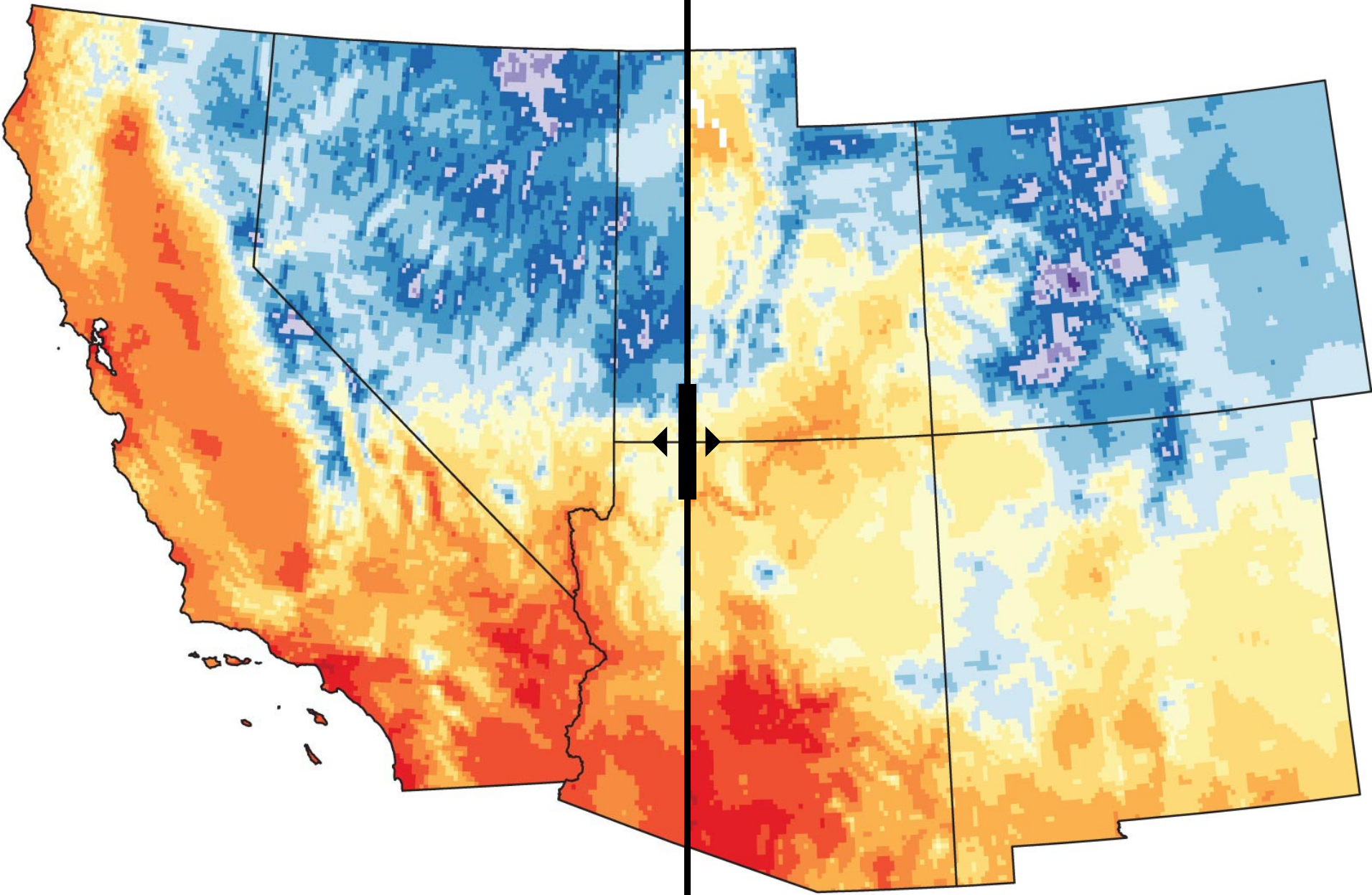
Under continued climate change, higher temperatures would shift plant hardiness zones northward and upslope (Figure 25.9). These changes would affect individual crops differently depending on optimal crop temperature thresholds. Some crops, including corn³⁷² and rice,³⁷³ are already near optimal thresholds 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}

Figure 25.9: Projected Shift in Agricultural Zones

Use
the
slider
to view
historical
and
projected
plant
hardiness
zones

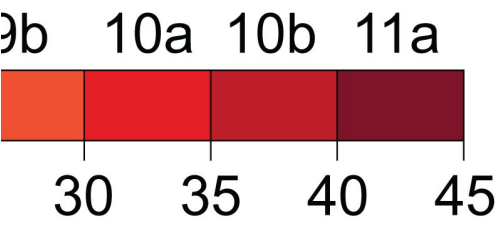
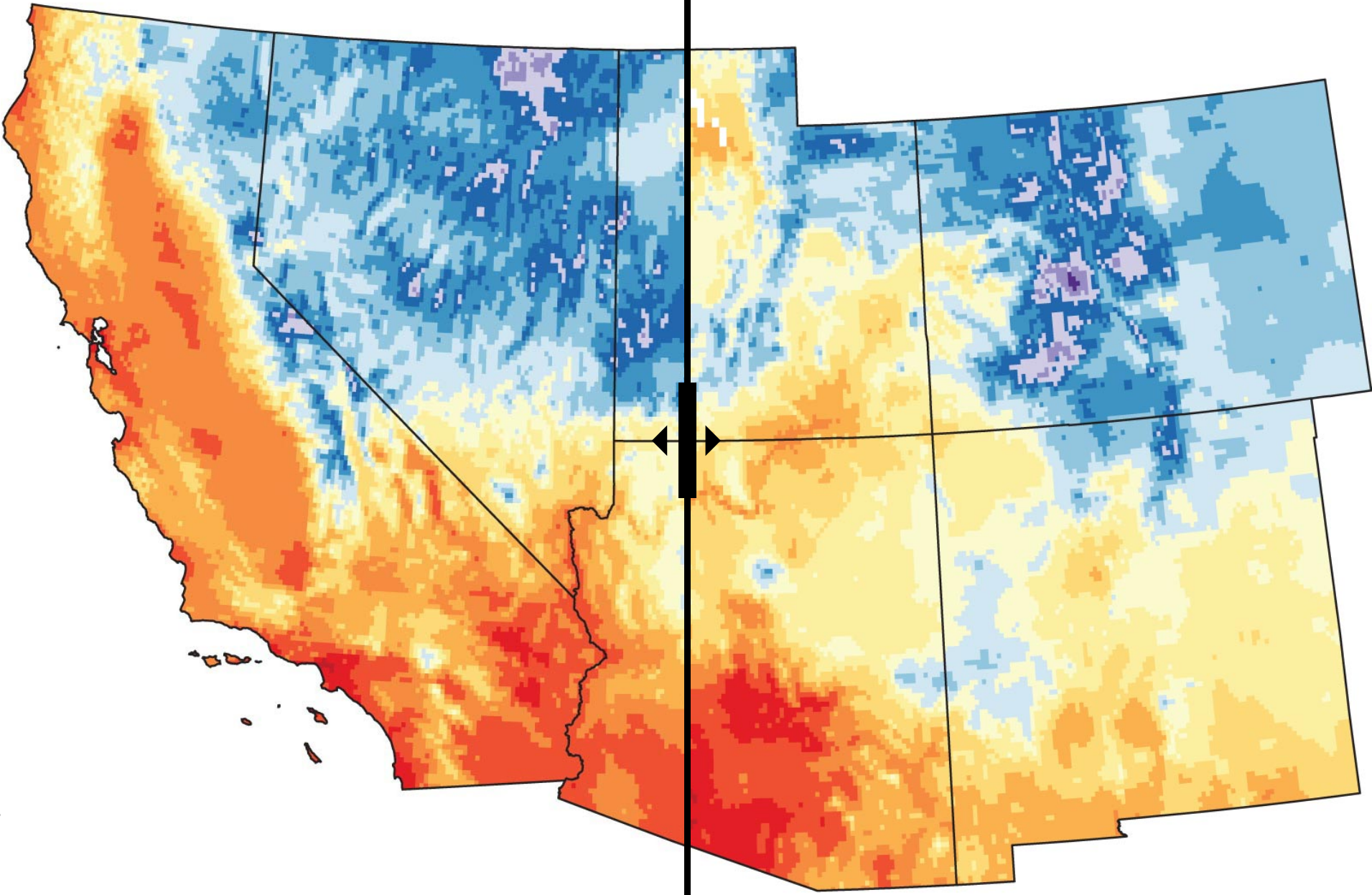
Historical (1976-2005)

Higher Scenario (2070-2099)



Historical (1976-2005)

Higher Scenario (2070-2099)



er cold temperature
(5), would shift these
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er, decreased winter chill
ay 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.

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).



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.

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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](#)}

Figure 25.10: 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

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 nights²³ 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}

Elevated levels of CO₂ 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](#)}



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