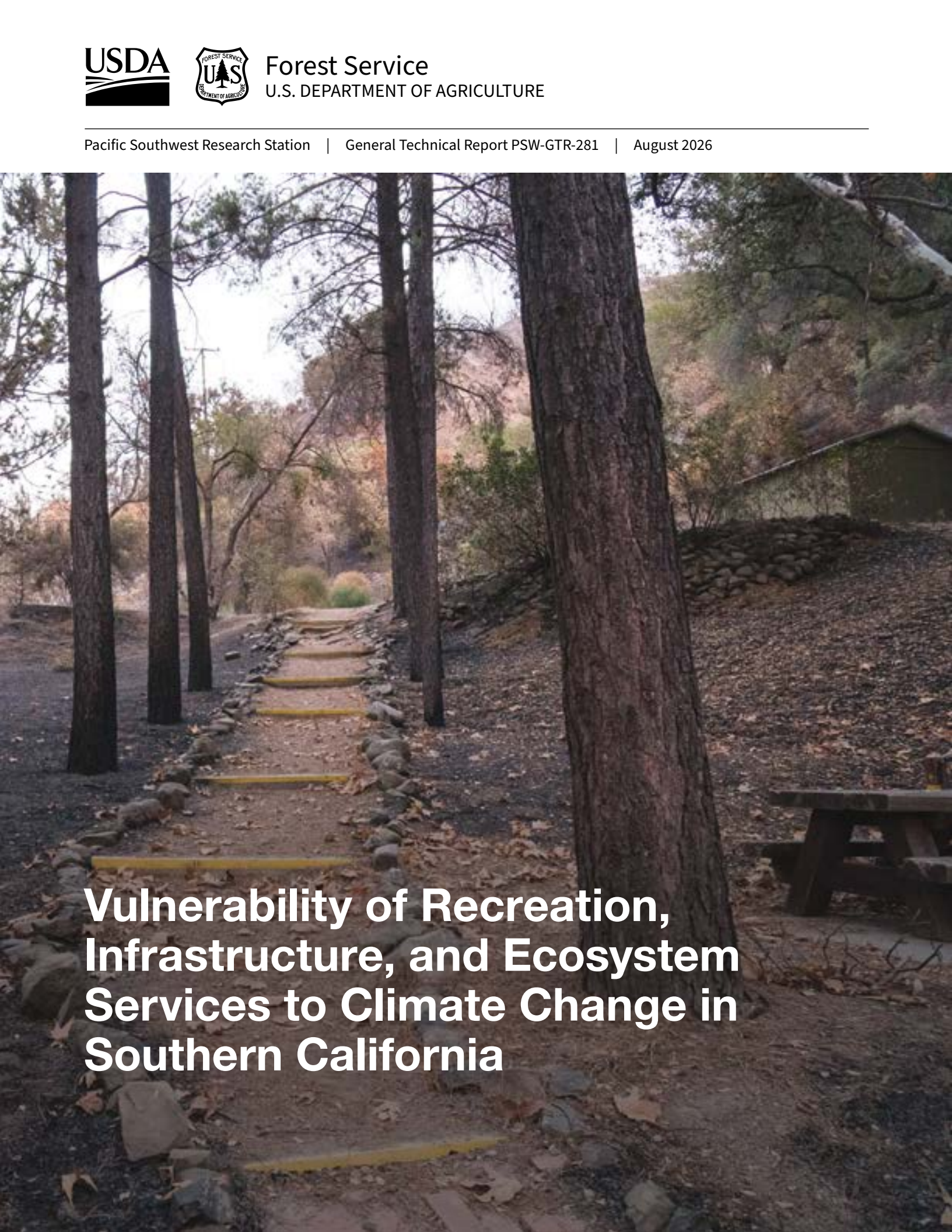




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A photograph of a dirt path in a forest, with several large trees on either side. The path has yellow-painted wooden steps. In the background, there is a stone wall and a small building. The ground is covered with fallen leaves and rocks.

Vulnerability of Recreation, Infrastructure, and Ecosystem Services to Climate Change in Southern California

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Cover photo: Pine trees and walking path damaged by the Thomas Fire along Highway 33 in Ojai, California. Photo by Jeremy Francis.

Vulnerability of Recreation, Infrastructure, and Ecosystem Services to Climate Change in Southern California

Jessica E. Halofsky, David L. Peterson, and Lara Y. Buluç, Editors

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Abstract

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The Southern California Adaptation Partnership identified climate change issues relevant for resource management on national forest and national park units in southern California. This partnership assessed the vulnerability of infrastructure, outdoor recreation, and ecosystem services to climate change and developed adaptation options that minimize negative effects of climate change and facilitate transition to a warmer climate.

High levels of use and aging roads and facilities on federal lands are increasing the vulnerability of infrastructure to the effects of climate change. Altered timing and amount of precipitation will likely create challenges when storing and allocating water for municipal water supplies, flood prevention, and recreation. Roads, bridges, and culverts are susceptible to increased runoff during storm events, causing failures. Increased magnitude of peak streamflows is expected to damage roads near perennial streams, especially following wildfires. Associated infrastructure, such as bridges, culverts, campgrounds, and facilities near streams and floodplains, will likely be particularly vulnerable. At vulnerable or flood-prone sites, resilience near stream crossings and in floodplains can be enhanced by designing infrastructure to withstand more frequent and severe flooding and upsizing or upgrading existing infrastructure to withstand future flooding. Some roads and other infrastructure can be decommissioned or moved to mitigate risks.

Nearly all recreation is affected by weather conditions, influencing decisions about if, when, and where to recreate. Warm-weather recreation will likely benefit from a longer period without cold weather and snow, especially during the spring and autumn shoulder seasons. Winter recreation (skiing, snowmobiling)

will likely be negatively affected by a warmer climate because of less and more transient snow. The effects of higher temperatures on hunting, fishing, water-based recreation, and gathering forest products may be variable and less certain.

Adaptation strategies for recreation include adjusting staffing and management to accommodate changes in seasonal access and recreation locations, and increasing resilience of recreation sites to changing conditions or higher demand.

Several ecosystem services are considered in the assessment: water resources; livestock grazing; carbon sequestration; air quality and pollution abatement; soil regulation; biodiversity and genetic diversity; and cultural, traditional, spiritual, and heritage values. Reduced water supply is one of the biggest potential effects of climate change, given demand by the large population of southern California. Conservation of urban and agricultural consumption of water is the best adaptation strategy for maintaining water supply.

KEYWORDS:

Adaptation
Climate change
Disturbance
Drought
Ecosystem services
Extreme weather
Infrastructure
Recreation
Resilience
Roads
Southern California
Wildfire

Summary

The Southern California Adaptation Partnership (SOCAAP) was developed to identify climate change issues relevant for resource management on national forest and national park units in southern California (Angeles, Cleveland, Los Padres, and San Bernardino National Forests and Santa Monica Mountains National Recreation Area). The direct effects of higher temperatures and altered precipitation, as well as the associated influence of extreme events (especially drought and wild-fire), are expected to cause significant effects on hydrology, human infrastructure, recreation, and ecosystem services throughout southern California.

Southern California is characterized by a Mediterranean climate with hot, dry summers and mild, wetter winters. Temperatures along the coast are heavily moderated by the ocean, whereas inland areas experience more extreme temperatures. With climate change, climate models project the largest increase in mean annual minimum temperature (from 44.4 to 49.8 °F by mid-21st century, under Representative Concentration Pathway 8.5) for Angeles National Forest, and the smallest increases for Los Padres National Forest and Santa Monica Mountains National Recreation Area (7.4 and 7.5 degrees F increase, respectively). Climate models project significant increases in the number of days with extreme heat. Six of the counties in the assessment area historically have zero days annually with a heat index above 105 °F. Climate models project that these counties will experience 3 to 12 days with this level of extreme heat by the end of the century. Riverside County, which historically experienced 12 days annually with a heat index above 105 °F, is projected to experience 63 days above 105 °F by end of century.

Projections for future precipitation are uncertain, ranging from small decreases to small increases for both mid- and end of century, depending on location. Most precipitation in southern California falls during relatively few precipitation events. This includes atmospheric rivers, which greatly influence southern California water resources and drive most major flood events. Although most models project more extremes in precipitation, this too is uncertain. Reduced snowpack and earlier snow-melt are expected to cause earlier timing of streamflow, and future peak flows are projected to occur earlier in the

season. As precipitation regimes at high elevation change from snow dominated to rain dominated, snowpack storage will likely decline.

Higher air temperature will likely increase potential evapotranspiration and drought stress in vegetation, decreasing live and dead fuel moisture and fire risk. Higher temperature will also likely reduce snow at high elevations; a no-snow future is possible except on the highest mountain peaks. Water availability may be less reliable from year to year, and more runoff will likely be produced for a given precipitation event. This translates into higher peak flows, flood risk, and sediment movement during the wet season, and lower runoff during the dry season. In addition, lower summer stream-flow paired with higher summer air temperatures will likely result in higher stream temperature and a more prolonged dry season.

Current transportation infrastructure, hydroelectric networks, recreation resources, and ecosystem services in southern California are coupled with hydrologic processes and vegetation. Higher demand for public access on federal lands may coincide with increasing occurrence of floods, landslides, and wildfires. Earlier and larger spring streamflows will potentially lead to lower low flows for streams that contribute to water supplies, support aquatic systems, and provide recreation opportunities during the summer.

National forests in the SOCAAP assessment area contain a combined 4,788 miles of roads, 3,211 miles of trails, 41 road bridges, 44 trail bridges, 39 dams, and 2,250 buildings and administrative sites, representing an investment of at least \$1 billion. The combined effects of increasing use, aging infrastructure, and changing climatic and hydrologic conditions are increasing the vulnerability of infrastructure and risk for users. Water resource infrastructure (including dams and reservoirs) stores water, reduces flooding, and provides recreational opportunities. Future changes in timing and amount of precipitation will likely create challenges when storing and allocating water for municipal water supplies, flood prevention, and recreation.

Outdoor recreation is a huge enterprise in southern California, providing diverse experiences, psychosocial values, and public health benefits to local communities and nonlocal visitors. Cumulative annual expenditures

from recreational visitors to the four southern California national forests is estimated at \$251 million. Economic values can be substantially higher when including the benefits that recreationists receive from engaging in a recreation activity. Warm-weather activities (hiking, viewing natural features, camping, etc.) account for the largest proportion of recreation. Nearly all recreation is affected by weather conditions, affecting decisions about if, when, and where to recreate. In general, warm-weather recreation is expected to increase (especially in areas with water access), snow-based recreation is expected to decrease, and other forms of recreation are expected to experience variable effects.

Federal lands in the SOCAAP assessment area provide many benefits—or ecosystem services—to people. Ecosystem services are the goods and services that individuals and communities receive from natural resources and amenities. Climate change is expected to affect the quantity, quality, and diversity of benefits that individuals and communities receive from public lands, with considerable variation in effects among ecosystem services and in different locations. Several ecosystem services are considered in this assessment: water resources; livestock grazing; carbon sequestration; air quality and pollution abatement; soil regulation; biodiversity and genetic diversity; and cultural, traditional, spiritual, and heritage values. Reduced water supply is one of the biggest potential effects of climate change, given demand by the large population of southern California.

Infrastructure

Climate Change Effects—

Higher temperatures and more droughts will likely increase the frequency and extent of wildfires and reduce or deplete some groundwater resources. Higher temperatures, higher evapotranspiration, and less available surface and subsurface moisture may reduce groundwater supplies, adversely affect water systems, and complicate dam management. A combination of more fire and higher storm intensity is expected to accelerate erosion on slopes and produce more sediment movement in the form of debris torrents and debris flows. Washouts, plugged culverts, and bridge damage can be expected, as well as damage to facilities and campgrounds.

Wildfire is the biggest hazard to infrastructure in the SOCAAP assessment area. After fires and floods, the region is subject to severe erosion problems, debris torrents, and debris flows from intense rainfall on steep, fractured rock and highly erosive soils. Roads and infrastructure near rivers and streams are periodically exposed to high flows that may contain large amounts of sediment. Peak flows from intense storms will likely increase erosion and washouts that damage roads and culverts, ranging from minor washouts to complete loss of the roads. Damage to infrastructure from flooding and debris flows affects public safety, water quality, aquatic habitat, and access for resource management.

Projected higher temperatures, more wildfires, and more intense storms with higher peak flows would expose roads and facilities to increased flood risk. More frequent debris flows will increase risks to downslope infrastructure. Wildfires will likely cause more damage to facilities, bridges, and trails. Maintenance and repair costs will grow as damage to infrastructure accumulates.

Adaptation Options—

Using established best management practices, while considering the additional influence of climate change, can facilitate long-term resilience of infrastructure. Specific adaptation options include the following:

- Assessing the risk and condition of potentially vulnerable roads and infrastructure can help managers prioritize and allocate limited funding and resources.
- Fire-proofing structures and creating defensible space around facilities can reduce fire danger.
- Building debris dams and sediment-retention structures in high-hazard areas can reduce debris-flow damage.
- Avoiding water concentration and managing waterflow on erosive soils can be critical.
- Adding trash racks to culverts and channels can reduce flood damage.
- Focusing maintenance and adaptation treatments in areas most vulnerable to extreme events and flooding can reduce storm damage.

- Implementing watershed restoration projects and improving stream-crossing structures (with bridges) can improve stream habitat and aquatic organism passage, and reduce flood vulnerability and risk.
- At flood-prone sites, designing future infrastructure to withstand more frequent and severe floods, and upsizing or upgrading existing infrastructure to withstand future flooding and erosion, can enhance resilience near stream crossings and in floodplains.
- Decommissioning or moving roads and other infrastructure can mitigate risks in the most vulnerable locations.

Collaborative adaptation efforts and an “all lands” approach are essential for effective responses to increasing disturbances. Expanding partnerships among multiple organizations can increase the capacity of federal agencies to maintain functional ecosystems, water resources, and recreation and transportation infrastructure. Public awareness of the connections among infrastructure, ecosystems, and disturbance can be promoted through outreach and education with local communities and stakeholders.

Recreation

Climate Change Effects—

The future of outdoor recreation participation in the SOCAAP assessment area will likely be influenced by climate change and by changes in urban populations. Layered with sociodemographic complexity is the biogeographic complexity of the area, offering a broad diversity of outdoor recreation opportunities. Altered temperature, precipitation, and seasonality of weather conditions will likely affect evolving recreation patterns in southern California over the course of the 21st century. Higher temperatures will likely be a primary driver, because most recreational activities are vulnerable to variable seasonal conditions and extreme events. As temperatures increase, communities near public lands will likely incur the socioeconomic effects, especially if those communities participate heavily in outdoor recreation or depend on it financially.

As air temperature increases, recreationists are more likely to seek respite from the heat in nearby natural areas, especially in warm-weather seasons, increasing overall recreation participation. Areas near water (coastal

and inland), shaded areas, and higher elevations are more likely to see higher participation. Concerns about overcrowding and ecological effects may be elevated. However, unusually hot days may lead to a decline in visitation, and unseasonably warm weather may diminish satisfaction with a location or recreation experiences. Elevated temperatures can lead to heat-related illnesses and other risks to recreationists.

Reduced snowpack has varied effects based on type of winter activity and availability of snowmaking (e.g., Big Bear Mountain Resorts). Reduced snowfall in lower elevation areas affects activities such as cross-country skiing, snowshoeing, and snowmobiling more than downhill skiing and snowboarding. In locations where snowmaking is not possible, low snowfall can close ski operations for one or multiple seasons.

Increased wildfire frequency and extent will continue to affect outdoor recreation. Negative effects generally dominate, although the presence of unusual blooms for viewing and other postfire ecological conditions can create recreation opportunities. Area closures may occur for long periods during high fire danger. Loss of tree canopy after fire can place visitors at increased risk from high temperatures because of shade loss. Viewsheds and visitor experiences are degraded by smoke and poor air quality during active fires.

Adaptation Options—

The U.S. Department of Agriculture, Forest Service; U.S. Department of the Interior, National Park Service; permittees; and partners can use an expanded portfolio of strategies to address climate change effects. Because recreation use is likely to increase across the SOCAAP assessment area, increased staffing with more seasonal flexibility will likely be needed to manage for high-quality recreation opportunities. Monitoring recreation visits, experience quality, and equitable access can help serve the diverse population of southern California.

Recreationists can adapt to a primary location being unavailable by going elsewhere, going another time, being flexible in plans and expectations, and gathering essential information about an area before a visit. Some opportunities currently available may change in their seasonality, form of experience, requirements for planning or access, or locations offered. Long-term climate-related effects on recreation quality, recreation

benefits, site substitution, and place attachments can use additional investigation to ensure these elements are incorporated in planning and management of outdoor recreation.

Agencies can implement several adaptation practices to facilitate resilience to climate change. In some cases, capacity limits, reservation systems, and use fees can be implemented to address demand. In other cases, larger adaptive management approaches involving site renovations and intensive site management will likely be needed. Extended closures across seasons may be needed at some locations to facilitate ecological recovery from drought and effects of heavy recreation use. Improved visitor communication, education, and monitoring (e.g., via agency websites, social media, and smartphone applications) can also be used to address effects and visitor safety. Partnerships and volunteer programs will likely continue to supplement management for diverse recreation opportunities and settings, supporting information needs for recreationists and informing adaptive responses.

Ecosystem Services

Climate Change Effects—

Water resources—Water availability in southern California will become more variable, with hotter summers driving higher demand and lower water supplies for municipal, agricultural, and industrial consumption. Climate change is projected to intensify stressors placed on water systems and put human uses at risk, especially as the population grows. More intense rainfall events can result in more sedimentation. Reduced water quantity may result in more concentrated pollutants in waterways, and warmer water encourages harmful algal blooms.

Livestock grazing—Climatic variability may alter the vegetation composition of grazing land, which could alter the production of grass and other forage for grazing. Higher concentrations of atmospheric carbon dioxide may improve the productivity of some rangelands by facilitating increased water-use efficiency (carbon fertilization), although increased grazing could have negative effects on other ecosystem services. The potential negative effects of grazing can be balanced with the benefits of grazing for local economies and fire risk.

Carbon sequestration—Rates of carbon storage in southern California ecosystems will largely depend on the effects of increased wildfire frequency and extent on the amount of vegetation cover, which can persist for decades. Drought frequency and potential changes in productivity in trees, shrubs, and grasses can also directly affect carbon storage. Conversion from chaparral to nonnative annual grassland may lead to reduced carbon storage. Climate change is likely to generally reduce the ability of ecosystems to store carbon, although vegetation models differ in their projections of potential carbon losses, particularly for areas dominated by chaparral.

Air quality and pollution abatement—Climate change is expected to exacerbate wildfire frequency and extent, which can increase health-related effects from wildfire smoke. A trend of increasing number of days with wildfire-related smoke (i.e., smoke days) in the SOCAAP assessment area is expected to continue. In addition, wildfire smoke will likely impair opportunities for recreationists to travel and exercise outside during periods of poor air quality. The expected increase in smoke days translates to increased exposure for residents with preexisting health conditions, reducing their physical activities and increasing medical costs.

Soil regulation—Altered storm frequency and intensity combined with altered vegetation cover (e.g., conversion from chaparral to nonnative grasses) can increase erosion risk. Increased wildfire frequency and extent contribute to this conversion. The interaction of these multiple factors will likely reduce the effectiveness of soil regulation and increase erosion and sedimentation in streams and water supplies.

Biodiversity and genetic diversity—Species with small population sizes, fragmented habitats, and low genetic diversity are generally less resilient to disturbances, such as wildfire and pathogens. Altered temperature and precipitation may influence the distribution and abundance of species, including those that are considered rare. Higher temperature will have direct effects on some species. Other species may be affected indirectly through altered timing of life history, shifts in habitat ranges, and modified interactions with other species. These effects are expected to interact with stressors, such as wildfire, leading to complex responses in biodiversity.

Cultural, traditional, spiritual, and heritage values—American Indian communities may be affected more by climate change than other communities because of their proximity to sensitive areas, specific cultural or traditional practices tied to the landscape, and other socioeconomic factors. Loss of specific plant and animal species may endanger ceremonial items, which may result in loss of culture and tradition. The effects of climate change on cultural and heritage value can be substantial when access to a valued place is lost, such as by wildfire destroying a cultural or historic site. Increased wildfire frequency and extent may convert chaparral to nonnative grasslands, reducing the availability of traditional foods and medicines.

Adaptation Options—

Water resources—Behavioral changes by users can shift water allocation by promoting conservation practices that reduce consumption in urban and agricultural settings. Additional water storage facilities would increase water availability during the dry season and provide a buffer against increased variability. Accelerating the pace and scale of fuel treatments in forested areas would help reduce wildfire frequency and extent, thus reducing negative effects on water quality. Removing water-hungry invasive plant species may free up water resources in some wildland areas.

Livestock grazing—Grazing can be used in some locations to reduce fuel loading and wildfire risk. Los Padres and San Bernardino National Forests, which both have high fire risk, also have a reasonably large capacity to expand grazing. Best practices for grazing can be implemented to avoid negative effects on the broader range of ecosystem services. As ecosystems become more susceptible to climate change, it may be necessary to curtail grazing to protect ecological values in some locations.

Carbon sequestration—Because large-scale disturbance events have a long-term effect on vegetation and carbon in drought- and fire-prone ecosystems of southern California, few management options are available to maintain current (or past) levels of carbon sequestration. Accelerating the pace and scale of thinning and surface fuel reduction in forested areas can reduce the likelihood of crown fires as well as conversion to other vegetation types. This can reduce the release of large pulses of

carbon into the atmosphere, although some carbon is removed in the treatments. Livestock grazing may also help to reduce fine fuels in some locations.

Air quality and pollution abatement—Improved communication about air quality conditions, including real-time data for wildfire events, can provide timely information that local communities can use to prepare for periods of poor air quality. Plans can be developed for managing outdoor recreation use and to establish protocols for when to close public-land access to reduce exposure to poor air quality. In some cases, it may be possible to reduce the duration of poor air quality caused by smoke by increasing the flexibility with which forest managers plan management activities, such as prescribed burns.

Soil regulation—Maintaining vegetative ground cover and reestablishing vegetation quickly after wildfires can reduce erosion during and after storm events. Revegetation can use grasses, brush, chaparral, and trees for ground cover, root strength, and soil protection. Drought-tolerant native plant species are more likely to successfully revegetate in most areas. In addition to species selection, soil preparation may be required to facilitate germination and growth in areas with high compaction, low organic matter content, and low fertility.

Biodiversity and genetic diversity—Reducing existing stressors on plant and animal species can improve resilience to future changes in climate. Increased monitoring of habitats, species populations, and human-use patterns can help inform management, planning, and postdisturbance restoration activities. In some locations, public-access closures can be implemented to protect sensitive habitat and avoid disturbance of critical life stages of certain species.

Cultural, traditional, spiritual, and heritage values—Incorporating traditional ecological knowledge and cultural burning in land management practices may help mitigate some climate change effects. Traditional burning contributes to community livelihood and conserves landscape heterogeneity and resilience. Such management practices may help increase waterflow, enhance wildlife habitat, control pathogens and insects, and promote the expansion of culturally relevant practices across the landscape.

Toward Climate-Informed Management and Planning

The SOCAAP achieved specific elements of national and regional climate change strategies for federal agencies, providing a scientific foundation for resource management and planning for infrastructure, outdoor recreation, and ecosystem services on federal lands and beyond. First, the scientific basis for current and projected climate change effects on natural resources, infrastructure, and recreation is now well established. Second, a large number of adaptation options have been developed, many of which are a component of current management practice, providing a pathway for slowing the rate of deleterious change in resource conditions. Timely implementation of adaptation can help (1) prevent the deterioration of infrastructure and the huge costs of repairs and replacement; (2) maintain facilities, access, and opportunities for recreation; and (3) ensure that minimal degradation occurs in a broad range of ecosystem services. Long-term monitoring can help detect potential climate change effects, as well as evaluate the effectiveness of adaptation options over time.

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Chapter 1: Introduction

Jessica E. Halofsky¹

Project Description and Objectives

The Pacific Southwest Region of the U.S. Department of Agriculture, Forest Service (Forest Service), in collaboration with the Forest Service's Pacific Northwest and Pacific Southwest Research Stations and Western Wildland Environmental Threat Assessment Center, formed a science-management partnership and conducted a climate change vulnerability assessment for infrastructure, recreation, and ecosystem services in four southern California national forests and one U.S. Department of the Interior, National Park Service unit. This Southern California Adaptation Partnership (SOCAAP) assessment covered the Angeles, Cleveland, Los Padres, and San Bernardino National Forests, and the Santa Monica Mountains National Recreation Area (fig. 1.1). The vulnerability assessment set the stage for development of adaptation strategies and tactics in a series of virtual science-management workshops. The outcomes of the SOCAAP are described in this report.

Specific objectives of the SOCAAP effort were as follows:

- Synthesize the best available science to assess climate change vulnerabilities and develop adaptation strategies for infrastructure, recreation, and ecosystem services on national forests and a National Park Service unit in southern California.
- Develop a framework and tools for managers to incorporate the best available science into Forest Service recreation and engineering program assessments.
- Define priority regional- and forest-level climate change vulnerabilities for integration in the land management planning process.

- Identify priority areas for cross-boundary partnerships and third-party investments to best leverage agency appropriations and to maximize opportunities for shared stewardship.

Climate change response is an agency-wide priority for the Forest Service. In 2008, the Forest Service released a Strategic Framework for Responding to Climate Change (USDA FS 2008). In 2010, the Forest Service provided specific direction to the National Forest System in the form of the *National Roadmap for Responding to Climate Change* (USDA FS 2010) and the *Climate Change Performance Scorecard* (USDA FS 2016). These directions were followed by the National Forest System land management planning rule (USDA FS 2012), which requires national forests and grasslands to address climate change in the land management plan (forest plan) revision process. More recently, the Forest Service developed the *Climate Adaptation Plan* (USDA FS 2022), which provides a comprehensive approach to climate change adaptation for the agency. The plan identifies key climate change risks and adaptation actions to reduce risks to the agency's mission and operations. This climate change vulnerability assessment and adaptation report is consistent with the recommendations in the Forest Service's *Climate Adaptation Plan*.

The assessment described in this report builds upon past climate change and related assessments conducted in the southern California region. For example, EcoAdapt and partners conducted a climate adaptation project for southern California that involved assessing vulnerabilities for key habitats in the region and developing adaptation strategies for each key habitat (Drake and Kershner 2017). This assessment also builds on a climate change vulnerability assessment conducted for national forests across the United States, including a similar assessment in the Sierra Nevada (Halofsky et al. 2021), as well as assessments in the Pacific Northwest (Halofsky and Peterson 2017; Halofsky et al. 2011, 2019; Raymond et al. 2014), Northern Rockies (Halofsky et al. 2018a), Intermountain West (Halofsky et al. 2018b), and Eastern United States (Butler et al. 2015; Swanston et

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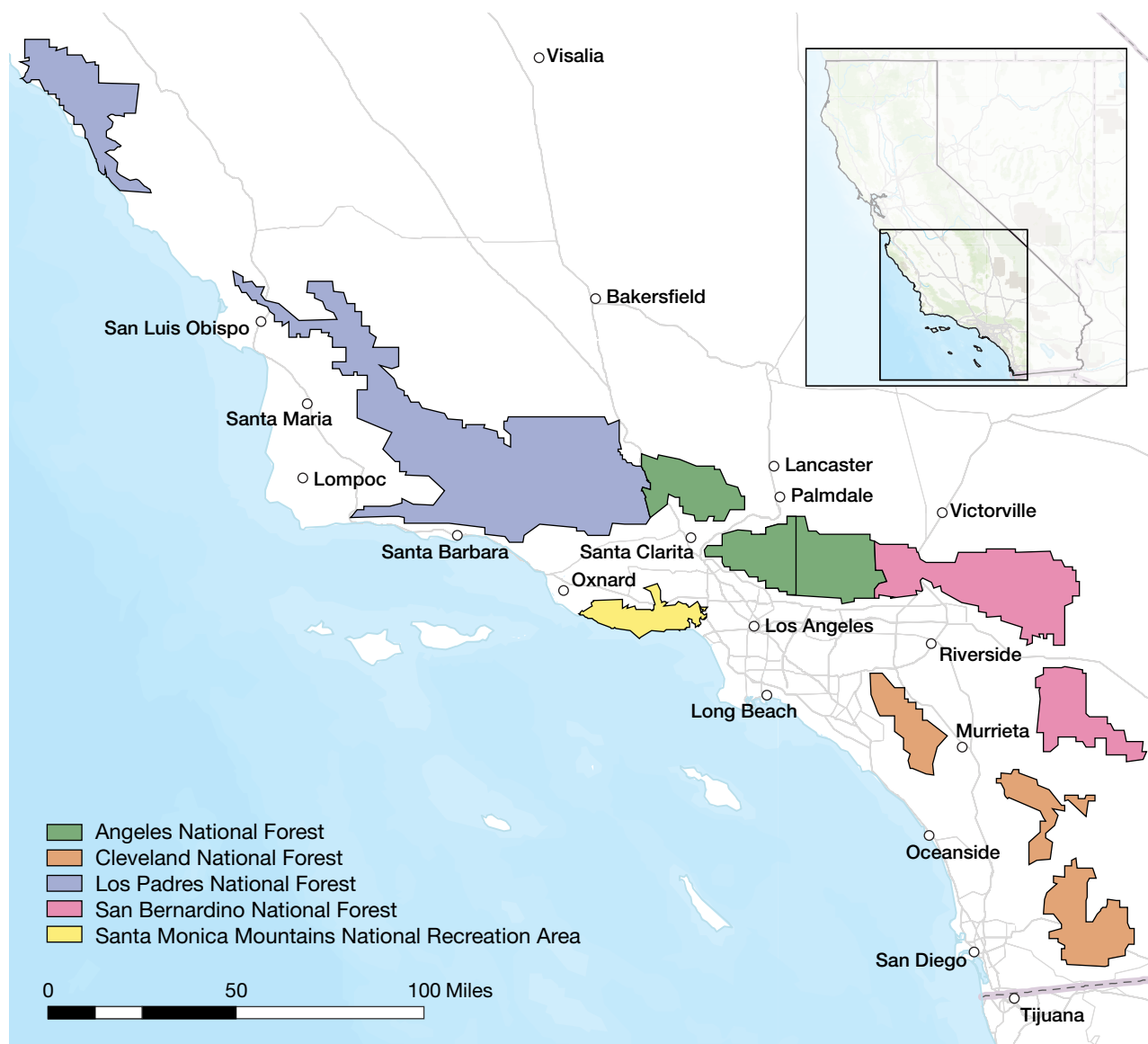


Figure 1.1—The Southern California Adaptation Partnership assessment area.

al. 2011, 2016). The processes, products, and techniques used for climate change efforts on national forests have been compiled in a guidebook for developing adaptation options for national forests (Peterson et al. 2011). The SOCAAP effort followed the principles and practices in the guidebook.

Approach

Vulnerability assessments typically incorporate exposure, sensitivity, and adaptive capacity (Parry et al. 2007). Exposure is the degree to which the system is exposed to changes in climate, sensitivity is an inherent quality of the system that indicates the degree to which it could be affected by climate change, and adaptive capacity is the ability of a system to respond and adjust to the exogenous influence of climate. We used scientific literature, model output, and expert knowledge to assess exposure, sensitivity, and adaptive capacity and identify key vulnerabilities for infrastructure, recreation, and ecosystem services in the SOCAAP assessment area.

The vulnerability assessment was conducted through a science-management partnership. Science-management partnerships have emerged as effective catalysts for the development of vulnerability assessments and land management adaptation plans at both the strategic and tactical level (Cross et al. 2013, Littell et al. 2011, McCarthy 2012, Peterson et al. 2011, Swanston et al. 2016). Partnerships among Forest Service, Research and Development scientists; National Forest System and National Park Service managers; and other agencies and universities have played a major role in advancing climate change adaptation in the agency (Halofsky et al. 2014). Science-management partnerships typically involve iterative sharing of climate and climate effects information by scientists, and of local climate, ecological, and management information by managers (Peterson et al. 2011). This iterative information exchange aids in the identification of vulnerabilities to climate change at the local scale and sets the stage for the development of adaptation strategies and tactics (Halofsky et al. 2014).

The vulnerability assessment process started with a virtual kickoff meeting in November 2021. Specialists from the management units attended, along with science teams for infrastructure, recreation, and ecosystem services; other Forest Service leaders; and partners. Project leads introduced the project, objectives, and general approach to the vulnerability assessment. Science team leaders then reviewed the vulnerability assessment outline, potential sources of information, and preliminary results. Meeting participants provided feedback to inform information sources and content for the vulnerability assessment.

Following the kickoff meeting, participants compiled and summarized climate and hydrology context and projections to inform the assessments for recreation, infrastructure, and ecosystem services. Science teams for recreation, infrastructure, and ecosystem services then developed the vulnerability assessment, consulting with regional- and unit-level land managers as needed. Each assessment team refined key questions that the assessment needed to address, selected values to assess, and determined which climate change effects models best informed the assessment. To the greatest extent possible, teams focused on effects and projections specific to the region.

After identifying key vulnerabilities for infrastructure, recreation, and ecosystem services, scientists, land managers, and stakeholders convened at three 1-day virtual workshops in April 2022. The workshops focused on presenting and discussing the vulnerability assessment and eliciting adaptation options from resource managers. During the workshops, scientists presented information on climate change effects for infrastructure, recreation, and ecosystem services. Participants used facilitated dialogue to identify key sensitivities and adaptation options. They identified strategies (general approaches) and tactics (on-the-ground actions) for adapting resources and management practices to climate change, as well as opportunities for implementing these adaptation actions in projects, management plans, partnerships, and policies. Participants generally focused on adaptation options that could be implemented based on current scientific understanding of climate change effects, but they also identified research and monitoring that would benefit future efforts to assess vulnerability and guide management practices. Facilitators captured information generated during the workshops with worksheets adapted from Swanston et al. (2016).

Assessment Overview

Chapter 2 of this report addresses expected climatological and ecological changes in the SOCAAP assessment area. Chapter 3 addresses expected hydrological changes; chapter 4 addresses infrastructure vulnerabilities to climate change; chapter 5 addresses recreation vulnerabilities to climate change; and chapter 6 addresses ecosystem services vulnerabilities to climate change. Chapter 7 summarizes adaptation strategies and tactics that were compiled from the workshop. Chapter 8 provides conclusions and a discussion on potential applications of the vulnerability assessment information and adaptation options.

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Chapter 2: Climate Change Effects in Southern California

Emily Fusco, Jessica E. Halofsky, Alex Dye, and John B. Kim¹

Climate Overview

The southern California assessment area spans from Monterey in the north to San Diego in the south. It includes four national forests and one national recreation area, which total more than 6,500 square miles (fig. 2.1). Elevations vary widely across the national forests and recreation area, ranging from sea level (0 feet) in Los Padres National Forest and Santa Monica Mountains National Recreation Area to roughly 11,500 feet on San Geronimo Mountain in San Bernardino National Forest (fig. 2.1, table 2.1). Outside the national forests and national recreation area, many of the surrounding urban areas are densely populated. Composed of nine counties, the region is home to more than 23 million people, with more than 10 million people living in Los Angeles County alone (chapter 5).

The region has a Mediterranean climate with hot summers and most precipitation falling in the winter when temperatures are cooler. Temperatures are milder in coastal areas because they are heavily moderated by the ocean; temperatures become more extreme 10 to 20 miles inland from the coast, with long dry periods typical throughout the region (Hall et al. 2018, Kalansky et al. 2018, Langridge 2018). Precipitation tends to decrease moving inland and from north to south (see chapter 3, fig. 3.1). The El Niño Southern Oscillation and Pacific Decadal Oscillation also play a significant role in inter-annual climatic variation in the region.

The assessment area is comprised of several ecoregions (Omernik 1987) (fig. 2.2) with subtle but distinct differences in their climates and ecologies. The Southern California Mountain ecoregion is dominant in the San Bernardino, Angeles, and Los Padres National Forests. Parts of this region near the coast have a Mediterranean influence, whereas inland and higher elevation areas (e.g., arid mountain slopes) that are closer to the Mojave Desert are drier, with some desert scrub vegetation communities (Griffith et al. 2016). Dense conifer vegetation occurs in areas of the Southern California Mountain ecoregion where cool, high-elevation temperatures are met with lower levels of evaporation (e.g., on north-facing slopes) (Griffith et al. 2016).

A substantial portion of Los Padres National Forest is also comprised of the Central California Foothills and Coastal Mountains ecoregion, which is similar to the Southern California Mountain ecoregion, but oak and chaparral dominate this lower elevation landscape, with fewer conifers (Griffith et al. 2016). Cleveland National Forest and Santa Monica Mountains National Recreation Area largely fall within the Southern California/Northern Baja Coast ecoregion, which is characterized by even lower elevation hills with hot, dry inland slopes (Griffith et al. 2016) (table 2.1).

Climate Baselines and Projections

Climate Models and Scenarios

Climate change is expected to influence future temperature, precipitation, and seasonal variation in climatic variables. Global climate models (GCMs), which represent physical processes in the Earth's climate system, are used to project potential future climate. These coarse-resolution models (e.g., 100 km) produce variable results based on differences in how climatic processes are represented (Pierce et al. 2018). The projections provided by California's Fourth Climate Change Assessment (Pierce et al. 2018) and included in this report use localized constructed analogs to downscale 10 GCMs, which were chosen based on their high performance for projecting daily temperature and precipitation in California, to 6-km resolution throughout the state (Pierce et al. 2018).

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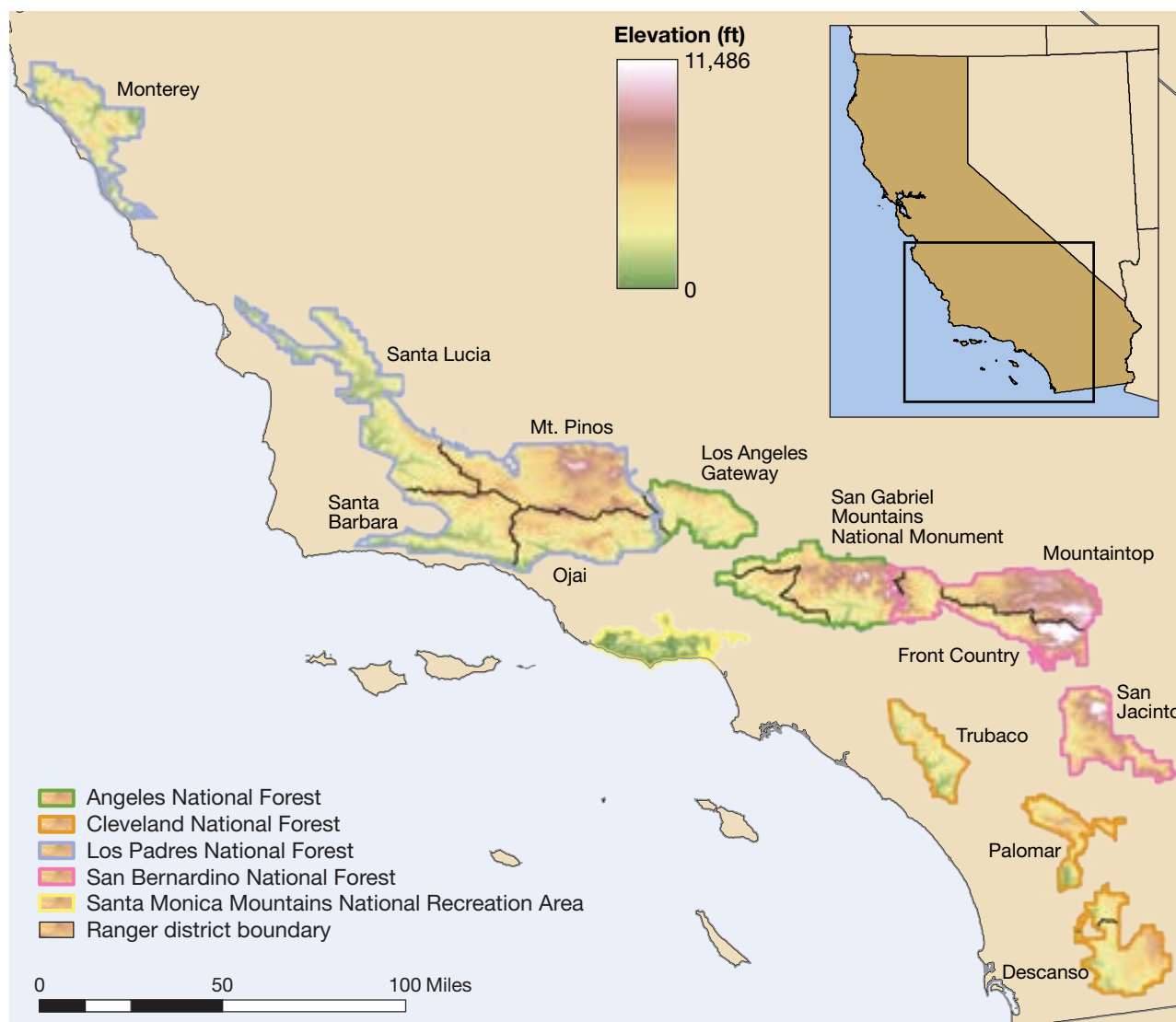


Figure 2.1—National forest and national recreation area units in the Southern California Adaptation Partnership assessment area. Map shows names of Forest Service ranger districts for each unit.

Table 2.1—Elevation for national forest and national recreation area (NRA) units in the Southern California Adaptation Partnership assessment area

Unit	Elevation		
Name	Minimum	Maximum	Mean
FEET			
Angeles National Forest	669	10,046	3,882
Cleveland National Forest	420	6,270	3,099
Los Padres National Forest	0	8,822	3,378
San Bernardino National Forest	1,348	11,486	5,466
Santa Monica Mountains NRA	0	3,015	1,148

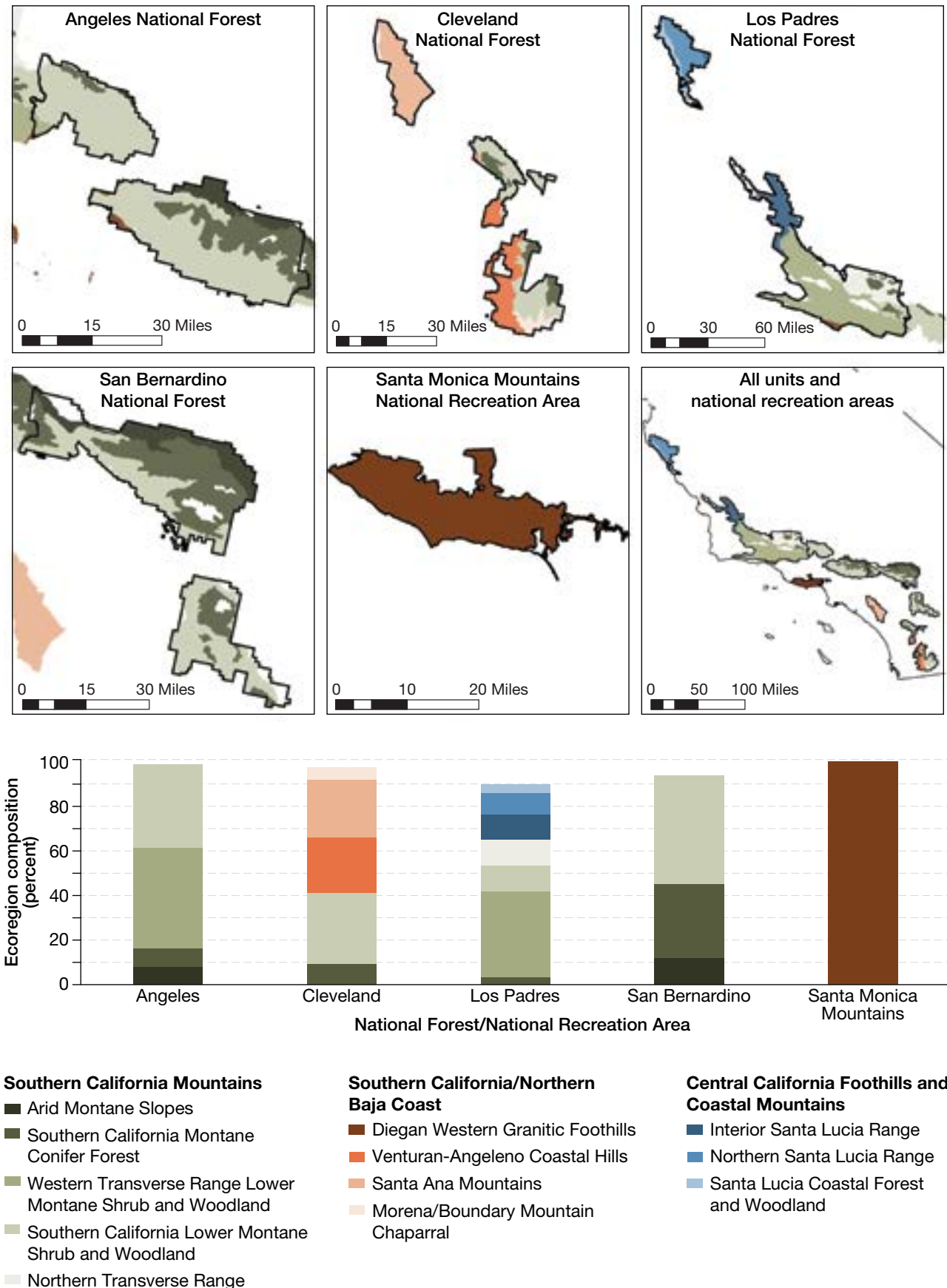


Figure 2.2—Level IV ecoregions (Omernik 1987) by national forest and national recreation area unit comprising the Southern California Adaptation Partnership assessment area. Excludes ecoregions that comprise less than 3 percent of the total forest area.

In addition to historical means, California’s Fourth Climate Change Assessment provides climate projections for temperature and precipitation under Representative Concentration Pathway (RCP) 4.5 and RCP 8.5 scenarios to mid- and end of century. GCMs run under the RCP 8.5 scenario assume emissions will continue to rise in a “business as usual” scenario, with no global effort to reduce greenhouse gas emissions. RCP 4.5 assumes emissions peak at mid-century with stable low levels by 2080. As a result, RCPs 4.5 and 8.5 typically have similar mid-century projections with more pronounced differences in end-of-century projections. In this report, we further analyze data produced for California’s Fourth Climate Change Assessment to provide climate projections specific to each of the national forests and the national recreation area. The data reported represent the multimodel means over each described 30-year period.

Temperature

Southern California climate is characterized by hot, dry summers and mild, moderately wet winters. Summer maximum temperatures are largely similar along the coast (Abatzoglou et al. 2009). Coastal temperatures are moderated in part because of low, stratiform clouds, including fog, which frequently occur during the summer (Clemesha et al. 2016), regulating land-surface temperatures (Iacobellis and Cayan 2013). Temperature is also heavily influenced by topography, with higher elevations experiencing cooler year-round temperatures (Abatzoglou

et al. 2009). Historical (1961–1990) mean annual minimum temperatures range from 37.1 °F in San Bernardino National Forest to 47.8 °F in Santa Monica Mountains National Recreation Area, while mean annual maximum temperatures range from 64.5 °F in Los Padres National Forest to 71.6 °F in Santa Monica Mountains National Recreation Area (Pierce et al. 2018) (table 2.2).

Warming is projected throughout the region, with inland areas experiencing the highest increases in temperatures (fig. 2.3), and coastal warming moderated by the ocean and associated marine layer clouds (Hall et al. 2018, Kalansky et al. 2018, Langridge 2018). However, the future of these moderating effects remains uncertain as marine-layer clouds are difficult to simulate in climate models (Kalansky et al. 2018). Increased temperatures will lead to substantial decreases in snowpack and snow-residence time, particularly in Los Padres, Angeles, and Cleveland National Forests (chapter 3). Snowpack and snow-residence time will also substantially decrease, although to a lesser degree, in the highest elevation areas of San Bernardino National Forest (chapter 3).

Mean annual maximum and minimum temperature are projected to increase under both emission scenarios, with the largest increases projected for end of century under RCP 8.5 (table 2.3). At mid-century (2035–2065), projections show that the largest increase in mean annual maximum temperature (6.0 °F) is expected in Angeles and San Bernardino National Forests under RCP 8.5. Projected mean annual maximum temperature

Table 2.2—Mid-century (2035–2065) climate projections for national forest and national recreation area (NRA) units in the Southern California Adaptation Partnership assessment area

Unit	Projected 30-year average								
	Tmin			Tmax			Precipitation		
Name	Baseline	RCP 4.5	RCP 8.5	Baseline	RCP 4.5	RCP 8.5	Baseline	RCP 4.5	RCP 8.5
	DEGREES FAHRENHEIT						INCHES PER DAY		
Angeles National Forest	44.4	48.7	49.8	68.8	73.6	74.8	0.070	0.067	0.065
Cleveland National Forest	42.9	46.8	47.9	71.5	75.9	77.0	0.056	0.054	0.053
Los Padres National Forest	37.9	41.2	42.1	64.5	68.3	69.3	0.072	0.072	0.071
San Bernardino National Forest	37.1	41.2	42.4	65.4	70.2	71.4	0.068	0.065	0.064
Santa Monica Mountains NRA	47.8	51.1	52.0	71.6	75.4	76.3	0.055	0.054	0.052

Minimum temperature (Tmin) and maximum temperature (Tmax) refer to the average annual minimum and average annual maximum temperatures, respectively, for each climate period and scenario. Representative Concentration Pathway (RCP) projection scenario 4.5 assumes emissions peak at mid-century, with stable low levels by 2080; RCP 8.5 assumes emissions will continue to rise. Projection data source: UOC GIF (2025).

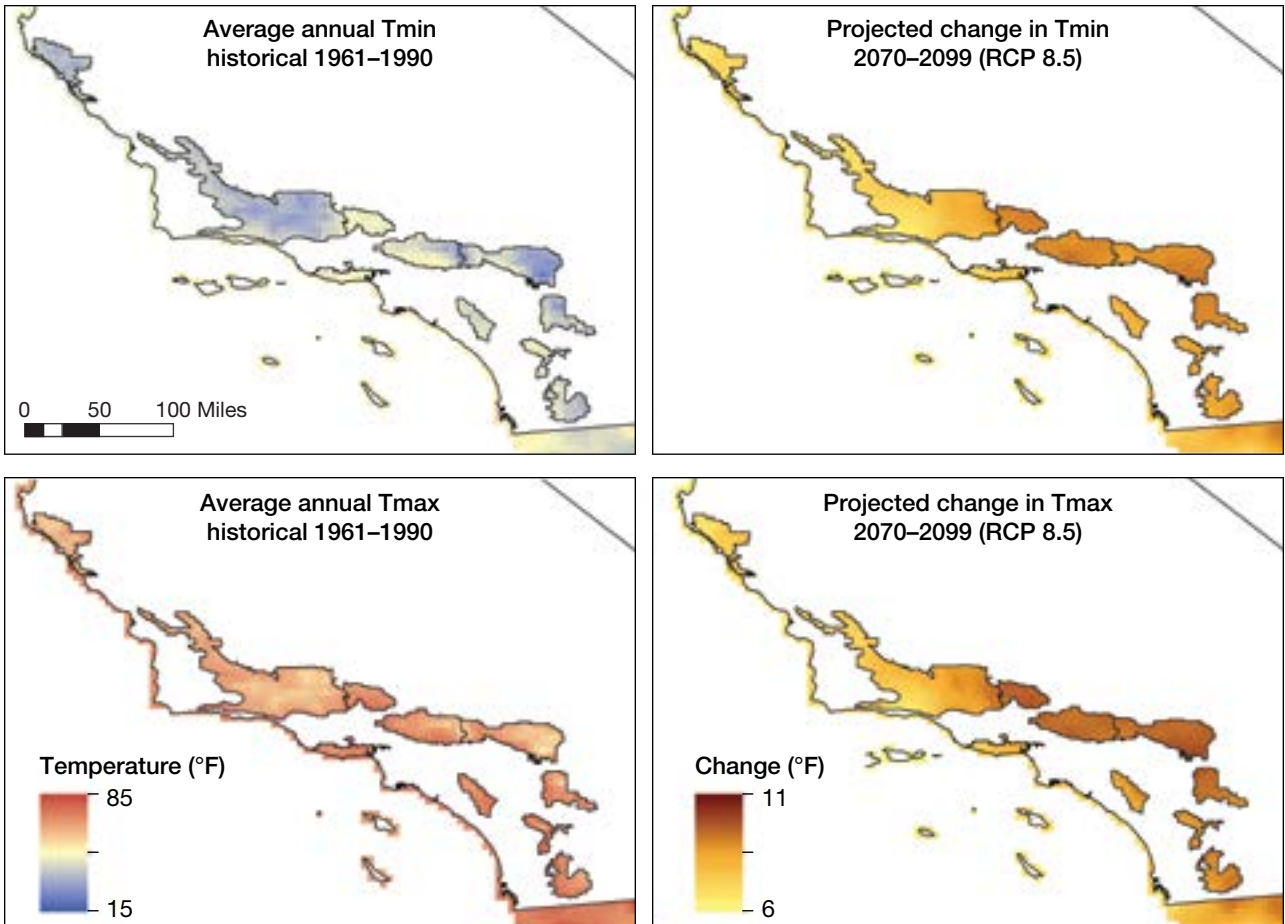


Figure 2.3—Historical mean annual minimum and maximum temperatures and projected changes for end of century under Representative Concentration Pathway (RCP) 8.5 (largest projected changes) in the Southern California Adaptation Partnership assessment area. Note that increases in temperature are projected to be higher in more inland areas.

Table 2.3—End-of-century (2070–2099) climate projections for national forest and national recreation area (NRA) units in the Southern California Adaptation Partnership assessment area

Unit	Projected 30-year average								
	Tmin			Tmax			Precipitation		
Name	Baseline	RCP 4.5	RCP 8.5	Baseline	RCP 4.5	RCP 8.5	Baseline	RCP 4.5	RCP 8.5
	DEGREES FAHRENHEIT						INCHES PER DAY		
Angeles National Forest	44.4	50.0	53.3	68.8	75.1	78.2	0.070	0.068	0.068
Cleveland National Forest	42.9	48.0	51.3	71.5	77.3	80.2	0.056	0.054	0.053
Los Padres National Forest	37.9	42.4	45.3	64.5	69.6	72.4	0.072	0.072	0.076
San Bernardino National Forest	37.1	42.5	46.0	65.4	71.7	74.8	0.068	0.066	0.065
Santa Monica Mountains NRA	47.8	52.3	55.3	71.6	76.7	79.4	0.055	0.054	0.056

Baseline refers to the historical (1961–1990) 30-year average. Minimum temperature (Tmin) and maximum temperature (Tmax) refer to the mean annual minimum and average annual maximum temperatures, respectively, for each climate period and scenario. Representative Concentration Pathway (RCP) projection scenario 4.5 assumes emissions peak at mid-century (2035–2064), with stable low levels by 2080; RCP 8.5 assumes emissions will continue to rise. Projection data source: UOC GIF (2025).

increases for all forests range from 3.8 to 6.0 °F (under both RCPs), with the lowest increases expected in Santa Monica Mountains National Recreation Area and Los Padres National Forest under RCP 4.5 (table 2.2). The largest increases in mean annual minimum temperature are projected for Angeles National Forest, with increases of 4.3 °F under RCP 4.5 and 5.4 °F under RCP 8.5. The smallest increases are projected in Santa Monica Mountains National Recreation Area and Los Padres National Forest, with both projected to see increases of 3.3 °F under RCP 4.5 and 4.2 °F under RCP 8.5. (table 2.2).

Projected increases in end-of-century (2070–2099) temperature are more extreme under both RCPs than they are under mid-century projections. However, general patterns follow mid-century projections. The greatest increases are expected for mean annual maximum temperatures, with projections for San Bernardino and Angeles National Forests increasing 9.4 °F under RCP 8.5 (table 2.3, fig. 2.3). These increases are projected to be at higher elevations and at more inland areas for both forests (fig. 2.3). The smallest increase in mean annual maximum temperature (5.1 °F) is projected for Santa Monica Mountains National Recreation Area and Los Padres National Forest under RCP 4.5. However, under RCP 8.5, these areas could see mean annual maximum temperatures increase by 7.9 °F and 7.8 °F, respectively, with the lowest increase expected in coastal areas (fig. 2.3). Projected mean annual minimum temperature increases for all forests (under both RCPs) range from 4.5 to 8.9 °F, with the lowest increases expected in Santa Monica Mountains National Recreation Area and Los Padres National Forest and the largest increases expected in San Bernardino and Angeles National Forests under both RCPs (table 2.3).

Precipitation

Precipitation in southern California has high interannual variability, which can be influenced by the El Niño–Southern Oscillation and Pacific Decadal Oscillation, particularly in the southern portion of the region (Abatzoglou et al. 2009). For example, strong El Niño events have been linked to precipitation between 80 and 160 percent higher than climatological normals for 10 recent El Niño events (Jong et al. 2016). This high interannual variability is demonstrated in Los Angeles County where winter (December, January, February)

precipitation ranged from as little as 2 inches to more than 25 inches from 1961 to 1990 (fig. 2.4). Total precipitation in the region is driven by relatively few precipitation events (Dettinger et al. 2011). For example, in the Los Angeles region, half of the annual precipitation falls during just five storm events (Hall et al. 2018).

There is high uncertainty around projected precipitation, with most forests projected to experience a slight decrease (up to –7 percent) under both RCP 4.5 and RCP 8.5 by mid-century, except for Los Padres National Forest, which may see a slight increase (0.2 percent) under RCP 4.5 (table 2.2). End-of-century projections are similar, with slight decreases in precipitation expected in most places (up to –6 percent), and slight increases projected for Los Padres National Forest (1–6 percent) (table 2.3). Note also that precipitation projections in this chapter suggest a slight **decrease**, while those in chapter 3 suggest a slight **increase**. This is because the GCMs used to make these projections differ, highlighting the uncertainty around precipitation projections.

Although changes in mean annual precipitation are projected to be small, precipitation extremes are expected to increase (Swain et al. 2018). This may lead to a more pronounced Mediterranean climate, with the potential for increased precipitation in the winter (Kalansky et al. 2018). Precipitation extremes include more frequent and severe droughts and possibly more frequent and intense atmospheric river events (Hall et al. 2018, Kalansky et al. 2018, Swain et al. 2018). See chapter 3 for a more detailed discussion on potential effects of precipitation changes on hydrology.

Extreme Events

Heavy Precipitation

In California, half to two-thirds of the total precipitation falls on just 5–15 days annually (Dettinger et al. 2011), highlighting the importance of extreme rainfall events for California water resources. Some of these extreme precipitation events can be caused by atmospheric rivers, which are narrow bands of high water vapor that move from tropical areas to higher latitudes (Dettinger et al. 2011, Harris and Carvalho 2018). Although atmospheric rivers are larger contributors to precipitation in northern California, they also contribute significant precipitation amounts in southern California (Kim et al. 2013).

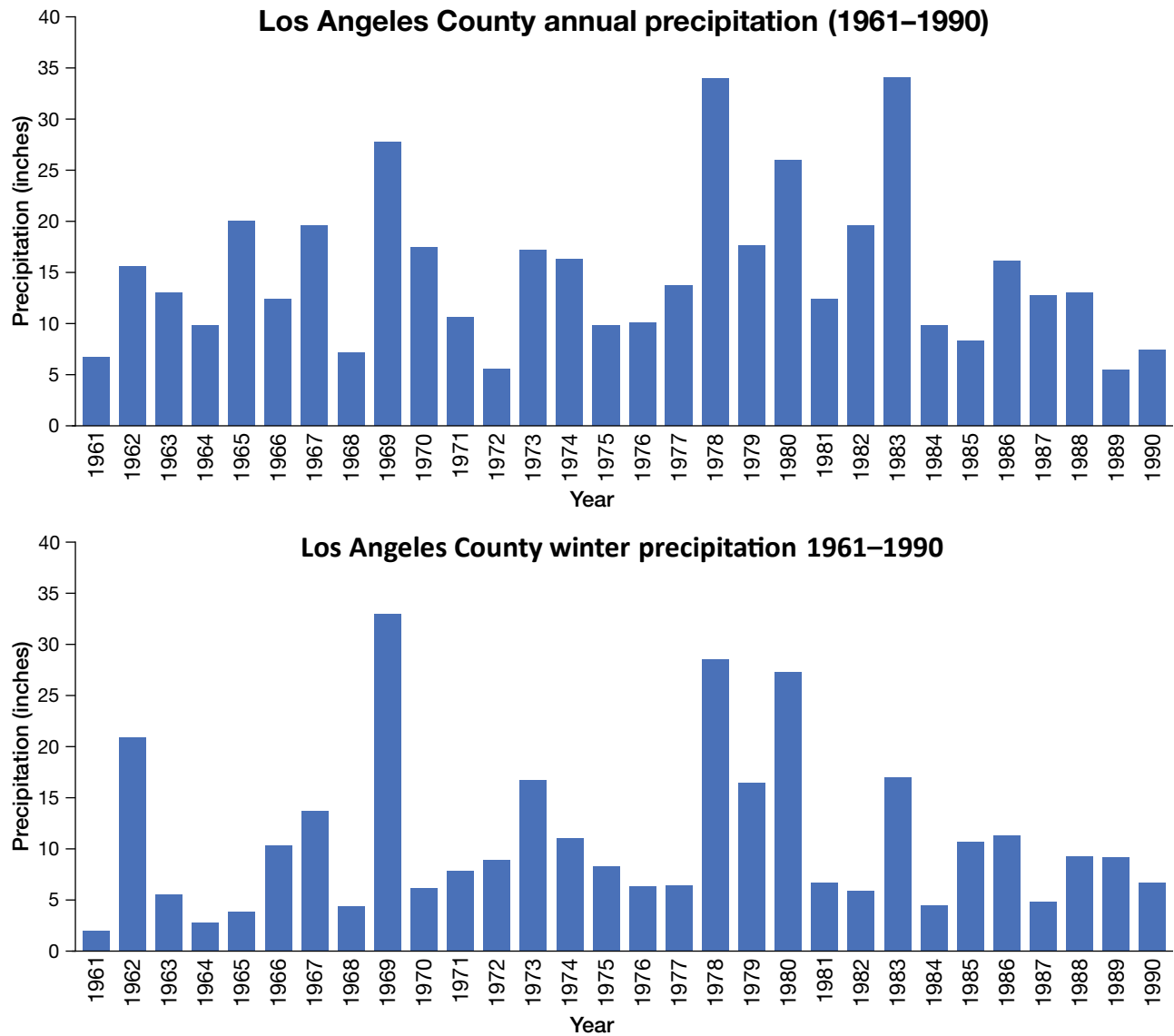


Figure 2.4—Historical (1961–1990) annual and winter (December through January) precipitation data for Los Angeles County. An example of the high interannual variability in precipitation that is common in the region. Source: USDC NOAA NCEI (2022).

Increased precipitation from atmospheric rivers is expected with climate change (Hall et al. 2018, Langridge 2018). However, it is uncertain how climate change will affect atmospheric river events locally in California (Espinoza et al. 2018). Peak season length, frequency, and intensity of events may increase because of the increased ability of storms to transport water vapor (Dettinger et al. 2011, Hall et al. 2018); climate change may have already increased the likelihood of events capable of producing catastrophic flooding (Huang and Swain 2022). Indeed, a 100–200 percent increase in extremely wet seasons (comparable to November–March precipitation in 2016–2017, or a 25-year return interval) was projected by end of century (2070–2100) under RCP 8.5 (Swain et al. 2018).

Extratropical storms also drive flood events in coastal areas and can contribute to inland flooding (Langridge 2018). Although an increase in extratropical storm events has been observed in recent decades (Vose et al. 2014), and projections indicate that there will likely be increased precipitation during future storm events (Osburn et al. 2018), projections under climate change remain uncertain (Langridge 2018).

Heat

Southern California is expected to experience an increase in the frequency, duration, and intensity of extreme heat events (Kalansky et al. 2018). These increases will be most apparent for inland areas and valleys compared

to coastal and high-elevation areas (Hall et al. 2018, Kalansky et al. 2018). In places where temperatures are typically more moderate, lower intensity heat waves can negatively affect people and wildlife that are not acclimatized to higher temperatures (Kalansky et al. 2018). For this reason, heat waves are defined based on typical temperatures within a region and can include days with temperatures as low as 79 °F on the coast to 101 °F inland (Dahl et al. 2019, Langridge 2018).

Dahl et al. (2019) assessed the number of historical and projected extreme heat days for counties across the United States (tables 2.4, 2.5). According to this assessment, heat index days above 90 °F are historically common in southern California and have ranged from 13 days annually in Orange County to 95 days annually in Riverside County, with more extreme temperatures in the east. By mid-century (2036–2065), in the 10 counties associated with the assessment area, heat index days above 90 °F are projected to increase by 29 to 122 days per year under RCP 4.5 and 34 to 128 days per year under RCP 8.5 (table 2.4). By end of century (2070–2099), heat index days above 90 °F are projected to increase to up to 148 days annually in Riverside County under RCP 8.5 (table 2.5).

Six of the counties in the assessment area (all of which are coastal counties) historically have zero days annually

with a heat index above 105 °F. However, these counties are projected to experience 3 to 12 days per year with this level of extreme heat by end of century (2070–2099) under RCP 8.5. Riverside County, which historically experienced 12 days annually with a heat index above 105 °F, is projected to increase to 63 days annually by end of century under RCP 8.5 (table 2.5).

Drought

Drought, or more specifically meteorological drought, refers to prolonged dry weather conditions (i.e., reduced precipitation and increased temperature). Beyond changes in temperature and precipitation, meteorological drought conditions can affect built and natural systems, resulting in hydrological drought, agricultural drought, and ecological drought. California experienced its driest 3-year period on record within the past decade (Diffenbaugh et al. 2015; Swain et al. 2014, 2016), and more frequent and intense droughts are expected in the SOCAAP assessment area in the future (Kalansky et al. 2018). End-of-century projections under RCP 8.5 suggest that southern California may experience up to a 200-percent increase in frequency of extremely dry seasons, similar to the 100-year drought in 1976–1977, despite minimal change in mean precipitation (Swain et al. 2018).

Table 2.4—Projected number of annual extreme heat days by mid-century (2036–2065) in the Southern California Adaptation Partnership assessment area based on county data reported by the Union of Concerned Scientists

County	Heat index above 90 °F			Heat index above 100 °F			Heat index above 105 °F		
	Baseline	RCP 4.5	RCP 8.5	Baseline	RCP 4.5	RCP 8.5	Baseline	RCP 4.5	RCP 8.5
NUMBER OF DAYS									
Kern	55	83	91	6	22	31	1	6	10
Los Angeles	29	55	63	1	8	12	0	1	3
Monterey	22	39	45	1	6	9	0	1	2
Orange	13	41	52	0	4	7	0	1	1
Riverside	95	122	128	33	60	69	12	34	42
San Bernardino	83	112	119	19	45	56	6	20	27
San Diego	42	69	77	9	21	26	2	9	13
San Luis Obispo	29	50	57	1	7	11	0	1	3
Santa Barbara	14	29	34	0	2	4	0	0	0
Ventura	14	32	38	0	3	5	0	1	1

Baseline data refer to mean annual number of extreme heat days for 1971–2000. Representative Concentration Pathway (RCP) projection scenario 4.5 assumes emissions peak at mid-century, with stable low levels by 2080; RCP 8.5 assumes emissions will continue to rise. Source: Dahl et al. (2019).

Table 2.5—Projected number of annual extreme heat days by end of century (2070–2099) in the Southern California Adaptation Partnership assessment area based on county data reported by the Union of Concerned Scientists

County	Heat index above 90 °F			Heat index above 100 °F			Heat index above 105 °F		
	Baseline	RCP 4.5	RCP 8.5	Baseline	RCP 4.5	RCP 8.5	Baseline	RCP 4.5	RCP 8.5
NUMBER OF DAYS									
Kern	55	92	116	6	29	56	1	9	28
Los Angeles	29	65	94	1	11	32	0	2	12
Monterey	22	47	69	1	9	22	0	2	9
Orange	13	54	93	0	6	27	0	1	11
Riverside	95	130	148	33	67	91	12	40	63
San Bernardino	83	119	139	19	52	80	6	25	49
San Diego	42	80	109	9	25	48	2	12	26
San Luis Obispo	29	60	86	1	11	28	0	2	11
Santa Barbara	14	36	59	0	3	13	0	0	3
Ventura	14	41	68	0	5	16	0	1	6

Baseline data refer to mean annual number of extreme heat days for 1971–2000. Representative Concentration Pathway (RCP) projection scenario 4.5 assumes emissions peak at mid-century (2035–2064), with stable low levels by 2080; RCP 8.5 assumes emissions will continue to rise. Source: Dahl et al. (2019).

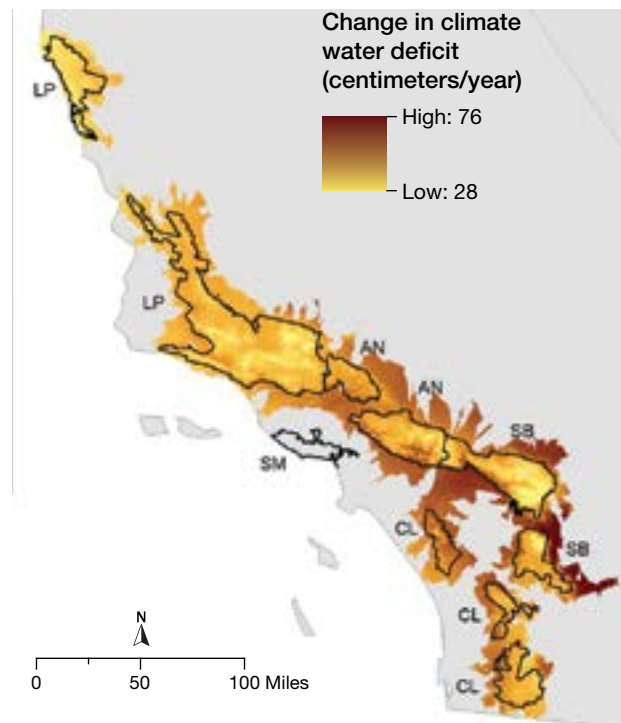


Figure 2.5—Projected change in climatic water deficit (CWD) by the end of century (2070–2099) under RCP 8.5 climate change scenario for a reference historical period (1970–1999). CWD shown represents the mean across 29 MC2 dynamic global vegetation model simulations driven by 29 global climate models: Access1-0, bcc-csm1-1-m, bcc-csm1-1, BNU-ESM, CanESM2, CCSM4, CESM1-BGC, CESM1-CAM5, CMCC-CM, CNRM-CM5, CSIRO-mk3-6-0, Fgoals-g2, FIO-ESM, GFDL-CM3, GFDL-ESM2G, GFDL-ESM2M, GISS-E2-R, HadGEM2-AO, HadGEM2-CC, HadGEM2-ES, INMCM4, IPSL-CM5A-LR, IPSL-CM5A-MR, IPSL-CM5B-LR, MIROC5, MIROC-ESM-CHEM, MIROC-ESM, MRI-CGCM3, and NorESM1-M. Outlines on map show Los Padres (LP), Angeles (AN), San Bernardino (SB), and Cleveland National Forests (CL) and Santa Monica National Recreation Area (SM). Results for SM were not available from MC2 simulations.

Climatic water deficit (CWD), a drought metric representing plant water stress, is the difference between potential evapotranspiration and actual evapotranspiration. Using simulation outputs from the MC2 dynamic global vegetation model (Bachelet et al. 2001), we obtained potential evapotranspiration and actual

evapotranspiration values for a reference historical period (1970–1999) and the end of the century (2070–2099) and calculated projected change in CWD under RCP 8.5 (fig. 2.5). The MC2 simulations were driven with 29 GCMs available in the NEX-DCP30 downscaled climate projection dataset (Thrasher et al. 2013). These simulations suggest that CWD is expected to increase throughout the region, with Cleveland National Forest experiencing the largest mean increase (52 percent). San Bernardino National Forest is projected to have the most variable increase, ranging from 28.0 to 69.5 percent, reflecting the high range of elevation within the forest extent (table 2.6).

Table 2.6—Projected change in climatic water deficit across the four national forests by end of century (2070–2099) in the Southern California Adaptation Partnership assessment area

Forest name	Change in climatic water deficit (RCP 8.5)				
	Min	Max	Range	Mean	SD
	PERCENT				
Angeles National Forest	32.9	61.9	28.9	50.7	4.9
Cleveland National Forest	40.0	61.0	21.0	52.0	4.4
Los Padres National Forest	32.2	59.3	27.1	45.5	4.3
San Bernardino National Forest	28.0	69.5	41.4	47.4	7.1

Climatic water deficit (CWD) was calculated from MC2 simulations of 29 global climate models (GCMs) using the Representative Concentration Pathway (RCP) 8.5 scenario (emissions continue to rise). GCM data are from the NEX-DCP30 downscaled climate projections dataset, with a 30 arc-second spatial resolution (Thrasher et al. 2013). CWD values illustrate spatial variability within each national forest. Simulation results are not available for Santa Monica Mountains National Recreation Area.

SD = standard deviation.

Climate Change Effects

Wildfire

Wildfire is common in the southern California region and plays an important role in maintaining ecological health in many southern California ecosystems, in particular, chaparral shrublands (Keeley and Davis 2007). However, wildfire frequency may increase in some areas in a changing climate. To evaluate future wildfire probability in the assessment area, Dye et al. (2023) ran the wildfire simulation model FSim (Finney et al. 2011) with fire weather derived from eight GCMs chosen to represent a range of potential climate futures under RCP 8.5 for mid-21st century (2040–2069) climate. Four representative example simulations are shown in figure 2.6. Relative to the historical baseline (1992–2015), moderate increases in burn probability are exemplified by simulations driven with IPSL-CM5A-LR (hotter, drier, and less humid) and CanESM2 (hotter, wetter, and more humid). In these simulations, increases in projected burn probability remain high in the southern forests but are not as widespread across the region. For example, they show a net increase in Los Padres National Forest and Santa Monica Mountains National Recreation Area (table 2.7), but several areas within these forests (e.g., southern Monterey and northern Santa Lucia Ranger Districts in Los Padres National Forest, and parts of the western Santa Monica Mountains National Recreation Area) show a decrease (fig. 2.6).

Alternatively, a much hotter, drier, and less humid future (as projected by the GCM HadGEM2-ES365)

results in burn probability increases across the entire region, particularly in northwestern Angeles and southern Cleveland National Forests where wildfire in several places is projected to increase by as much as 0.05 (i.e., an annual burn probability of 5 percent, or equivalent to an extra fire every 20 years). However, a moderately warmer, wetter, and more humid future (BCC-CSM1-1-M) may lead to a decline in burn probability across most of the region, with many of the biggest declines occurring in the same areas of the southern forests where HadGEM2-ES365 projects large increases.

Overall, six out of eight simulations projected a net increase in landscape-wide burn probability, except for Los Padres National Forest for which five simulations projected a net increase and three projected a net decrease (table 2.7). This pattern is consistent with Dye et al. (2020), which showed that model agreement is more uncertain along California’s central coast compared to the southern coast. Across all simulations, the least change was always projected in Santa Monica Mountains National Recreation Area, whereas the largest increases tended to occur in Cleveland and San Bernardino National Forests (table 2.7). Such wide variability in projected burn probability is not uncommon for southern California where precipitation affects burn projections and for which projections of future precipitation are uncertain (Chang et al. 2015, Neelin et al. 2013).

In addition to uncertainty around precipitation, the models described here did not simulate high-wind events.

Table 2.7—Projected change in annual burn probability from historical baseline (1992–2015) to mid-21st century (2040–2069) for national forest and national recreation area (NRA) units in the Southern California Adaptation Partnership assessment area

	Global climate model						
	BCC-CSM1-1-M	CanESM2	GFDL-ESM2M	HadGEM2-CC365	HadGEM2-ES365	IPSL-CM5A-LR	MIROC-ESM-CHEM
Angeles National Forest	-0.0023	0.0061	-0.0063	0.0011	0.0091	0.0038	0.0161
Cleveland National Forest	-0.0028	0.0087	-0.0083	0.0018	0.01173	0.0047	0.0218
Los Padres National Forest	-0.0012	0.0031	-0.0019	-0.0008	0.0065	0.0016	0.0065
San Bernardino National Forest	-0.0026	0.0080	-0.0077	0.0019	0.0107	0.0047	0.0200
Santa Monica Mountains NRA	-0.0003	0.0008	-0.0011	0.0000	0.0010	0.0004	0.0016
							0.0002

Simulated with climate change projections from eight global climate models (GCMs) using the Representative Concentration Pathway 8.5 scenario (emissions continue to rise). Decreases in probability shown as negative values, increases are positive values. All GCMs are from the MACA-v2-METDATA downscaled climate dataset (Abatzoglou and Brown 2012). Four representative GCMs are highlighted in figure 2.6: BCC-CSM1-1-M (moderately warmer, wetter, and more humid); CanESM2 (hotter, wetter, and more humid); HadGEM2-ES365 (much hotter, drier, and less humid); and IPSL-CM5A-LR (hotter, drier, and less humid).

In particular, the Santa Ana winds, which are prominent from October to April, are another major driver of wildfire events for which climate change effects are uncertain (Hall et al. 2018). Historically, there has been significant spatial variability in the strength and consistency of Santa Ana winds events during wildfire across southern California (Dye et al. 2020).

An increase in favorable fire conditions (e.g., high fuel aridity, vapor pressure deficit) in southern California has been observed in recent decades, particularly during autumn months, and this trend is projected to continue with climate change (Goss et al. 2020, Khorshidi et al. 2020, McEvoy et al. 2020). This includes the number of days with climatic conditions favorable for large (>99 acres) fire events (Dong et al. 2022). Increased fire potential is consistent with a projected 10-percent and 200-percent increase in burned area in the southern and northern portions of the assessment area, respectively, by mid-century (Yue et al. 2014). However, future fire risk in the region remains uncertain (Langridge 2018) because future precipitation projections are highly uncertain, and factors other than climate may influence fire risk more in this arid region (Keeley and Syphard 2016).

Climate and weather play important roles in explaining area burned on Forest Service lands in the region (Syphard et al. 2017). However, people account for most wildfire ignitions (74–88 percent) in the four national forests, and patterns of human population density influence the total number of fires that have occurred historically (1910–2016) (Keeley and Syphard 2018). In addition to ignition, fuel loading varies across landscapes and affects local fire hazards. FSim simulations do not account for fine-scale variability in fuels and the resulting effects on fire hazard and intensity.

Modeling the effects of climate change alone on burn probability is useful for bracketing a base set of plausible planning scenarios (Williams and Abatzoglou 2016). However, temperature and precipitation will interact with a variety of other factors, such as changes in vegetation distribution (Harris et al. 2016), and wind intensity (Guzman-Morales and Gershunov 2019), making specific projections difficult. Including multiple drivers, such as high-wind events and ignition sources, may help better predict favorable conditions for very large fire events.

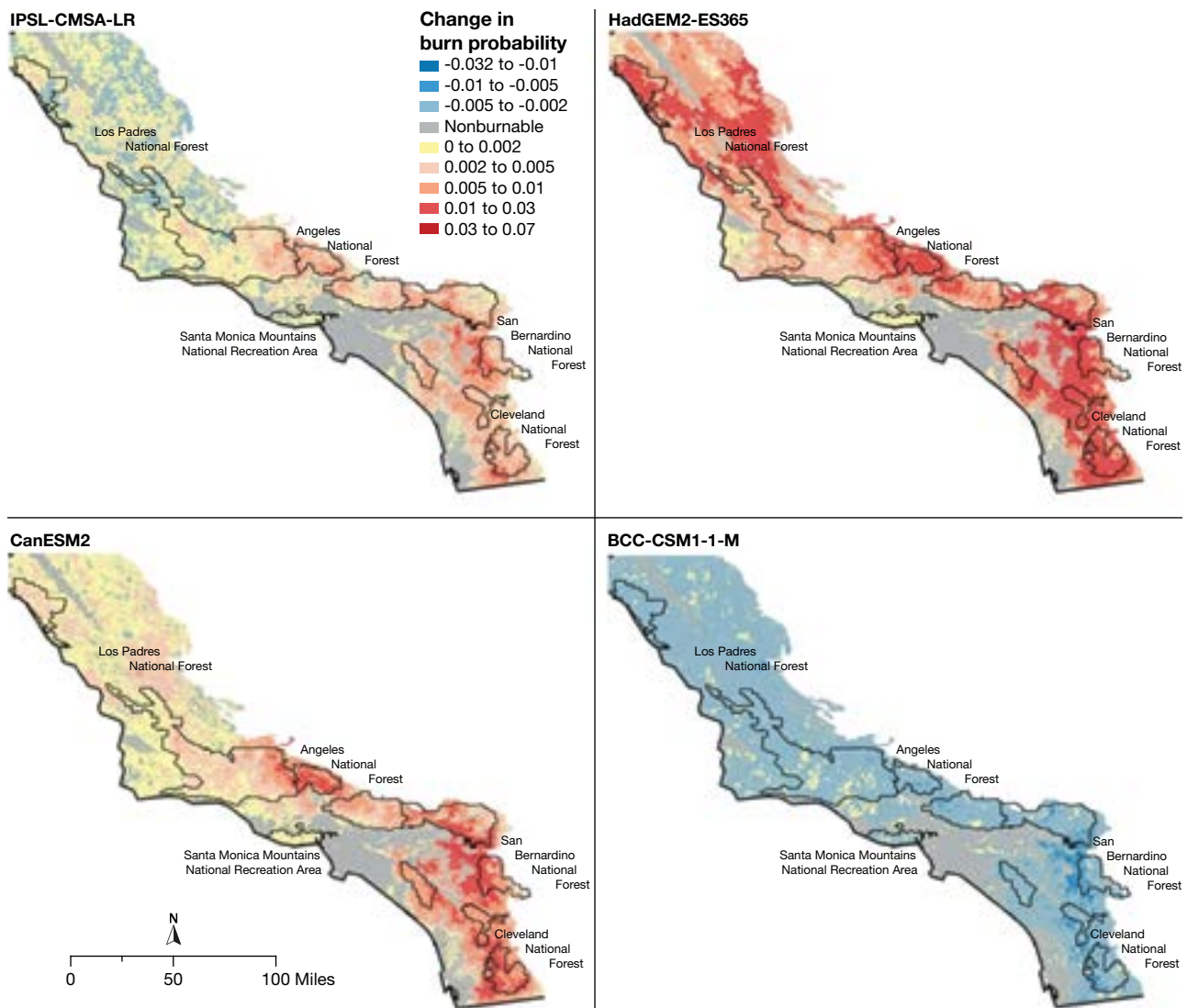


Figure 2.6—Projected change in annual burn probability from baseline period (1979–2005) to mid-21st century (2040–2069) for four representative example simulations. IPSL-CM5A-LR (hotter, drier, and less humid) and CanESM2 (hotter, wetter, and more humid) show moderate increases to burn probability. HadGEM2-ES365 (much hotter, drier, and less humid) represents an extreme case in which burn probability increases across the entire region; BCC-CSM1-1-M (moderately warmer, wetter, and more humid) projects a decline in burn probability across the region.

Fog

Fog, or low-lying clouds, common along the coast, helps alleviate ecological stress during the dry season by regulating land-surface temperatures (Iacobellis and Cayan 2013), provides shade and additional moisture for vegetation (Fischer et al. 2009, Johnstone and Dawson 2010), improves agricultural water-use efficiency (Baguskas et al. 2018), reduces wildfire potential by slowing fuel moisture loss (Williams et al. 2018), and maintains cooler stream temperatures (Sawaske and Freyberg 2015). Because the atmospheric processes responsible for fog formation have proven difficult to incorporate in GCMs, there is little consensus on the future trajectory of coastal fog for southern California (Cesana and Chepfer 2012,

Koračin et al. 2014). Historical airport observations in northern California suggest that fog has been declining since the 20th century (Johnstone and Dawson 2010), but projections of a continuing trend are not available.

With climate change projected to bring increasingly warmer temperatures to southern California, the ecological importance of summertime fog will increase, and fog could potentially help mitigate some of the negative effects of warming by slowing down moisture loss and maintaining lower surface temperatures. However, if fog becomes less frequent in the future, it could instead contribute to a positive feedback cycle that enhances the detrimental effects of warming, such as drought, heat waves, and wildfire. Taken together, these wide-ranging effects suggest

that a more comprehensive understanding of the underlying drivers and environmental effects of coastal fog occurrence are needed for the Western United States, including southern California (Torregrosa et al. 2014).

Sea-Level Rise

Climate change-induced sea-level rise is primarily caused by melting ice sheets and thermal expansion of ocean water. In southern California, sea-level rise at rates of 0.04–0.08 inches per year have been observed over the past century, although local tide-gauge measurements are sensitive to tectonics, which can affect local vertical land movement and sea-level measurements (Griggs et al. 2017). By mid-century (2050), sea-level rise projections from California’s Fourth Climate Change Assessment indicate that relative to current levels, 5th and 95th percentile sea-level rise in Los Angeles will range from 1.1 to 11.1 inches (RCP 4.5) and from 2.3 to 13.3 inches (RCP 8.5) (Hall et al. 2018). However, by 2100, projected changes are much more pronounced, with 5th and 95th percentile estimates of sea-level rise in Los Angeles ranging from 10.2 to 51.7 inches (RCP 4.5) and from 24.8 to 90.9 inches (RCP 8.5) (Hall et al. 2018). These estimates were similar to those for La Jolla and Santa Barbara (Pierce et al. 2018).

Consequences of sea-level rise include inundation and the potential conversion of marshes to mudflats (Langridge 2018). Pacific coastal areas are projected to be particularly vulnerable to this conversion because of low levels of sediment accretion and high levels of coastal development, resulting in a lack of suitable upland area for marsh migration (Thorne et al. 2018). These consequences

are pronounced in southern California where projections suggest substantial conversion to mudflats and subtidal zones under both moderate and high sea-level rise scenarios by 2110 (Thorne et al. 2018). In the southern part of the assessment area, wave and storm events may cause erosion on sandy beaches (Hall et al. 2018).

Vegetation

The assessment area has high levels of biodiversity (Hall et al. 2018) due in part to a mild climate, a high degree of spatial heterogeneity, and varied microclimates (Kalansky et al. 2018, Langridge 2018). The following vegetation alliance classifications are based on the Forest Service, Pacific Southwest Region’s Classification and Assessment with Landsat of Visible Ecological Groupings (CALVEG) system and the associated *South Coast and Montane Ecological Province: CALVEG Zone 7* vegetation description guide (USDA FS 2009).

The region is composed of mostly chaparral shrubland with some woodland, forest, and grasslands (fig. 2.7). “Lower montane mixed chaparral alliance” is the most common vegetation type in the assessment area. It can be found from sea level up to 8,000 feet in elevation and is predominately located in the western portions of the assessment area (fig. 2.7). It is characterized by many nondominant shrubby species (e.g., *Ceanothus* spp., *Quercus* spp., *Arctostaphylos* spp.), with shrub-like live oaks—e.g., interior live oak (*Q. wislizeni* A. DC.), canyon live oak (*Q. chrysolepis* Liebm.)—found at slightly higher elevations (USDA FS 2009). Chamise (*Adenostoma fasciculatum* Hook. & Arn.) is also common but not dominant

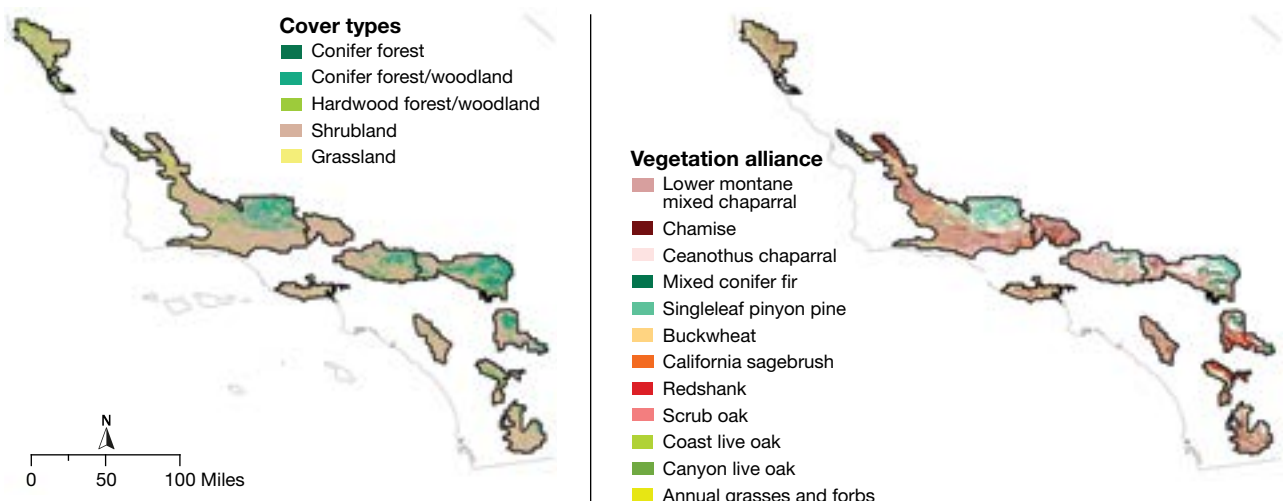


Figure 2.7—Cover and vegetation in the Southern California Adaptation Partnership assessment area is dominated by shrubland ecosystems with some conifer forests/woodlands at higher elevations inland (left). Shrubland vegetation consists of the lower montane mixed chaparral alliance with other shrubland areas dominated by chamise and ceanothus chaparral species (right). Singleleaf pinyon pine is dominant inland and at higher elevations (right). Source: CALVEG (USDA FS 2009).

in this vegetation alliance (USDA FS 2009). On sunnier and drier slopes, relative to the adjacent lower montane mixed chaparral alliance, chamise becomes the dominant chaparral species and characterizes the “chamise alliance” (Keeley and Davis 2007, USDA FS 2009).

Oak woodlands are typically found in more coastal areas (fig. 2.7). Common oak woodland types include those dominated by canyon live oak and coast live oak (*Q. agrifolia* Née). Canyon live oak is common at elevations up to 4,400 feet in coastal areas and up to 8,500 feet inland, growing in a shrub-like form in rocky and steep areas. Coast live oak is considered highly fire resistant and grows from sea level to 5,000 feet. Inland and at higher elevations (3,000–9,000 feet), particularly in the Mt. Pinos Ranger District of Los Padres National Forest and the easternmost portion of the Mountaintop Ranger District of San Bernardino National Forest, singleleaf pinyon (*Pinus monophylla* Torr. & Frém.)-dominated conifer woodlands with shrubby understories are present (Minnich 2007, USDA FS 2009) (fig. 2.7). Mixed-conifer-fir forests dominated by white fir (*Abies concolor* (Gord. & Glend.) Lindl. ex Hildebr.), Jeffrey pine (*P. jeffreyi* Balf.), Sierra lodgepole pine (*P. contorta* var *murrayana* (Balf.) Engelm.), sugar pine (*P. lambertiana* Douglas), Coulter pine (*P. coulteri* D. Don), and incense cedar (*Calocedrus decurrens* (Torr.) Florin) become prominent at 5,400–9,400 feet. At the highest elevations (above 8,000 feet) in the San Bernardino Mountains, limber pine (*P. flexilis* James) is also present (USDA FS 2009).

Grasslands are widespread in the assessment area at elevations up to 7,800 feet and include both native and nonnative grass and forb species. Other notable vegetation includes the redshank alliance in which redshank (*Adenostoma sparsifolium* Torr.) is dominant, for example in Cleveland National Forest on the eastern side of the Palomar Mountains (fig. 2.7). The ceanothus chaparral (*Ceanothus* spp.) and the California sagebrush (*Artemisia californica* Less.) alliances also commonly can be found at low elevations (USDA FS 2009) (fig. 2.7). California buckwheat (*Eriogonum fasciculatum* Benth.) can be found as part of the California sagebrush alliance or may be a dominant species in the California buckwheat alliance, typically found in former chamise and mixed chaparral sites after disturbance (USDA FS 2009).

Climate change is expected to alter species distribution and abundance and in some cases ecosystem function. Although temperature changes along the coast are projected to be less than inland, species near the coast tend to be less acclimated to temperature extremes than

those farther inland (Kalansky et al. 2018), indicating that coastal systems may be sensitive to even small temperature changes. Indeed, some species ranges have already shifted upslope to track suitable climate ranges (Kelly and Goulden 2008). In addition, recent drought and wildfire patterns have caused vegetation-type conversions in some locations (Deweese et al. 2022, Syphard et al. 2022) and could be exacerbated under climate change.

Vegetation type conversion in southern California is typically characterized by a biome shift from forest to woodland/shrubland and from woodland/shrubland to grassland. Wildfire plays a major role in altering ecosystem dynamics, and some evergreen forests are projected to shift to shrublands under warm, regardless of fire, and under cooler scenarios if fire is present. One example of such a shift is the Jeffrey pine forest on Laguna Mountain in Cleveland National Forest, which converted to shrubland and grassland with some oak following drought, fire, and insect outbreaks—Jeffrey pine beetle (*Dendroctonus jeffreyi* Hopkins) and goldspotted oak borer (*Agrilus auroguttatus* Schaeffer) (Guiterman et al. 2022). Pine conversion to oak is also expected under future climate conditions that project increased drought stress (McIntyre et al. 2015).

In ecosystems that are already characterized by woodland and shrubland vegetation, fire and drought stress can lead to conversion to grassland (Lenihan et al. 2008, Syphard et al. 2022). However, hot/dry climate scenarios may lead to grassland conversion regardless of whether fire is present (Lenihan et al. 2008). This conversion is a prominent phenomenon in inland ecosystems across the assessment area (Syphard et al. 2018). Substantial conversion of chaparral shrubland to grasslands along the southern California coast has also been observed and is apparent in arid areas where chaparral may already be water stressed (Syphard et al. 2019).

EcoAdapt conducted a series of assessments (Hilberg et al. 2017; Reynier et al. 2017a, 2017b, 2017c, 2017d) to determine vegetation community vulnerability to climate change in southern California. These assessments concluded that the highest risk ecosystems were alluvial scrub because of their high sensitivity to changes in flood and scouring regimes, and pinyon-juniper, because of high drought sensitivity in pinyon pines (Hilberg et al. 2017, Reynier et al. 2017a). Because they are generally well adapted to drought and fire, chaparral and oak-woodland habitats were determined to have the lowest (low-moderate) vulnerability (Reynier et al. 2017b, 2017d), although as discussed previously, these

ecosystems are still at risk of conversion to grassland. This is because climate change will likely interact with changing fire regimes, increasing the risk of chaparral ecosystem conversion to grassland.

The southern California region contains several endemic ecosystems, including serpentine grasslands, and carbonate, gabbro, and pebble plains, which were determined to have moderate vulnerability to climate change (Reynier et al. 2017c). Vulnerability is due in part to small population numbers for endemic plants and low connectivity, if any, between habitat patches (Reynier et al. 2017c). Many of these ecosystems have low-nutrient soil with narrowly adapted endemic plant life (Reynier et al. 2017c). Serpentine grasslands can be found in Los Padres National Forest, carbonate and pebble plains in San Bernardino National Forest, and the largest area of gabbro in Cleveland National Forest (Reynier et al. 2017c). For the remainder of the ecosystems evaluated as part of this series of assessments, continued ecosystem health and function were determined to be moderately vulnerable to negative effects from climate change.

In addition to reviewing climate change risk to ecosystems in southern California, we completed a modeling assessment within each of the national forests in the assessment area. Vegetation types (plant functional types) were simulated by the MC2 dynamic global vegetation model and compared between a reference historical period (1970–1999) and the end of the century (2070–2099) under RCP 8.5. The MC2 simulations were driven with 29 GCMs available in the NEX-DCP30 downscaled climate projection dataset (Thrasher et al. 2013). According to the MC2 simulations, about half of each national forest is within the highest risk category for vegetation shifts (table 2.8, fig. 2.8).

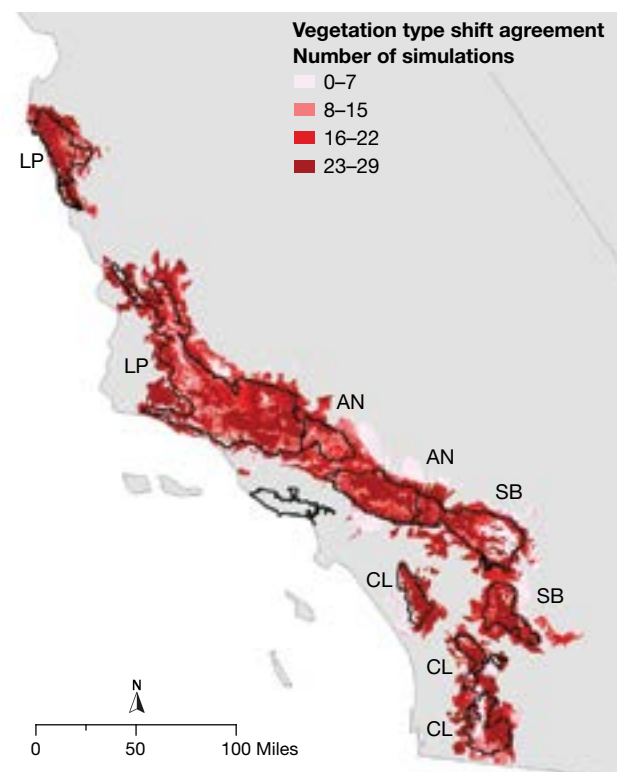


Figure 2.8—Projected vegetation type shift agreement across 29 global climate model (GCM)-driven MC2 simulations for the Southern California Adaptation Partnership assessment area. Vegetation types (plant functional types) simulated by MC2 dynamic global vegetation model were compared between a reference historical period (1970–1999) and end of century (2070–2099) under Representative Concentration Pathway 8.5 climate change scenario. One simulation for each of 29 GCMs was available. Map represents the number of simulations where a change in the vegetation type was simulated with “high-risk” defined as model agreement (23 to 29 models). Outlines show Los Padres (LP), Angeles (AN), San Bernardino (SB), and Cleveland (CL) National Forests. Results for Santa Monica Mountains National Recreation Area were not available from MC2 simulations.

Table 2.8—Projected high-risk areas for vegetation shifts in national forests within the Southern California Adaptation Partnership assessment area by end of century (2070–2099)

Forest name	Area in highest risk category	Biome type in highest risk category			
		Forest	Woodland	Shrubland	Desert
		PERCENT			
Angeles National Forest	45.9	51.0	29.0	19.9	0.1
Cleveland National Forest	56.3	29.7	27.6	42.6	0.0
Los Padres National Forest	46.8	15.1	30.8	53.9	0.2
San Bernardino National Forest	51.0	59.6	29.7	10.6	0.0

Projections are based on high model agreement (23 to 29 of 29 models) under the Representative Concentration Pathway 8.5 scenario (emissions continue to rise). Results for Santa Monica Mountains National Recreation Area are not available from MC2 dynamic global vegetation model simulations.

In San Bernardino National Forest, most of the high-risk area is forested and about a third of the high-risk area is woodland (table 2.8). In Angeles National Forest, vegetation types at high risk are similar to San Bernardino National Forest. However, high-risk vegetation types in Los Padres and Cleveland National Forests comprise mainly shrub-steppe ecosystems (chaparral dominant), with nearly a third of high-risk area in woodland. Cleveland National Forest also has a significant portion of high-risk area in forest, which comprise mainly Jeffrey pine, white fir, and bigcone Douglas-fir (*Pseudotsuga macrocarpa* (Vasey) Mayr) (table 2.8).

Conclusions

Climate change effects are projected across the assessment area, with the highest temperature increases projected for inland regions. The region also faces uncertainty in future precipitation projections; however, some evidence suggests that extreme events related to precipitation (heavy rain events and droughts) are likely to increase even if annual means remain similar. Many climate scenarios also suggest that the region will face an increase in the probability of wildfire. These combined effects will influence hydrology, infrastructure, recreation, and ecosystem services in the region, and will likely require a climate-informed management approach to maintain desired conditions in the national forests and national recreation area.

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Chapter 3: Climate Change and Water Resources in Southern California National Forests

David N. Dralle and Charles H. Luce¹

Introduction

National forests and other public lands in southern California are biodiversity hotspots that provide water to adjacent urban populations and agricultural lands (Klausmeyer and Shaw 2009, Miles et al. 2006). Upland forests provide high-quality outdoor recreation opportunities for southern California residents (Baerenklau et al. 2010). These forests exist in mountainous islands in an otherwise arid region of the state. Given the importance of water in the assessment area, surprisingly little is known about the vulnerability of forest water supply

under climate change. To ensure safety and sustainability of water resources, it is essential to understand natural hazards, such as flooding and drought, and to project shifts in hydrology under altered temperature and precipitation.

Southern California forests experience a seasonally dry Mediterranean-type climate; most annual precipitation falls during a mild, wet winter, which is followed by a protracted dry season (Vico et al. 2015). Figure 3.1 shows mean annual precipitation across Angeles, Cleveland, Los Padres, and San Bernardino National Forests (Daly et al. 2008). Strong seasonality in rainfall means that water availability in forests and streams varies throughout the year, typically peaking between December and February, with minimum availability between September and November. Under this climatic regime, water storage and release by the landscape determines how stressed ecosystems may become during the dry months (Klos et al. 2018). In the upland mountainous landscapes in

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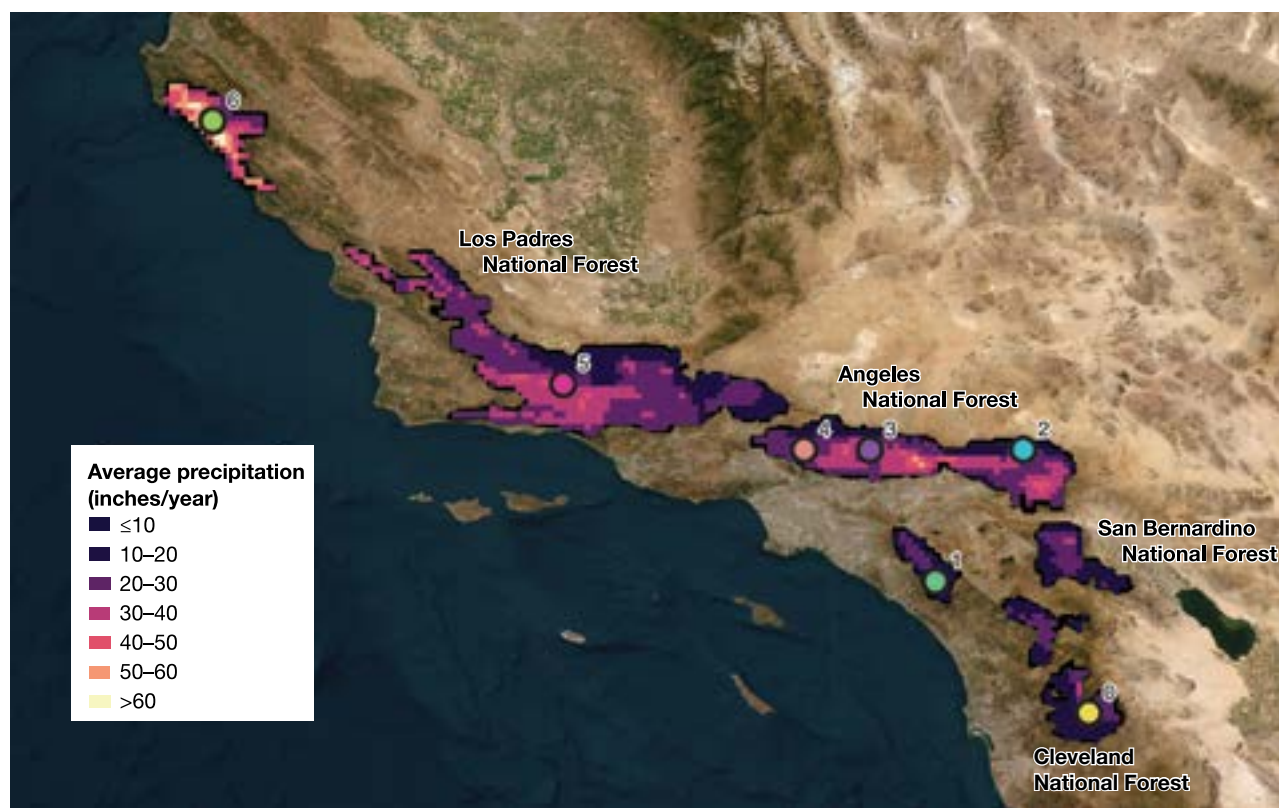


Figure 3.1—Mean annual precipitation across national forests in the Southern California Adaptation Partnership assessment area. Focus sites are highlighted with colored points and correspond to colors and numbers in subsequent figures.

the southern part of the assessment area, water storage and release processes are dictated by the hydrology of **hillslopes** (fig. 3.2), which can be thought of as the fundamental hydrological response units of watersheds. Hillslopes store wet-season precipitation as soil moisture, rock moisture, and groundwater, and then release that water to forests and streams during dry periods.

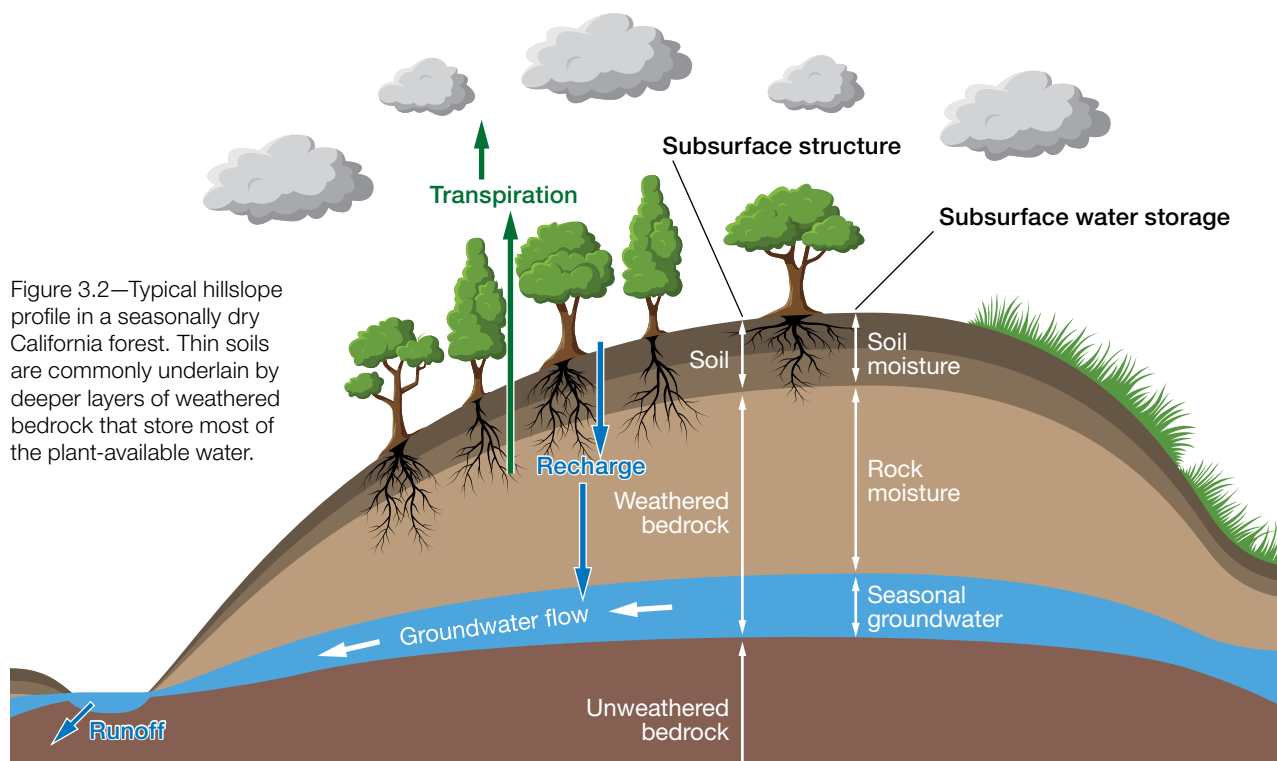
In this chapter, we use well-established modeling approaches to capture hydrological functions of hillslopes to inform how a changing climate might affect recreation opportunities in southern California. Because of limitations in model runs and data availability, the assessment area in this chapter is limited to the four southern California national forests (Angeles, Cleveland, Los Padres, and San Bernardino National Forests) and excludes the Santa Monica Mountains National Recreation Area. We begin with a brief examination of current normals and future trends in precipitation in the assessment area, then assess how expected shifts in precipitation affect the streamflow regime: annual total flows, runoff efficiency (the fraction of precipitation that becomes streamflow), peak flows and floods, and low flows (Yarnell et al. 2015). We highlight changes at exemplary locations—including areas of recreational interest, such as Big Bear Mountain Resort and Bear Mountain

Ski Resort (fig. 3.1: point 2)—to illustrate the range of hydrological responses. We discuss expected shifts across other facets of the hydrological cycle, such as snow-pack, subsurface water storage, and plant water stress. Significant changes are expected, but strong uncertainty in climate projections of precipitation **across** models warrants cautious interpretation and ongoing analysis as improved climate projections become available.

Streamflow Response Calculations

Variable Infiltration Capacity Model

Changes in streamflow were calculated from outputs of the Variable Infiltration Capacity (VIC) hydrologic model (Liang et al. 1994) stored at the Downscaled CMIP3 and CMIP5 Climate and Hydrology Projections archive (PCMDI and WCRP 2025). We used the Bias Correction and Spatial Disaggregation downscaling method (Wood et al. 2004) on CMIP5 data (USDI BOR TSC 2014) to produce data to force the VIC model. In this effort, climate data were downscaled to a 1/8-degree (~7.5 mile) cell size, and daily VIC runoff outputs were calculated for each cell. We used historical climate data (1977–2006) and end-of-century (2070–2099) data under Representative Concentration Pathway (RCP) 8.5.



The choice of a single, high-emission scenario (RCP 8.5) is not intended to suggest that this is a likely outcome, nor does it reflect that some literature suggests it is a likely outcome (Schwalm et al. 2020). Rather, it is a choice to reduce the complexity of information, so users do not need to make a choice of scenario to illustrate relative spatial changes. It seems apparent that RCP 8.5 is a scenario with some potential to occur, while at the same time representing a general maximum emission scenario frequently used by the research and adaptation communities. Other scenarios generally show a lesser effect and a somewhat different trajectory over the course of the century.

In California, intensification of precipitation through thermodynamics is expected, but there are competing circulation components leading to higher uncertainty and slight moistening in contrast to other mediterranean climates (Polade et al. 2017). Acknowledging uncertainty in the dynamic component, current understanding therefore supports thinking of RCP 8.5 as an end-member scenario from which a simple scaling of precipitation effects may be reasonable for land management applications. If a different scenario is expected, users can consider that the effect would generally be less than depicted in this set of maps, and that changes would scale roughly with the amount of added greenhouse-gas forcing compared to RCP 8.5.

Wenger et al. (2010) calculated flows in each stream segment in the National Hydrography Dataset Plus Version 2 (NHDPlusV2) (USDI USGS 2012) in the contiguous United States from the gridded VIC data. They distributed runoff from each VIC grid cell proportionally to the area of NHDPlusV2 catchments intersecting the VIC grid cell. They lagged runoff slightly by applying a unit hydrograph to simulate the distribution of lag times required for runoff to arrive from hillslope generation areas into the stream; these flows were then accumulated downstream (Wenger et al. 2010). Wenger et al. (2010) did not perform hydraulic routing in the channel network, as the response timescales in the channel network for the relatively small watersheds of interest (less than 770 square miles) are comparable to or faster than the daily temporal resolution of the input forcing data.

In work with simpler downscaling algorithms, we first averaged the hydrographs from VIC cells into ensemble cell hydrographs, which were then routed into the NHDPlusV2 stream network, and we calculated metrics

from the hydrographs in the network. In the Bias Correction and Spatial Disaggregation approach to downscaling, the input data were modeled stochastically, with resampled months scaled to projected monthly precipitation and temperatures, to represent appropriate spatial and temporal correlations for the projected climate. This means that individual flood events and severe drought events could fall on different days in different models of the future. Consequently, to calculate metrics of extremes, it was necessary to calculate flood and drought magnitudes for each model on each segment individually, then create ensembles of the metrics. This is more computationally demanding because it requires distributing the VIC grid hydrographs for each global climate model (GCM) through the NHDPlusV2 network before averaging across models. To keep the computations reasonable while still representing a balanced diversity of models in the ensemble, we reduced the number of GCMs to 5 from the 29 available in the BCSD CMIP5 dataset following the selections used by the U.S. Department of Agriculture, Forest Service's 2020 Resources Planning Act Assessment (Joyce and Coulson 2020):

- Least warm: MRI-CGCM3 (Meteorological Research Institute)
- Hot: HadGEM2-ES (Met Office Hadley Centre/ Instituto Nacional de Pesquisas Espaciais)
- Dry: IPSL-CM5A-MR (Institut Pierre-Simon Laplace)
- Wet: CNRM-CM5 (Centre National de Recherches Meteorologiques/Centre Européen de Recherche et Formation Avancée en Calcul Scientifique)
- Middle: NorESM1-M (Norwegian Climate Centre)

The calculations resulted in two, 3-decade time series of daily streamflow for each stream segment: one for the historical period and one for the end of the century. For each stream segment and period, we calculated 26 streamflow metrics describing magnitude and timing of flows and flow extremes and their changes. We then averaged the results of the five GCMs above to produce an ensemble projection. In this analysis, we show maps of only three of the flow metrics: mean annual flow; mean flow during June, July, and August; and magnitude of the 1.5-year flood. Additional flow metrics can be viewed and mapped at the ArcGIS story map

associated with this climate assessment (USDA FS OSC 2024; <https://storymaps.arcgis.com/stories/6a6be7d624db41638a24b659305af522>). We also retained the metrics from the five individual GCMs for in-depth analyses of uncertainty in projections.

Budyko Water Balance Model

To complement the process-based VIC modeling framework, this chapter includes an analysis of streamflow **sensitivity** to precipitation changes using an empirical approach based on the Budyko principle. In 1948, Mikhail Budyko proposed that the long-term water balance of a natural watershed can be predicted based on the two fundamental inputs: energy (often represented using potential evapotranspiration) and precipitation (Budyko 1948). Since then, several extensions that affect water balance have been added to the framework, including lateral groundwater flows, snow fraction (fraction of precipitation that arrives as snow), and seasonality (Gan et al. 2021).

Researchers have used the Budyko framework to calculate the **sensitivity of annual flows to changes in annual precipitation** (Yang and Yang 2011). This sensitivity analysis provides an important complement to the VIC model projections, which are vulnerable to climate forcing and data uncertainty. This uncertainty is particularly high in California, as described in the next section and in chapter 2. Using the Budyko sensitivity results, one might explore expected changes in streamflow for any climate model projection. Because these results are climate-model neutral, the approach provides an analysis tool with ongoing utility. New or better precipitation projections can be added to the sensitivity framework to produce new flow projections.

The Budyko sensitivity was calculated using the **elasticity** of discharge to precipitation. Elasticity is a concept from economics that can be interpreted as the expected percentage of change in a dependent variable (in our context, mean annual discharge) for a given percentage of change in an independent variable, in this case precipitation (Cooper et al. 2018, Zhang et al. 2018). If there is an X -percent change in mean annual precipitation, and the elasticity is η_p , then the corresponding percentage of change in mean annual discharge is the product, $\eta_p \times X\%$. To calculate the Budyko sensitivity, we used the Google Earth Engine platform and gridded datasets of

precipitation and evapotranspiration from October 1, 2000 through September 30, 2021 to evaluate the water balance across southern California. For evapotranspiration, we used the Penman-Monteith-Leuning evapotranspiration data product (Zhang et al. 2019), and for precipitation (P) we used the PRISM Climate Group data gridded precipitation product (Daly et al. 2008, 2015).

Precipitation

Historical mean annual precipitation ranges from 28 inches in Los Padres National Forest to 0.1–16 inches in parts of Cleveland and San Bernardino National Forests (fig. 3.1). These are spatial averages; parts of coast-adjacent Los Padres National Forest receive more than 59 inches of annual rainfall. However, averages do not paint a complete picture of precipitation regimes in southern California, which have high variability influenced by the El Niño-Southern Oscillation and the Pacific Decadal Oscillation. Long dry periods are typical, and most precipitation falls during relatively few events (Albano et al. 2020). Variability and extremes are projected to increase significantly across California under most climate change scenarios (Dominguez et al. 2012, Swain et al. 2018).

Here, we provide a summary of expected changes in precipitation across southern California, with emphasis on precipitation changes that affect hydrology. We highlight expected changes at seven focus areas chosen as case-study locations (points in fig. 3.1). See chapter 2 for comprehensive expectations of changes in climate across the assessment area.

Sites for case studies were chosen to represent the range of variability observed across the assessment area, and in some cases, sites coincide with important recreation areas. As described above, we report on outputs from the five GCMs under RCP 8.5 used to force the VIC hydrological model (CNRM-CM5, HadGEM2-ES, IPSL-CM5A-MR, MRI-CGCM3, NorESM1-M). Under the same RCP, the ensemble of 10 models from chapter 2 projects a small **decrease** in mean annual precipitation across southern California, whereas the five models here project an **increase** in mean annual precipitation. This seeming discrepancy highlights the uncertainty associated with projections of mean annual precipitation across California. Nevertheless, projections at focus sites (fig. 3.3: a) agree with expectations of a slight increase in mean annual precipitation across most of southern

California (Persad et al. 2020). Expected increases are, on average, less than 25 percent, with significant variability across the five GCMs at each study location, with some GCMs projecting decreases.

Changes in extreme precipitation and precipitation seasonality are more certain, with greater agreement across climate models (Swain et al. 2018). Increased frequency of extremes and changes in seasonality are expected throughout the Western United States (Dominguez et al. 2012), with consequences for water supply in southern California (Pagán et al. 2016). The frequency of “extremely wet” conditions during wet seasons is projected to increase significantly, with a small but significant increase in the frequency of “extremely dry” conditions occurring during the dry seasons (Swain et al. 2018). In addition, the wet season is expected to “sharpen,” with more precipitation arriving during the peak wet-season months (December, January, February), a pattern that may already be occurring (Feng et al.

2019, Persad et al. 2020, Swain et al. 2018). Projections of wet-season sharpening are consistent with expected increases in the frequency and intensity of atmospheric river events (Huang et al. 2020), which deliver most annual precipitation to southern California (Dettinger et al. 2011) (chapter 2). If mean annual precipitation does not change significantly, the concentration of precipitation during the wet season implies less precipitation will fall during the late spring and late fall/early winter (Persad et al. 2020), with effects on forest dynamics (e.g., higher fire risk) (Swain 2021).

Air temperature will affect how water is delivered to southern California mountains. In particular, increasing temperatures are projected to decrease the fraction of precipitation that arrives as snowfall and how long it persists on the ground (Lute and Luce 2017, Siirila-Woodburn et al. 2021). In California, many studies have explored the effects of a warming climate on snowpack in the Sierra Nevada, but few have focused on the mountains

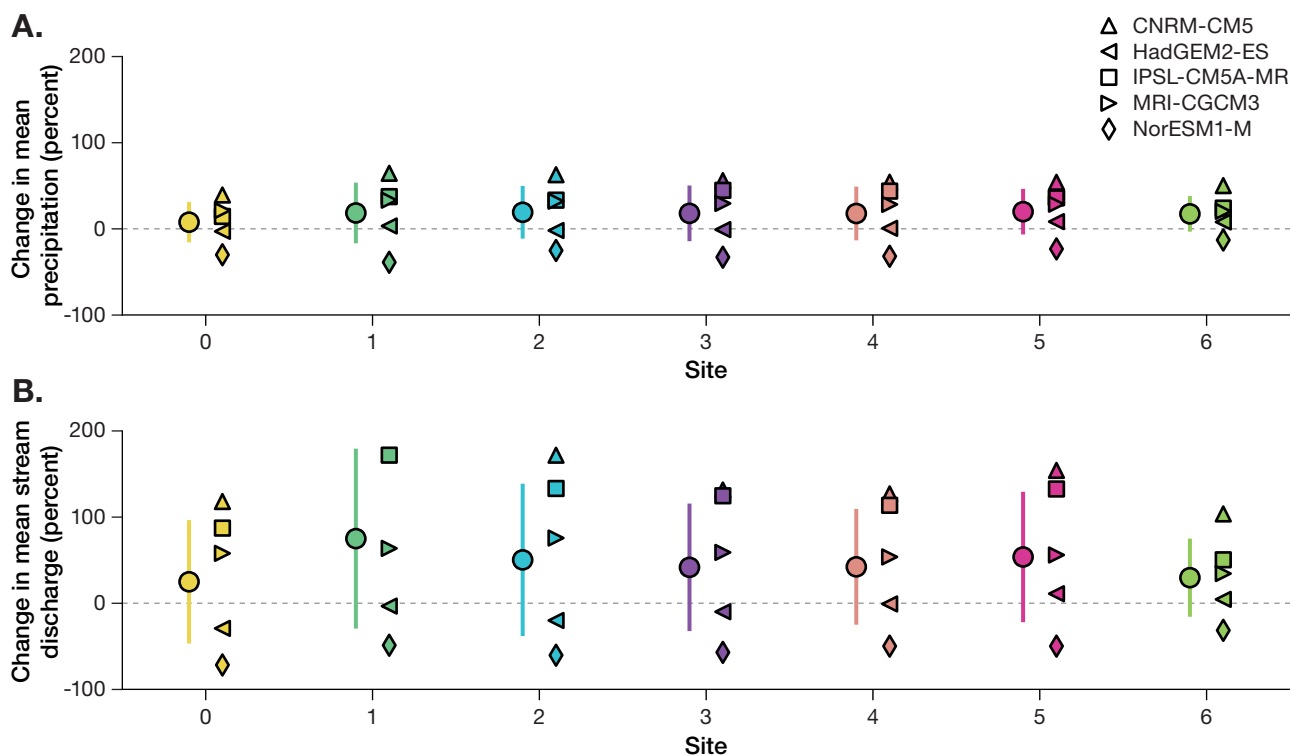
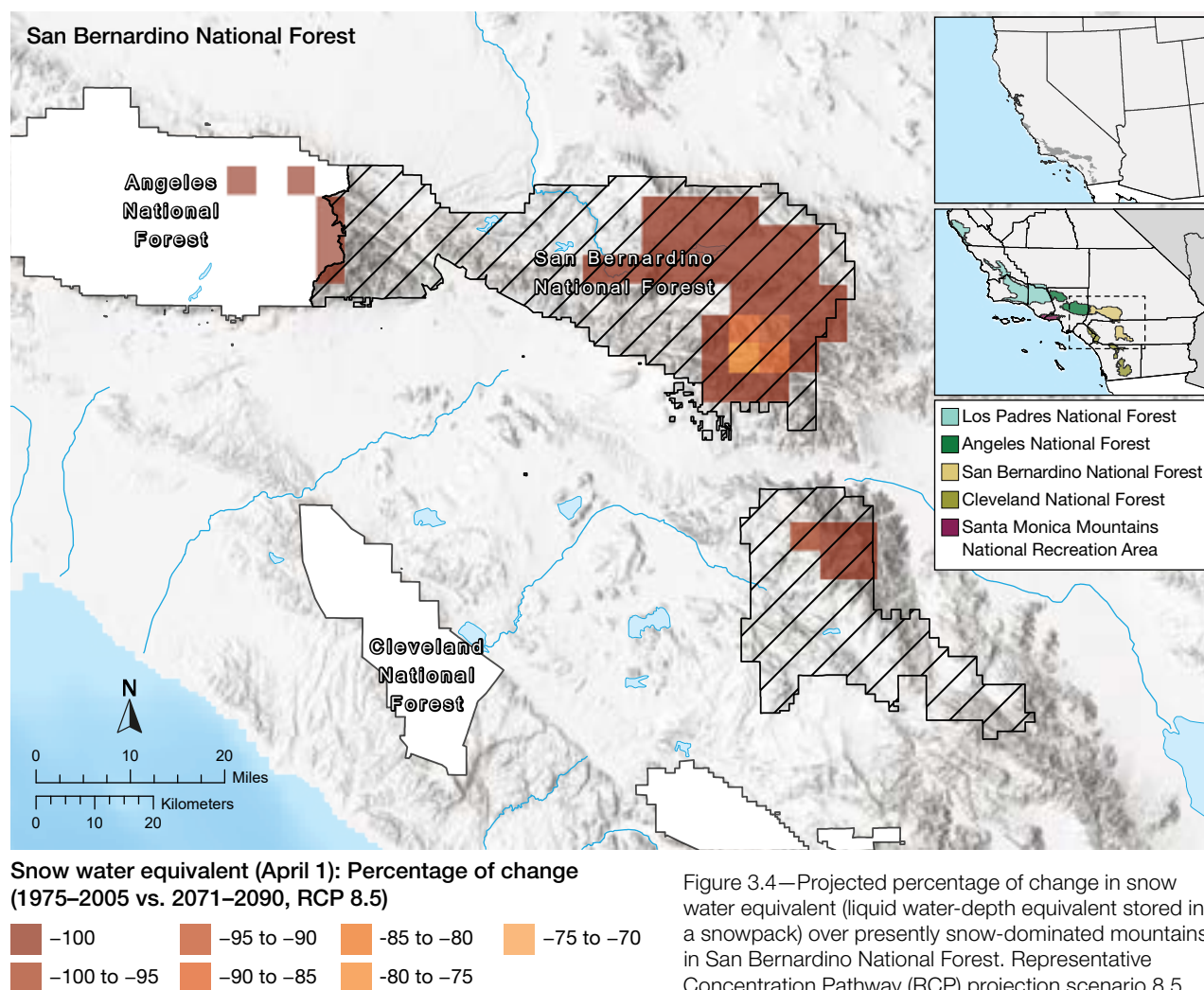


Figure 3.3—Projected percentage of change in mean (circle points) (A) annual precipitation and (B) annual stream discharge, averaged across the five global climate models (noncircle, geometric shapes) used to run the Variable Infiltration Capacity hydrological model for the Southern California Adaptation Partnership assessment area. Error bars represent one standard deviation around the ensemble model mean. Sites modeled (from south to north): 0 = Pine Valley, Descano District, Cleveland National Forest; 1 = southern Santa Ana Mountains, Trabuco Ranger District, Cleveland National Forest; 2 = Big Bear Mountain Resort and Bear Mountain Ski Resort, Mountaintop District, San Bernardino National Forest; 3 = San Gabriel River headwaters, San Gabriel Mountains National Monument District, Angeles National Forest; 4 = Big Tujunga Creek headwaters, Los Angeles Gateway District, Angeles National Forest; 5 = western Dick Smith Wilderness, Santa Barbara District, Los Padres National Forest; 6 = central Ventana Wilderness, Monterey District, Lost Padres National Forest.

of southern California. This is partly because it is difficult to resolve the complex topography of mountains with the coarse computational grids used in most GCMs. As a way around this, Sun et al. (2016) used a hybrid dynamical-statistical downscaling approach to generate snowfall and snowpack response under RCP 8.5 for the mountains of southern California. By around 2050, snowpack is expected to decrease to 70 percent of its mean historical value under RCP 8.5, versus only 80 percent under RCP 2.5. If RCP 2.5 could be achieved, snowpack in southern California would be expected to remain at 80 percent of baseline through the end of the century.

Mean winter temperature and precipitation can be used to calculate expectations for April 1 snow water equivalent and mean snow residence time, which is the average lifespan of a snowflake on the ground (typically around half of the snow season length) (Lute and Luce

2017, Luce et al. 2014). Over the Los Padres, Angeles, and Cleveland National Forests, April 1 snow water equivalent is expected to go to zero, and already short snow residence times will shorten or disappear (data not shown). In the highest elevations of San Bernardino National Forest (San Gorgonio Wilderness Area), fractional declines in April 1 snow water equivalent are expected to be substantial (fig. 3.4) but less extreme than in these other areas. The nearby Big Bear Lake area is expected to see large changes in April 1 snow water equivalent, with snow nearly disappearing. The snow residence time was historically around 1 month in the Big Bear Lake area and nearly 3 months in the San Gorgonio Mountain area (fig. 3.5) and is expected to transition to values of around several days in the Big Bear Lake area and around 1 month in the San Gorgonio Mountains (fig. 3.6).



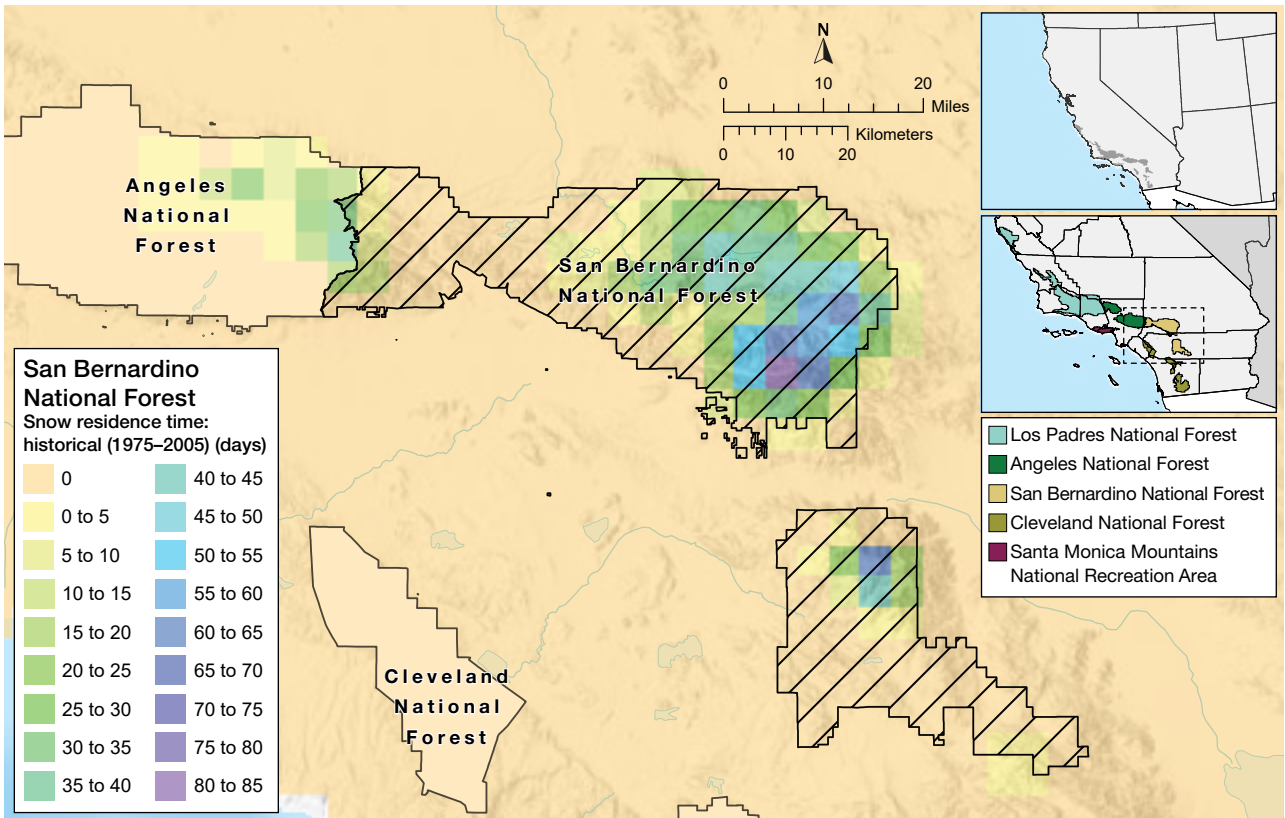


Figure 3.5—Historical snow residence time in San Bernardino National Forest.

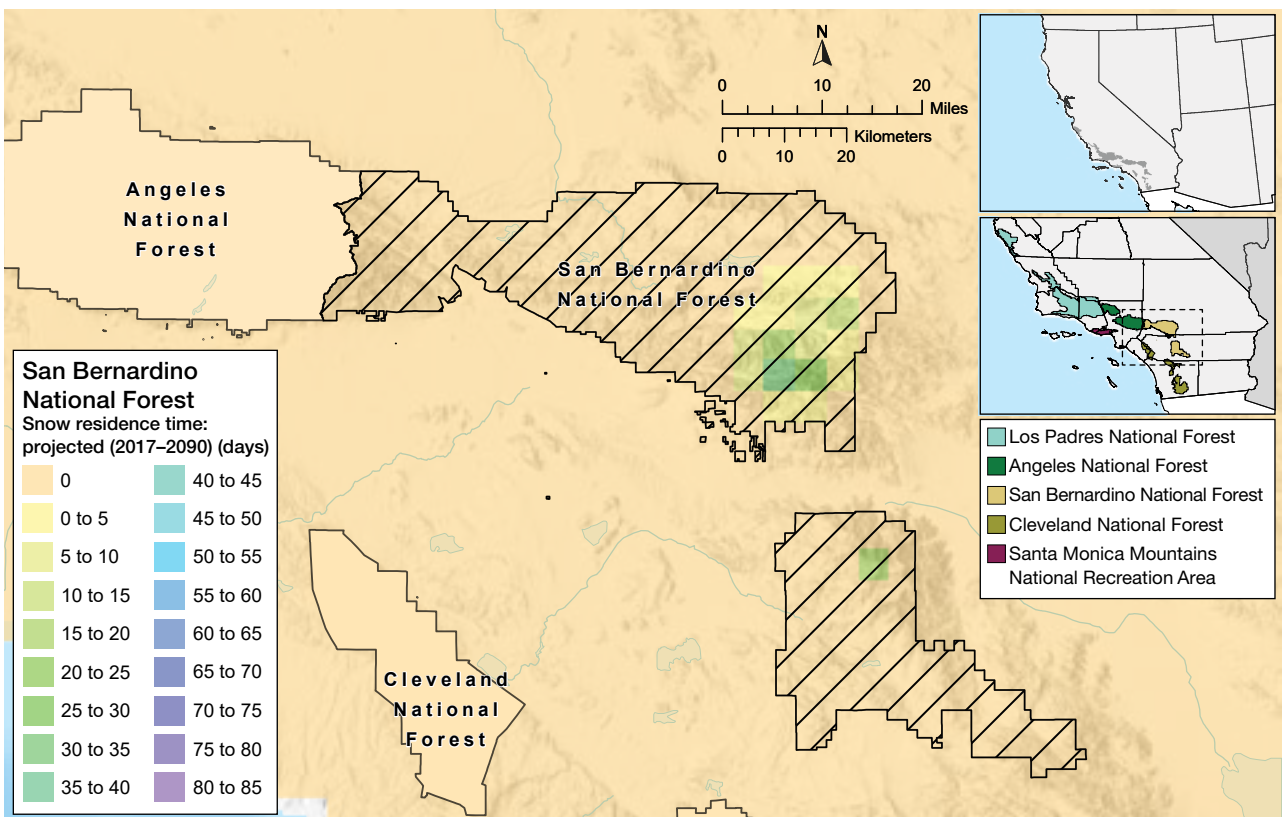


Figure 3.6—Projected snow residence time in San Bernardino National Forest. Representative Concentration Pathway (RCP) projection scenario 8.5 assumes emissions will continue to rise.

Annual Flows

Figure 3.7 uses Budyko elasticity to compute percentage of change in mean annual discharge for a 10-percent change in mean annual precipitation. Because of the linearity of the Budyko approach, the change can be interpreted as the expected response to either a 10-percent increase **or** decrease. In the latter case, the sign of the flow response will be opposite from that in the figure. The empirical Budyko analysis reveals that southern California streams are highly sensitive to potential shifts in precipitation. In fact, watersheds across most forests tend to **amplify** changes in precipitation; a 10-percent change in mean annual precipitation translates into an even larger percentage of change in mean annual discharge, in some cases exceeding 30 percent. The largest observed mean sensitivity was found in Angeles National Forest. In general, streams in southern California are more sensitive than the state as a whole (plotted for reference). Amplification of precipitation changes to streamflow is projected by other mechanistic modeling frameworks (Feng et al. 2019), including the VIC modeling framework presented here.

At the focus sites, VIC model output corroborates findings from the Budyko analysis; percentages of change in mean annual discharge are considerably larger than corresponding percentages of change in mean annual

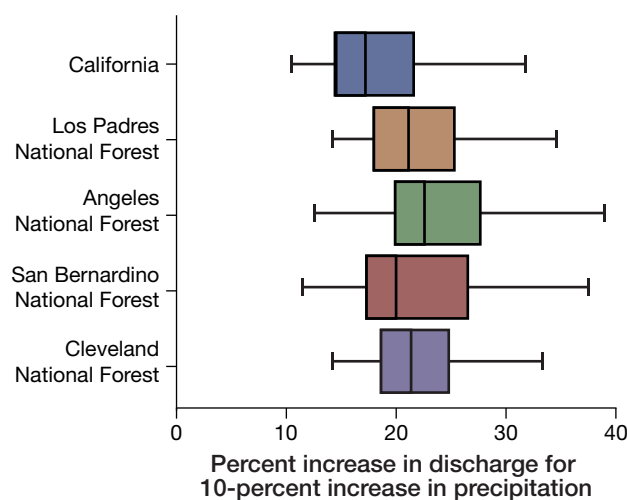


Figure 3.7—Budyko analysis plotting the sensitivity of mean annual discharge to changes in mean annual precipitation, quantified as the percentage of increase in mean annual discharge for a 10-percent increase in precipitation. In all cases across southern California national forests, and California as a whole, discharge increases are amplified relative to precipitation; that is, a 10-percent increase in precipitation results in >10-percent increase in discharge.

precipitation, in some cases by a factor of two or three under the GCM scenarios (fig. 3.3: b). However, not all GCMs project similar signs for trends in precipitation. In particular, the Norwegian Earth System Model (NorESM1-M) projects significantly less total annual precipitation. In both cases of increase and decrease, flow changes generally exceed percentages of change in the underlying precipitation variable. Such “amplification” is expected in southern California, where vegetation-driven water storage deficits in the subsurface exert a strong control over runoff generation (Müller et al. 2021), and runoff efficiency may shift as a result of changes in the sequencing of precipitation. Wet-season sharpening and the arrival of precipitation in less-frequent, larger events will tend to increase runoff efficiency (the amount of runoff obtained for a given amount of precipitation) because increased soil wetness and higher intensity water delivery activates faster flow paths (Modrick and Georgakakos 2015).

Across the assessment area, increases in mean daily flow differ considerably (figs. 3.8–3.10). In the southern part of Cleveland National Forest, flow increases are expected to be less than 20–40 percent (fig. 3.8). Moving northward along the coast, mean daily flow values are expected to increase more, exceeding 100 percent (a doubling of mean daily discharge) in the northernmost parts of Cleveland National Forest. Mean daily flow increases in San Bernardino and Angeles National Forests are comparable to those in Cleveland National Forest, with moderate to high increases in the high-elevation, western, and northern parts of the forests (fig. 3.9). Changes to mean daily flow in Los Padres National Forest are relatively small, with increases of only 20–40 percent in the northern part of the forest (fig. 3.10). However, given the relatively high flows in this region, a 20–40-percent increase in flow translates to a high discharge volume.

The empirical Budyko framework and the process-based VIC model indicate that streams in southern California are sensitive to projected shifts in rainfall patterns. Both frameworks suggest that a culmination of different watershed processes, such as plant water use in the root zone and increased runoff efficiency caused by intensified rainfall events, will amplify precipitation trends. As a result, streams will exhibit percentages of change in discharge that exceed the magnitude of percentages of change in rainfall.

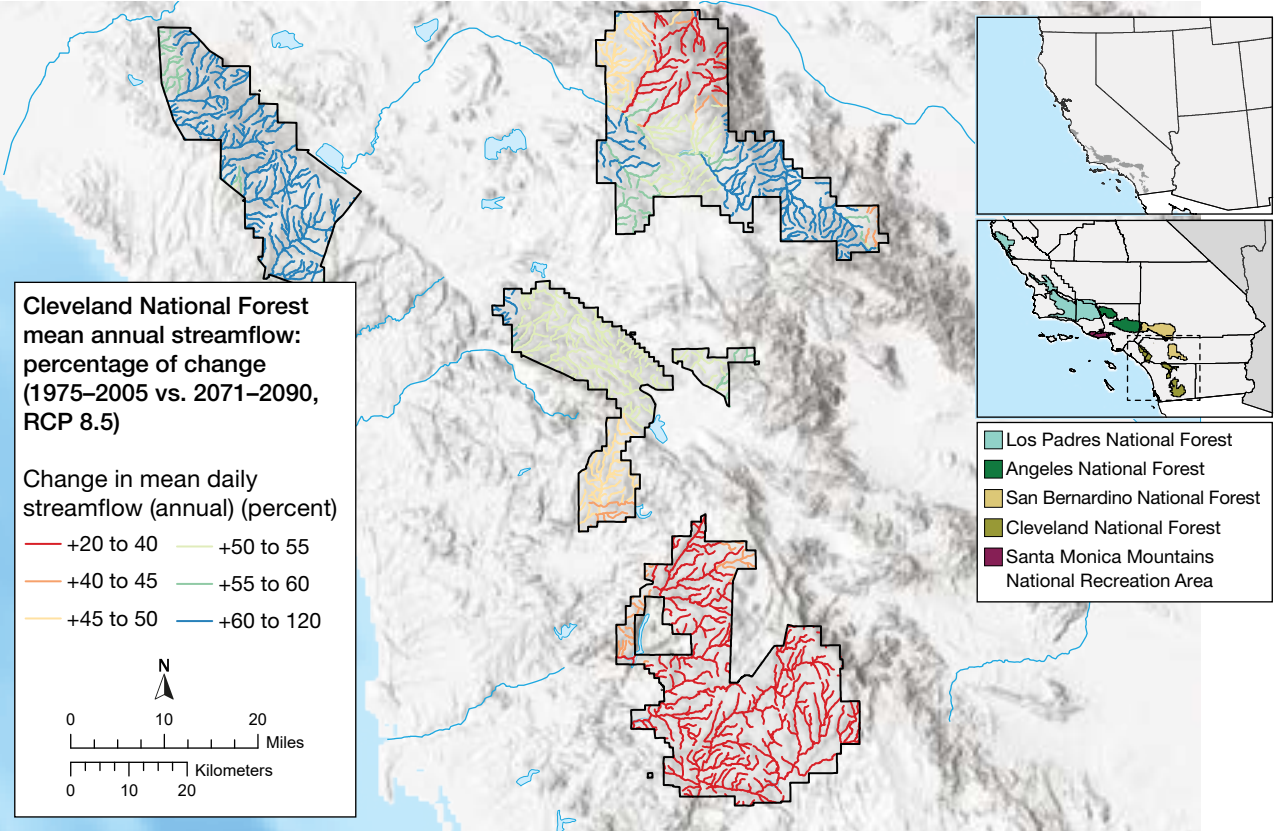


Figure 3.8—Projected percentage of change in mean daily streamflow (annualized) in Cleveland National Forest.

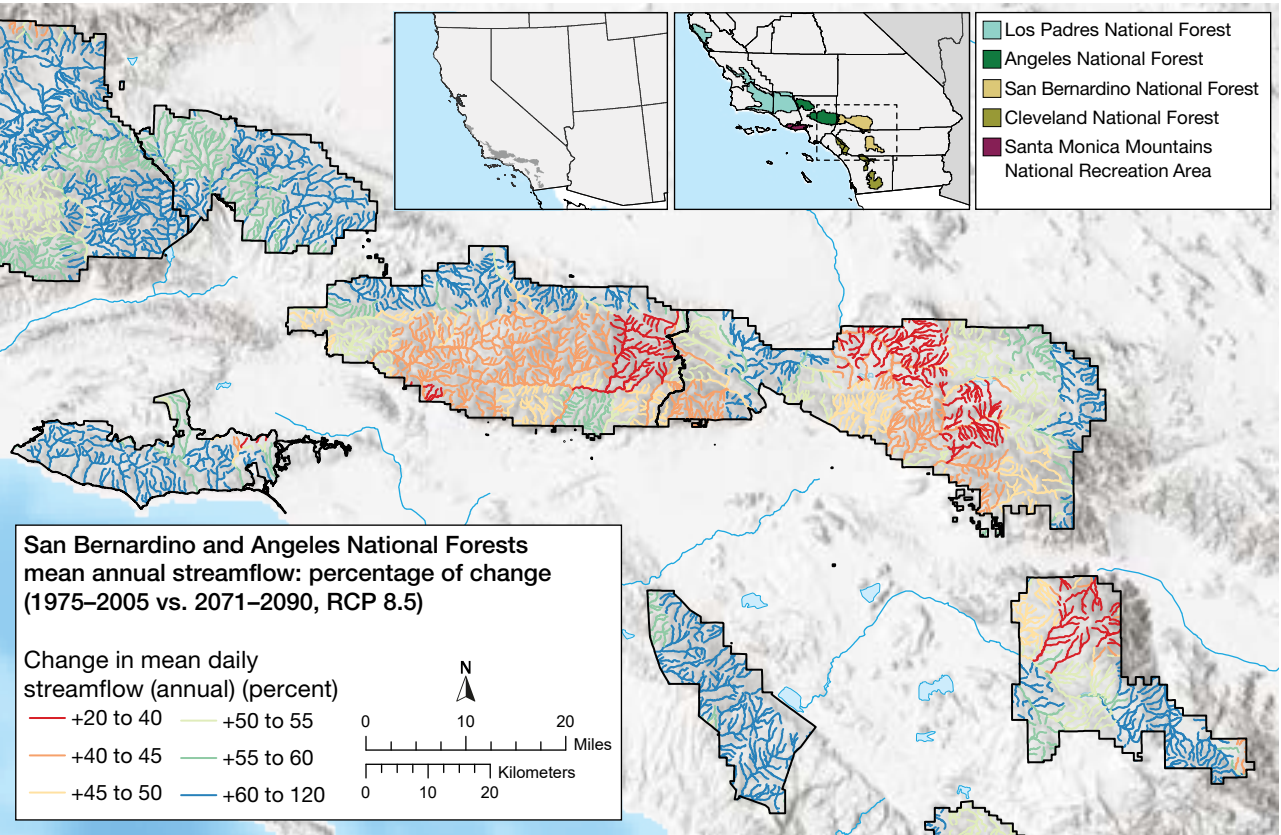


Figure 3.9—Projected percentage of change in mean daily streamflow in San Bernardino and Angeles National Forests.

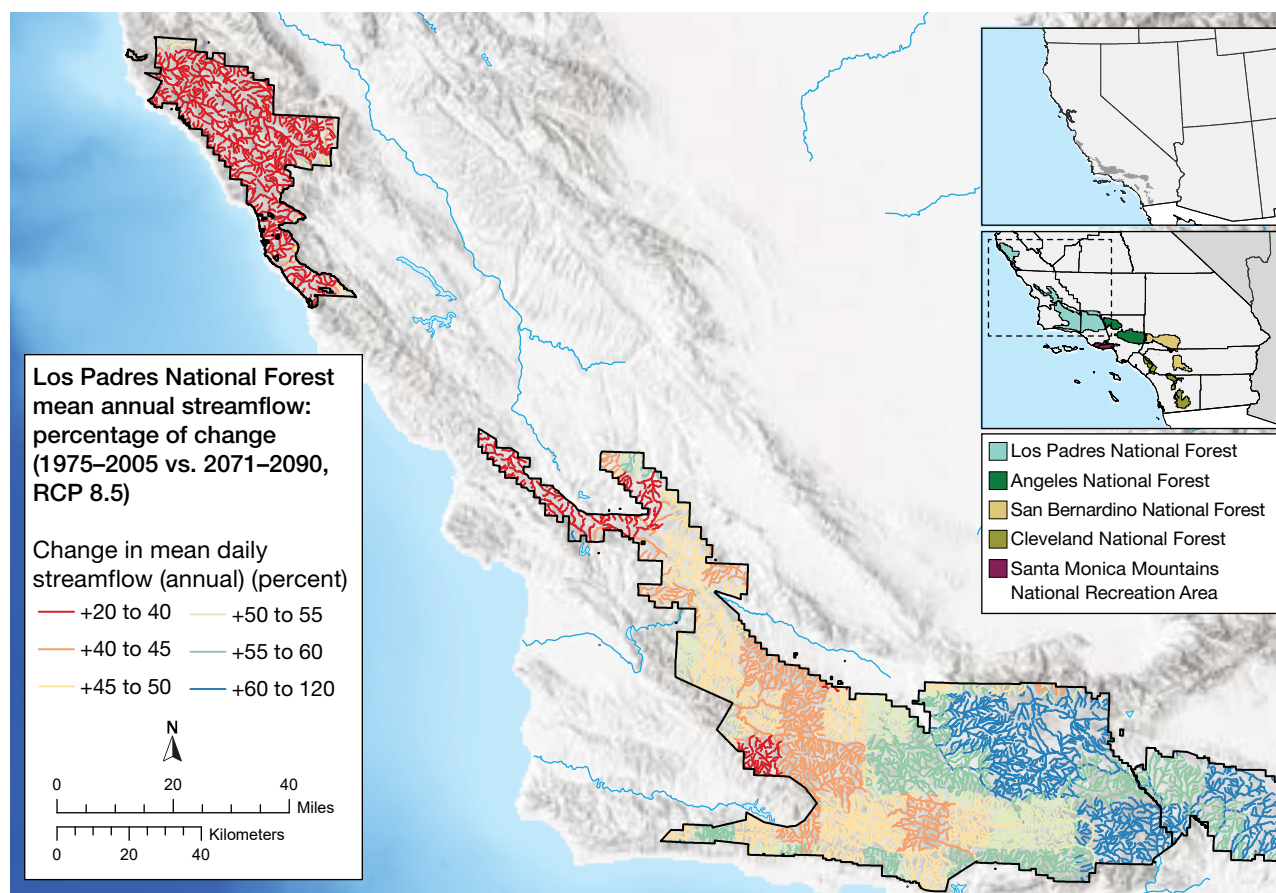


Figure 3.10—Projected percentage of change in mean daily streamflow in Los Padres National Forest.

Low Flows

Low flows are notoriously difficult to project in the small, arid watersheds in southern California (Salinas et al. 2013). Local and highly variable channel factors, such as alluvial sediment thickness, influence whether flow is present in the channel at a given point (Moidu et al. 2021), and low flows are sustained by deeper groundwater systems in fractured bedrock that are cryptic and difficult to observe (Lovill et al. 2018).

Comprehensive studies of expected climate-related changes to low flows in southern California forests have not been conducted, although empirical trends show that summer baseflows are decreasing (Ficklin et al. 2016), and several factors point toward continued decreasing trends in low-flow conditions. Snowpack, a primary driver of dry-season runoff in snowy watersheds, is projected to disappear 1 to 3 weeks earlier on average across southern California (Sun et al. 2016). Summer temperatures are expected to be higher, which may result in increased water demand from vegetation and potentially less water for flows. Low flows in some

southern California watersheds were found to be far more sensitive to summer evaporative demand (four to five times larger) than to winter precipitation, so modest increases in winter precipitation may not compensate for increasing evaporative demand (Cooper et al. 2018).

Wet-season sharpening may also affect summer low flows; a decrease in spring and fall rainfall may effectively increase the duration of the dry season (Swain 2021). Late wet-season conditions set the stage for the summer-flow recession period (Dralle et al. 2016), especially in rain-dominated watersheds in southern California. Less reliable precipitation during this period could produce less reliable flows during the summer dry season. Similarly, less reliable onset of wet-season precipitation may delay the return of flows that are sensitive to precipitation arrival in the fall and early winter (Sayama et al. 2011). Flow feedbacks with other landscape processes, especially wildfire (Swain 2021), may alter dry-season water yield in ways that are difficult to project (Kinoshita and Hogue 2015).

VIC model projections of low flow are mixed across southern California. In Los Padres, Angeles, and

northern San Bernardino National Forests, decreased mean summer flows (June, July, August) are expected; in southern San Bernardino National Forest and most of Cleveland National Forest, some increases in summer mean daily flows are expected (figs. 3.11–3.13). These projections are consistent with a related study that found the change in the 50-year return interval annual minimum runoff (the expected smallest flow year over a 50-year period) is expected to switch from a decrease to an increase in the 50-year return interval annual minimum runoff, progressing from the north of the SOCAAP assessment area southward (Pagán et al. 2016).

Peak Flows

Several factors suggest that climate change will increase the likelihood of flood risk in southern California. Historically, much of the assessment area receives more than half of its annual rainfall in fewer than 10 days out of the year (Dettinger et al. 2011). Large events of this sort are projected to increase in frequency and magnitude in southern California (Gao et al. 2017, Huang et al. 2020). Other factors may compound the hydrological consequences of increased event size, such as the ongoing shift from snow to rain in

high-elevation watersheds (Huang et al. 2020), although the dominant driver of larger flow events will likely be increased intensity and duration of individual rainfalls.

More intense clustering of rainfall during peak wet-season months will increase the likelihood that large rainfall events occur on already-wet soil, more efficiently producing runoff and increasing the risk of flash floods (Modrick and Georgakakos 2015) as well as total annual runoff (Pagán et al. 2016). Perhaps somewhat counterintuitively, increased peak flows do not necessarily translate into improvements in water supply. Unpredictable, large flows may require more frequent reservoir releases during the wet season (Pagán et al. 2016), and more intense delivery of water can lead to lower recharge to support base-flows in the subsequent dry season (Underwood et al. 2018).

VIC model output is consistent with other studies in the literature. Runoff efficiency increases by 10–50 percent across all study sites (fig. 3.14). However, similar to the annual flow results, the Norwegian Earth System Model (NorESM1-M) projects overall drying, and thus lower runoff efficiency. In both cases, altered runoff efficiency is likely caused by increases (decreases) in precipitation intensities and concentration (or decreasing amounts) of

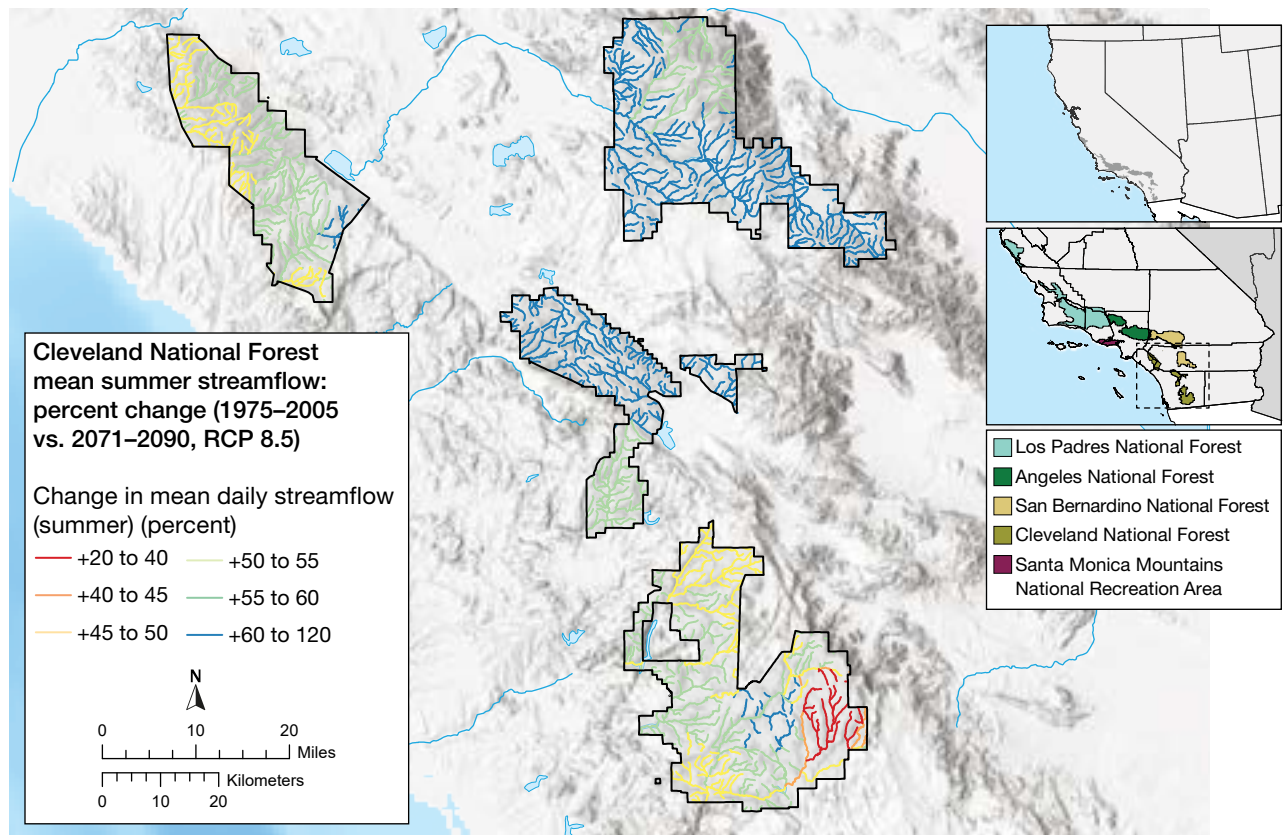


Figure 3.11—Projected percentage of change in mean summer streamflows (June, July, August) in Cleveland National Forest.

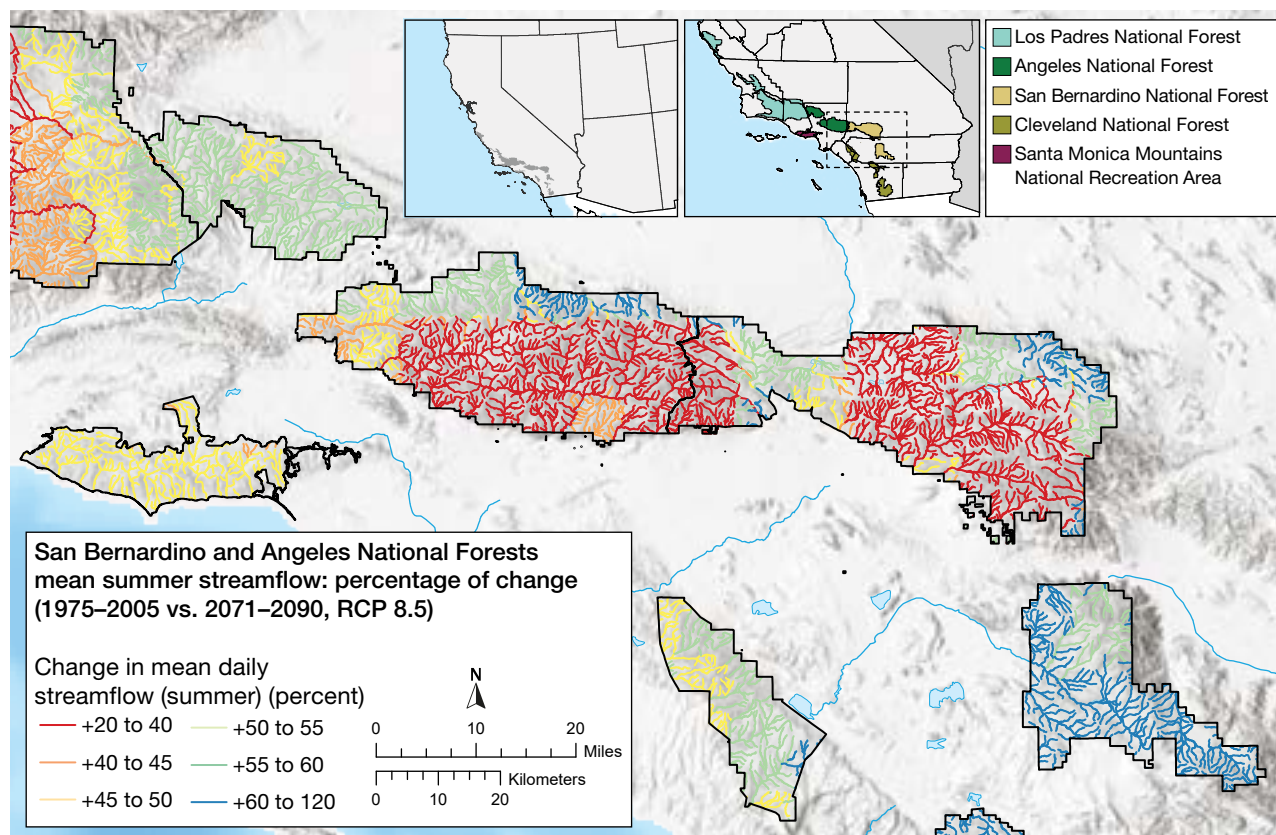


Figure 3.12—Projected percentage of change in mean summer streamflows (June, July, August) in San Bernardino and Angeles National Forests.

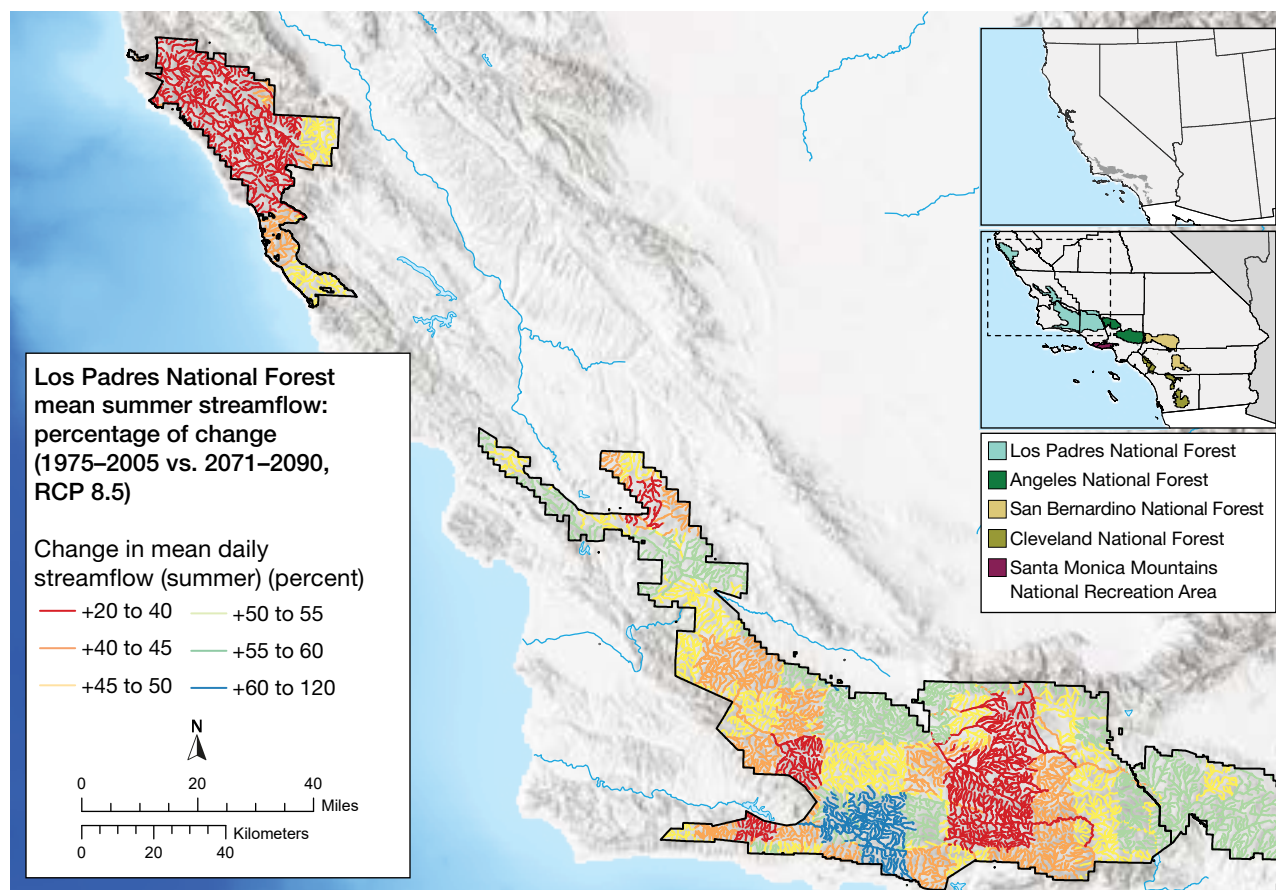


Figure 3.13—Projected percentage of change in mean summer streamflows (June, July, August) in Los Padres National Forest.

rainfall during peak wet-season months. Because runoff efficiency is defined as the amount of discharge obtained for an amount of precipitation (discharge divided by precipitation, also known as runoff ratio), increased efficiency explains how mean annual discharge can increase more (as a percentage) than mean annual precipitation (fig. 3.3). VIC output for runoff efficiency, which is linked to changes in flood likelihood, also agrees with existing literature (Das et al. 2013, Huang et al. 2020, Modrick and Georgakakos 2015). The magnitude of the 1.5-year-return-interval flood (fig. 3.15) increases greatly

(greater than 200 percent) in Angeles and northern San Bernardino National Forests. Changes are more modest but positive in Cleveland and Los Padres National Forests.

Subsurface Water Storage and Forest Water Stress

Droughts are increasing in frequency and severity, but patterns of forest mortality and streamflow reduction are not entirely explained by aboveground or near-surface factors like plant density, snowpack, and soil moisture (Young et al. 2017). The missing piece of the puzzle lies

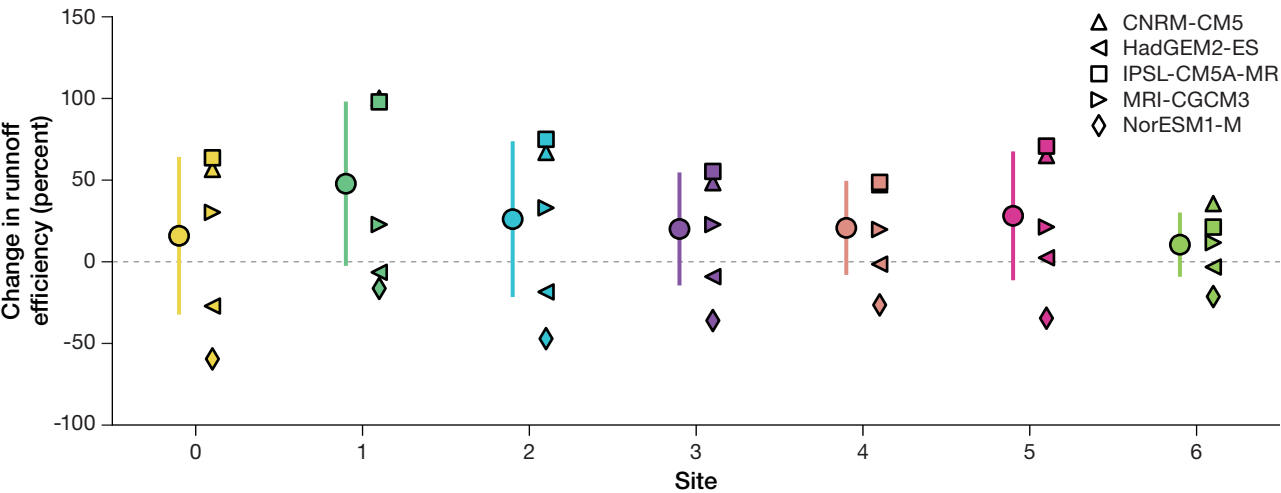


Figure 3.14—Projected percentage of change in runoff efficiency (circle points) quantified as the long-term ratio of total runoff to total precipitation. Error bars represent one standard deviation around the ensemble model mean. Runoff efficiencies for each global climate model are denoted by noncircle, geometric shapes.

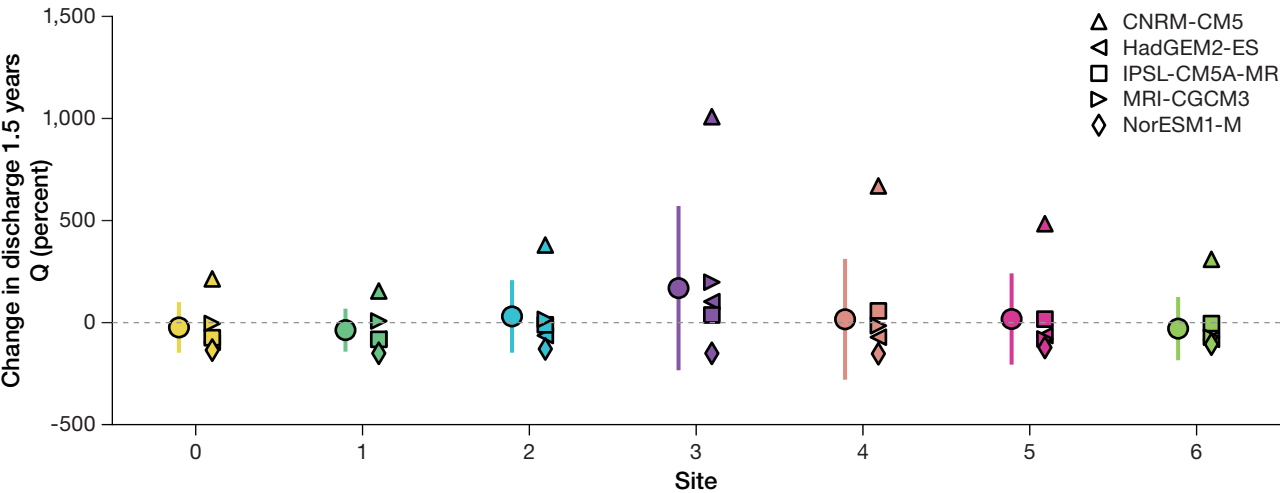


Figure 3.15—Projected percentage of change in the discharge of the streamflow event that recurs every 1.5 years on average (circle points). Error bars represent one standard deviation around the ensemble model mean. Discharges (percentage of change) for each global climate model used are denoted by noncircle, geometric shapes. Sites modeled (from south to north): 0 = Pine Valley, Descanso District, Cleveland National Forest; 1 = southern Santa Ana Mountains, Trabuco Ranger District, Cleveland National Forest; 2 = Big Bear Mountain Resort and Bear Mountain Ski Resort, Mountaintop District, San Bernardino National Forest; 3 = San Gabriel River headwaters, San Gabriel Mountains National Monument District, Angeles National Forest; 4 = Big Tujunga Creek headwaters, Los Angeles Gateway District, Angeles National Forest; 5 = western Dick Smith Wilderness, Santa Barbara District, Los Padres National Forest; 6 = central Ventana Wilderness, Monterey District, Lost Padres National Forest.

deeper below ground, where wet-season precipitation is stored in fractured, weathered bedrock (fig. 3.2), which slowly releases water to forests and streams over the summer (McCormick et al. 2021). This is especially true in southern California forests, where the dry season can be more than 8 months of the year (Klos et al. 2018).

Foundational research in deep root-zone water storage has been conducted in southern California forest and chaparral ecosystems (Arkley 1981, Hellmers et al. 1955, Jones and Graham 1993, Sternberg et al. 1996). Subsequent research consistently identifies the importance of deep-water storage beyond soils, especially during drought. Water stored in unsaturated, weathered bedrock, or “rock moisture,” can store more than one-third of annual precipitation during dry years, supplying more than 75 percent of dry-season moisture to large mixed hardwood-conifer evergreen forests in northern California (Rempe and Dietrich 2018). Several studies in the Sierra Nevada have used indirect methods and mass balance to suggest that interannual storage (wherein deep-water storage provided moisture to plants over a multiyear drought) explains patterns of plant response and mortality in the recent historical drought (Goulden and Bales 2019, Oroza et al. 2018).

Although deep storage can supply water over a multiyear drought, large water-storage deficits can be difficult to replenish with only a single year’s precipitation (Hahm et al. 2019). Such large multiyear storage deficits have been shown to be a strong predictor of drought-caused plant mortality (Goulden and Bales 2019). The effect of multiyear storage may be related to the concept of structural overshoot, in which high forest-biomass densities accrue during climatically favorable periods, but this biomass is unsustainable during drought conditions (Jump et al. 2017). This suggests that forest treatments to reduce biomass may be effective in reducing mortality risk under increased drought frequency expected under climate change (Bart et al. 2021a, 2021b). The potential for interannual storage, and therefore drought mortality, is high in southern California forests. Water storage capacity of the root zone is large relative to mean annual precipitation in much of the assessment area (McCormick et al. 2021), decreasing the likelihood of storage replenishment during a drought (Hahm et al. 2022).

Atmospheric metrics and vegetation modeling suggest that ecohydrological drought will increase across the assessment area. Temperature increases, which increase atmospheric moisture demand and plant water stress (Goulden and Bales 2019), are expected throughout southern California, with large increases occurring inland (chapter 2). Temperature changes in coastal adjacent regions are potentially moderated by the ocean and marine layer clouds, although capturing changes in these processes in GCMs is difficult (Kalansky et al. 2018).

Climatic water deficit (CWD) is a metric of plant water stress calculated as the difference between potential evapotranspiration (how much plants **could** transpire under well-watered conditions) and actual evapotranspiration. In chapter 2, the MC2 dynamic global vegetation model was run to project changes in CWD between historical (1970–1999) and end-of-century (2070–2099) periods under RCP 8.5. Simulations showed that CWD (and therefore plant water stress) is projected to increase across the assessment area (see chapter 2, fig. 2.5). MC2 also projected shifts in vegetation cover type, with around half of each national forest expected to experience changes in plant community composition (see chapter 2, fig. 2.8). At-risk forest ecosystems are primarily in Angeles and San Bernardino National Forests, whereas at-risk chaparral ecosystems are more common in Los Padres and Cleveland National Forests. Altered vegetation cover, whether caused by higher wildfire frequency or climate stress, may have important consequences for overall water balance in southern California (Bart et al. 2021a, Kinoshita and Hogue 2015).

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Chapter 4: Infrastructure Vulnerability Assessment, Adaptation, and Resilience on Southern California Forests

Gordon R. Keller, Donald N. Lindsay, and Allen King¹

Introduction

The southern California region is a biologically diverse, geologically complex, and socially important region of California. It provides water, recreation, wildlife habitat, some timber and rangeland, and many other ecosystem services to the region and its major population centers. A significant amount of infrastructure (roads, culverts, bridges, trails, facilities, and dams) exists in support of these values and population demands. The region is known for its history of frequent, extensive wildfires. Recent climate change-related periods of drought followed by extreme wildfires and storm events have led to debris flows, washouts, bridge failures, and significant erosion. Many millions of dollars of damage to roads and other infrastructure have occurred in recent years. Efforts are underway to assess the vulnerability of the local infrastructure and make that infrastructure investment more resilient to fires and extreme events.

The Southern California Adaptation Partnership (SOCAAP) has synthesized the best available scientific information to assess the vulnerability of recreation, infrastructure, and ecosystem services to climate change in Angeles, Cleveland, Los Padres, and San Bernardino National Forests, and Santa Monica Mountains National Recreation Area. The SOCAAP has developed information and tools for resource managers to incorporate the best available climate change science into programs, restoration activities, land management plans, monitoring programs, and National Environmental Policy Act projects. This chapter includes a scientific assessment of climate change

effects as well as adaptation options that can be implemented in planning and project management. These adaptation options will be included in the *Climate Change Adaptation Library for the Western United States* (Adaptation Partners 2019).

Vulnerability assessment generally involves the following steps:

1. Form an interdisciplinary team.
2. Identify the relevant assets and infrastructure at risk.
3. Evaluate the risk of damage to the infrastructure from climate-related factors and other causes.
4. Consider site condition and history.
5. Estimate asset sensitivity to climate.
6. Identify and rate vulnerability problem spots.
7. Prioritize actions that can minimize the risk.

High-risk sites will generally have high priority. Funding needs can then be prioritized to implement adaptation measures suitable for vulnerability reduction beginning with the higher risk sites. Timely evaluation of risk will help determine where limited funds can be allocated to minimize wildfire and storm effects.

Many effects of climate variability, climate exposure, and disturbances can damage roads and other infrastructure (fig. 4.1). Climate-related effects on hydrology and erosion are significant in the southern California forests. Small changes in annual precipitation are projected for this region but with potentially larger, more extreme individual storm events, longer periods of drought, and higher temperatures. Storms will likely be warmer so there will likely be more precipitation as rain and less high-elevation snow. Storm patterns are projected to be more erratic, runoff peaks earlier in the year, and rainfall intensities higher (Pierce et al. 2018). This can (1) modify recreation patterns and timing of construction contracts, (2) alter timing of needed maintenance, (3) increase road use in some areas, (4) increase road damage, and (5) accelerate erosion and gully. Infrequent but increased peak flows will likely increase scour problems and risk

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Figure 4.1—Ways that the effects of climate stressors, climate change, and other disturbances affect roads and other infrastructure. Multiple pathways are common. Figure from Strauch et al. (2014).

to culverts and bridges. Sequences of drought and storms, as well as higher temperatures, will likely promote more wildfires, followed by increased erosion, landslides, floods, and debris-flow events.

The United States experienced a record-breaking \$22 billion in damage from natural disasters in 2020 (National Academy of Sciences 2021). For transportation and other infrastructure systems, extreme events of relatively short duration, particularly during the summer months (as opposed to annual or seasonal averages), often cause the most significant damage or are the most disruptive to operations. Heat waves, winter storms, and flooding affect infrastructure over short time scales (days to months), whereas climate-related changes such as droughts, construction season length, and snowmelt hydrology affect infrastructure over longer periods (years to decades) (Furniss et al. 2018).

Measures to minimize unwanted climate change effects are being addressed at the global, national,

regional, and local scales. The publication *Climate-Resilient Infrastructure: Adaptive Design and Risk Management* (ASCE 2018) provides a comprehensive overview of climate change issues, risk, and adaptation involving infrastructure from the engineering perspective. Local and federal governments and agencies, such as the U.S. Department of Agriculture, Forest Service, are implementing programs to reduce carbon emissions (Reidmiller et al. 2018). Specific actions for reducing emissions include carpooling, using efficient and alternative-energy buses, using electric or hybrid fleet vehicles, building bike paths, using efficient light emitting diode (LED) products, constructing energy-efficient buildings, promoting reduction in visitor vehicle idling, using recycled office materials, promoting more sustainable “green” procurement practices, installing low-flow water facilities, and incorporating more efficient transport systems in forest and recreation management.

Because forests sequester carbon, sustainable forest management is important and includes good logging practices (e.g., reduced impact logging), minimizing conversion of forests to other uses, promoting rapid reforestation in timber harvest and burned areas, and supporting fuel reduction and forest thinning programs to reduce wildfire intensity, particularly near urban areas. In addition, agencies can benefit from being involved in public education, training, and visitor outreach to increase awareness of climate change effects and appropriate responses, as well as funding to support adaptation measures (USDI NPS 2011).

U.S. Department of Transportation, Federal Highway Administration literature and similar sources often refer to **climate adaptation**. Adaptation provides a means by which the negative effects of climate change are minimized and vulnerability is reduced through the implementation of certain practices or tools. It is a process of adjustment to actual or expected climate changes and their effects to moderate harm or exploit beneficial opportunities (IPCC 2022). This may include policy and planning decisions as well as design, construction, and maintenance activities to increase infrastructure resilience (Partington et al. 2017). **Resilience** is the characteristic of a system that allows it to absorb, cope with, recover from, or more successfully adapt to adverse events. **Vulnerability** is the degree to which a system is susceptible to or unable to cope with adverse effects of climate change or extreme weather events. **Mitigation** consists of actions to limit the magnitude of long-term climate change via measures to reduce greenhouse gas emissions. In this document, the term “adaptation” refers most often to measures engineers can use to improve road resilience and reduce risk of infrastructure damage.

Forest adaptation options, many of which are discussed in detail below, may include the following:

- Thinning and fuels reduction around flammable infrastructure, such as buildings and timber bridges
- Fire hardening structures with nonflammable siding and metal roofing
- Planning for earlier access on forest roads because of less snowpack but when subgrade soils are still saturated
- Ensuring that maintenance is current and road surface drainage measures are functioning properly and minimizing concentration of water
- Managing roads to deal with moderate use, washouts, and severe erosion
- Modifying bridge and culvert designs to accommodate higher flows, debris, and sediment
- Addressing potential scour problems at bridges
- Installing trash racks and culvert diversion prevention measures to deal with increased debris in channels
- Designing culverts to match channel bankfull width
- Repairing or strengthening old retaining structures and fill slopes that are currently in marginal condition
- Strengthening the roadway structural section by adding base or surfacing aggregate
- Applying additional dust palliatives on project roads during droughts
- Building debris retention structures to stop or retard debris flows
- Moving some facilities away from streams or areas of potential debris slides
- Ensuring that critical slopes are well covered with vegetation

Infrastructure at Risk

This SOCAAP assessment area encompasses the four national forests in southern California plus the Santa Monica Mountains National Recreation Area (chapter 1: fig. 1.). This area also includes several state and regional parks as well as designated special areas and wilderness areas, such as the San Gabriel Mountains and the Santa Rosa and San Jacinto Mountains National Monument as well as Ventana, San Rafael, Sespe, Cucamonga, San Geronio, Cahuilla Mountain, and Pine Creek Wildernesses. These areas represent a wide range of chaparral, mountain, high desert, and coastal environments.

The southern California national forests contain a significant amount of infrastructure. This includes 4,788 miles of roads, 3,211 miles of motorized and nonmotorized trails, 41 road bridges, 44 trail bridges, 39 dams

(plus many small debris-retention dams and other privately managed dams on national forest land), more than 2,200 buildings and administrative sites, 150 developed campgrounds, and 74 developed picnic areas. These represent an investment of at least \$1 billion.

Roads and facilities are subject to a wide variety of climate-induced events, including droughts, fires, floods, landslides, debris flows, and erosion, all of which can damage or destroy infrastructure (fig. 4.1). Fires represent the greatest risk to infrastructure and facilities in the assessment area. Virtually all infrastructure is vulnerable to wildfires, particularly recreation and administrative facilities (fig. 4.2). Roads, bridges, culverts, and surface drainage measures are susceptible to increased runoff during storm events as well as failures caused by washouts, plugging, overtopping, stream diversion, erosion, and scour (fig. 4.3). Storm-induced landslides,

debris flows, and rockfalls occur because of saturated soils during major storms (fig. 4.4), particularly if storms include high-intensity rainfall following a fire. The combination of fires followed by heavy rains can cause debris flows from canyons on steep slopes. Debris flows often damage or destroy most types of infrastructure in their path.

Significant effects to infrastructure can result from more subtle climate change phenomena. This includes (1) early access to and use of roads, trails, campgrounds, and facilities caused by drier winters and less snowpack; (2) more dust on roads during prolonged drought periods; (3) drying of traditional water sources and streams in late summer; and (4) limited funding for maintenance because of decreasing budgets and increased allocation of funds to fire management.



Figure 4.2—Forest infrastructure. Wildfires often damage administrative sites, recreation facilities, and other infrastructure (including walls, culverts, and bridges) such as these. Upper photos by Allen King, and lower photos by Gordon Keller.



Figure 4.3—Examples of southern California forest roads with erosion and infrastructure, including culverts and fords damaged by flooding, storms, and fires. Left photos by Vincent Barandino, USDA Forest Service, National Technology and Development Program; right photos by Donald Lindsay.



Figure 4.4—Landslides, slope failures, rockfalls, and debris flows that occur because of saturated soils from major storms and after wildfires. Left photos by Allen King, right photos courtesy of Donald Lindsay.

Geology and Geologic Hazards

Regional Geology

The geology in the SOCAAP assessment area is diverse and complex (fig. 4.5). The region straddles the boundary between the Pacific Plate and the North American Plate, which helps create a wide range of geological structures. More than 600 different rock units have been named and mapped in this area. Each rock unit has different chemical and physical properties and responds

differently to earthquakes and landslides, erosion, weather events, excavations, and other land uses (USDA FS 2005). Because southern California is one of the most tectonically active regions in the United States, many of the mountains are young, the rocks are fractured and deformed, and the slopes are steep (fig. 4.6).

The Transverse Ranges are a 300-mile-long, east-west oriented physiographic province within California, with steep mountains underlain by diverse rock types that are mostly sedimentary in coastal areas and granitic

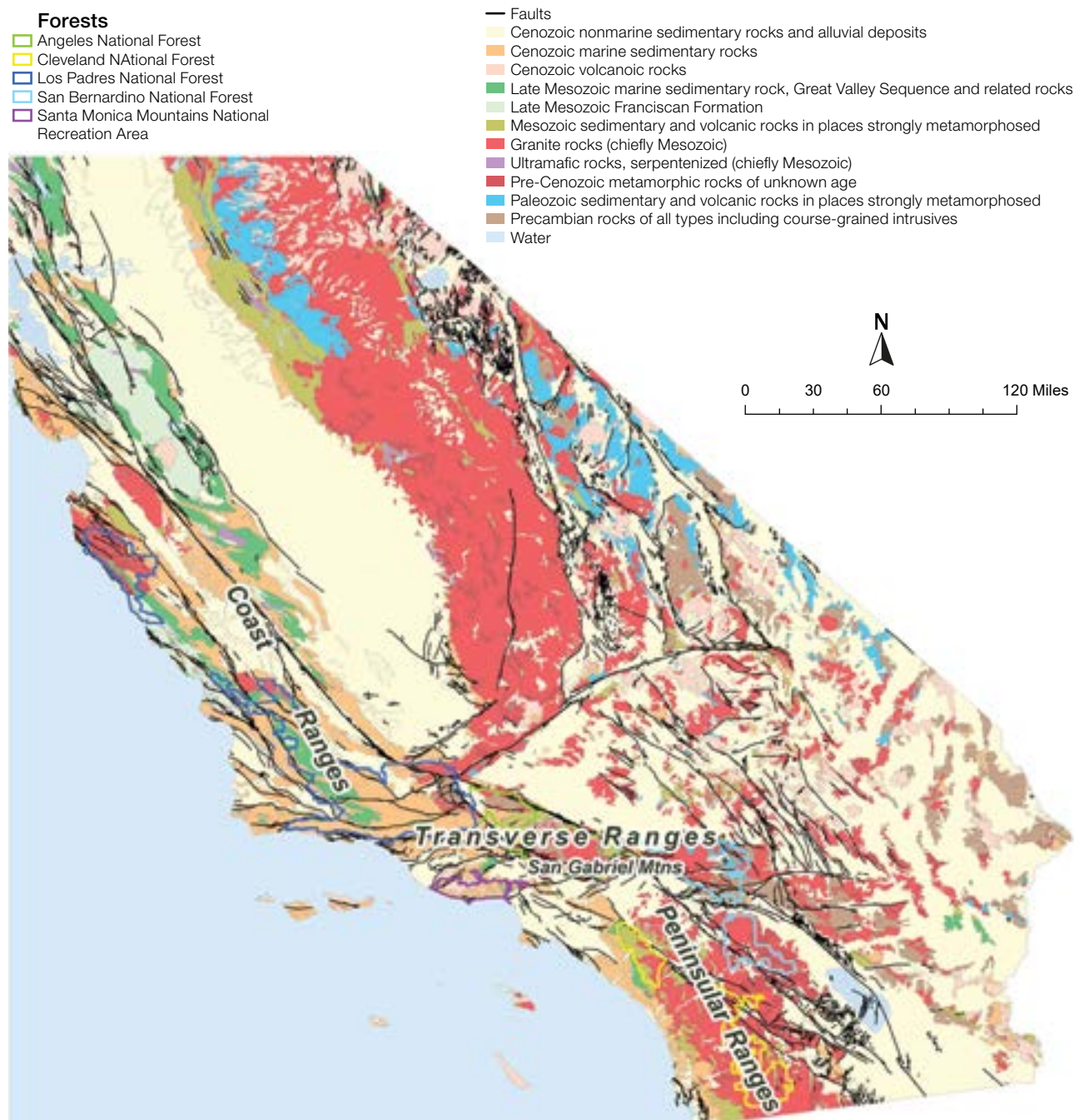


Figure 4.5—Simplified geologic map of the southern California region and national forests. Map developed by the California Geological Survey.

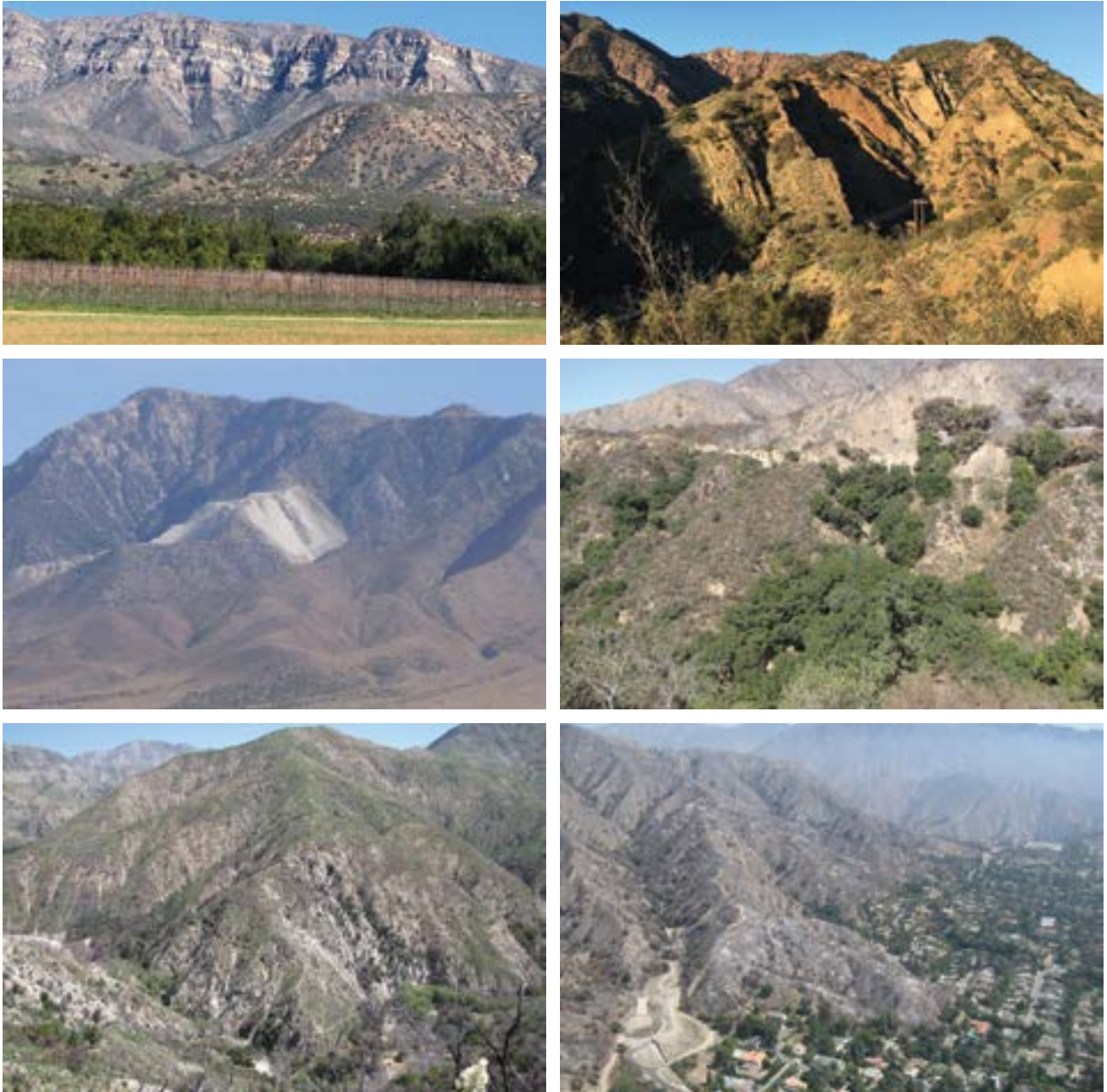


Figure 4.6—Examples of the diverse, steep, fractured, and geologically complex landscape of southern California mountains. Top photos by Gordon Keller, bottom and middle photos by Allen King.

inland. Angeles National Forest and parts of Los Padres and San Bernardino National Forests are within this physiographic province. South of the Transverse Ranges are the Peninsular Ranges, characterized by a series of northwest-trending mountain ranges that include terrain on San Bernardino and Cleveland National Forests. The San Andreas Fault and other fault systems separate the two ranges. The dominant rock types in these ranges are granitic rock. However, significant units of sedimentary rock and ultramafic Franciscan Formation rock are in Los Padres National Forest.

Starting from the north and moving southward, the Coast Ranges in Los Padres National Forest consist of the Santa Lucia Range (from Monterey to the Cuyama River); Caliente and La Panza Ranges (San Luis Obispo County); and San Rafael, Sierra Madre, and San Emigdio Ranges (including Mount Pinos). They are a series of mountains that roughly parallel the San Andreas Fault and the Pacific Ocean coastline between San Francisco Bay and Santa Barbara County. Geologic structures, such as faults and folds, strongly control river drainage patterns, producing major river systems, such as the San

Antonio, Nacimiento, Cuyama, and Sisquoc Rivers. The Sespe Creek river system extends to the southern end of Los Padres National Forest, and the Santa Clara River starts farther south in Angeles National Forest.

Dominant on the Monterey Ranger District (Los Padres National Forest) are two different types of basement rock that have been thrust upward and exposed within the Coast Ranges. Between the San Andreas and Sur-Nacimiento Faults, basement rocks known as the Salinian Block consist of metamorphic rocks and granitic plutons. Southwest of the Sur-Nacimiento Fault Zone, basement rocks are ocean crust sedimentary and volcanic rocks of the Franciscan Formation. Farther south in the Santa Lucia Ranger District (southern Santa Lucia Range), the Franciscan rocks phase out, and younger sedimentary sandstones, shales, and conglomerates dominate. Dibblee (2001) summarizes the geology of Los Padres National Forest.

The Transverse Range province includes subparallel mountain ranges and intervening valleys that extend eastward from the offshore Channel Islands in the Pacific Ocean to the desert where the province forms the boundary between the Mojave and Colorado Deserts. The mountain ranges included within Angeles National Forest and parts of Los Padres and San Bernardino National Forests are, from west to east, the Santa Ynez, Topatopa, Sierra Pelona, San Gabriel, and San Bernardino Mountains. These ranges are characterized by a diverse and structurally complicated array of rock types that form a rugged landscape.

The Santa Ynez and Topatopa Mountains, and smaller mountain segments to the north within Los Padres National Forest, are composed almost entirely of marine sedimentary rocks of Cenozoic and late-Mesozoic ages. North of Santa Barbara is the southernmost extent of the disorganized ocean-floor rock types called the Franciscan Formation. Near Mount Pinos are older Mesozoic granitic rocks and Precambrian and Mesozoic metamorphic rocks. These basement rocks are elevated adjacent to the major active San Gabriel and San Andreas Faults, which border Los Padres National Forest on the northeast. Other major fault zones include Santa Ynez and San Cayetano Faults.

The Sierra Pelona Mountains and Ridge Basin block cover the western part of Angeles National Forest. They are composed of metamorphic (notably Pelona Schist)

and plutonic rock or volcanic rock at higher elevations and folded and faulted sedimentary rocks in the lower elevations and along the San Gabriel Fault Zone. Pelona Schist is a geologic formation known for numerous, large, slow-moving landslides that have affected waterflow and road stability in some areas. The San Gabriel Mountains consist of some of the most tectonically active mountains in the United States, including some of the oldest granitic and metamorphic (schist and gneiss) rocks in California. Along the margins of the San Gabriel Mountains are exposures of younger sedimentary and volcanic rocks. The San Gabriel Fault Zone traverses the length of the southern part of Angeles National Forest. The San Andreas Fault is located along the northern side of the mountains, crossing Big Pines Highway and California State Route 2. Abundant landslides form widespread and important physiographic elements in the highly fractured rocks.

Cajon Pass separates the San Gabriel and San Bernardino Mountains. The San Bernardino Mountains consist primarily of Mesozoic and older crystalline basement rocks. Included are granitic rocks of Cretaceous, Jurassic, and Triassic ages and metamorphic rocks of Mesozoic, Paleozoic, and Precambrian ages. These mountains include the highest peak and the only mapped glacial deposits in southern California. The San Andreas Fault Zone borders the southern edge of these mountains. Landslides are common in the San Bernardino Mountains.

South of the Transverse Ranges, the Peninsular Ranges include the San Jacinto and Santa Rosa Mountains within the San Jacinto Ranger District (San Bernardino National Forest), along with the Santa Ana, Palomar, and Cuyamaca-Laguna Mountains on the Cleveland National Forest. The core of the ranges in southern California is the Peninsular Ranges Batholith, composed of granitic intrusive rocks and surrounded on the east and west sides by older metamorphic rocks. These ranges have been faulted and eroded in place longer than other California mountain systems, have not been significantly folded, and have erosional surfaces and drainage patterns quite different from the Transverse and Coast Ranges. They also have fewer landslides than the San Gabriel and San Bernardino Mountains.

The San Jacinto and Santa Rosa Mountains have a core or basement of granitic (quartz diorite plutons) rocks, some metamorphic (banded gneiss) and metasedimentary rocks, and minor amounts of younger sedimentary rocks and valley fill deposits. The Santa Ana

Mountains (within the Trabuco Ranger District of the Cleveland National Forest) are mostly older (Mesozoic), deformed marine sedimentary rocks intruded by granitic rocks, overlain by volcanic rocks, and flanked by younger sedimentary rocks. The major active Elsinore Fault Zone forms the northeastern range boundary. Many smaller faults are located within the mountains, especially in the sedimentary rock units. Landslides are abundant in the sedimentary, volcanic, and prebatholithic rocks; only a few landslides occur within the batholithic rocks.

Included within the Palomar Ranger District (Cleveland National Forest) are the Palomar Mountains and Pine Mountain areas in the north and the more subdued topographic area west of Mesa Grande. The district is underlain mainly by batholithic, metamorphic rocks and intermixed granitic and metamorphic rocks. Younger sedimentary rock is mostly confined to valley bottoms. The Cuyamaca-Laguna Mountains cover the east side of the Descanso Ranger District (Cleveland National Forest), with smaller peaks and ranges to the west. This district is dominantly granitic with scattered zones of gabbro intrusive and hybrid rocks (mixed granitic-metamorphic rocks). A large zone of schist

extends from north of Cameron Guard Station to north of Julian. The schist contains some gold-bearing veins. The active Elsinore Fault Zone borders the eastern side of the district, but no extensive landslides are recognized.

Geologic Hazards

A geologic hazard is a geologic feature or condition that can pose risks to humans, facilities, and other resources. Examples include landslides (many different types); rock-falls; earthquake fault zones; floods; channel avulsion; snow avalanches; rocks containing naturally occurring asbestos (usually chrysotile) or radon; acid mine drainage; dust; coastal cliff erosion; abandoned mines; abandoned landfills; contaminated groundwater; volcanic activity; and areas of subsidence, collapse, or liquefaction. Climate change increases the likelihood of effects caused by geologic hazards. Roads, culverts, and bridges are the infrastructure most affected by geologic hazards, especially floods and landslides (fig. 4.7). However, debris flows emanating from burned watersheds during intense rainstorms can be a significant threat to facilities and campgrounds as well as to human life and safety. Risk assessment and associated adaptation options are discussed below.



Figure 4.7—Roads, culverts, and bridges are the infrastructure most affected by geologic hazards, especially landslides, debris flows, and floods. Left photos by Donald Lindsay, upper right photo by Alan Yamada, lower right photo by Allen King.

Southern California is one of the most tectonically active regions in the United States. Many of the mountains are younger, the rocks are more fractured and deformed, and the slopes are steeper and more often subject to landslides and intense surface erosion than most other mountain ranges. Certain rock types are prone to erosion and landslides, which can increase risks to humans, facilities, and other resources. These include shale and Franciscan Formation rocks on the Los Padres National Forest; schist, decomposed granite, and other weathered basement rocks on the Angeles and San Bernardino National Forests; and certain volcanic and metasedimentary rocks on the Cleveland National Forest.

Management activities may affect or influence the following climate-related geologic hazards:

- Slope and channel instability (landslides, debris flows, rockfalls, mudflows, soil slips, dry ravel) and associated issues of appropriate disposal of slide waste materials
- Foundation failures associated with dams, roads, bridges, and retaining structures
- Flooding and snow avalanches
- Wind-blown dust (source of silicosis and mesothelioma)
- Coastal cliff erosion (only at the Monterey Ranger District, Los Padres National Forest) and hazardous streambank erosion
- Contaminated groundwater or depleted groundwater resources

Other geologic hazards such as earthquakes, liquefaction, toxic minerals from acid mine drainage, ground subsidence, and abandoned mine hazards are present in the assessment area but not affected by climate change.

Geologic hazards can affect human health and safety and can cause costly repairs; environmental effects; and inconveniences for communities, travel corridors, and businesses. Encroaching urbanization and increasing recreation uses can affect and be affected by the hazards listed above. Wildfire, weather extremes, and disturbance from land management activities increase the risk of creating or exacerbating geologic hazards and risks to humans, facilities, and other resources. A tragic example is the loss of 15 lives during the Christmas Storm of 2003 in and around San Bernardino National Forest in which debris flows from saturated slopes that burned in the Old Fire and Grand Prix Fire (October 2003) damaged church retreat facilities, commercial campgrounds, and residential developments in floodplains and on alluvial deposits (fig. 4.8).

The coastal areas of Los Padres National Forest, particularly along the Big Sur coast, are a recreational destination where sea-level rise, coastal erosion, and slope instability are a concern. The California Department of Transportation struggles to keep California State Highway 1 open along the coastal bluffs, and this problem is expected to worsen. Wildfires have also affected the area. Debris flows triggered on rain-soaked fire scars from the Dolan Fire (2020) plugged a 66-inch culvert, overtopped the highway, and subsequently washed out a portion of the road, closing Highway 1 for 3 months in



Figure 4.8—Damaged permittee buildings on Forest Service land and private residences damaged from debris flows after the 2003 Old and Grand Prix Fires. Photos by Gordon Keller.



Figure 4.9—A 2021 debris flow, caused by heavy rain in the Rat Creek watershed after the 2020 Dolan Fire, plugged a major culvert and subsequently washed out a portion of California State Highway 1. The highway was closed for 3 months. Photos by Donald Lindsay.

2021 (fig. 4.9). Debris-flow modeling conducted by the U.S. Department of the Interior, U.S. Geological Survey showed that the Rat Creek area had a 60–80 percent probability of triggering a postfire debris flow at a rainfall intensity of 1 inch per hour over a 15-minute duration. Fires and debris flows also damaged other upslope forest roads and downstream recreation facilities in the area (Cavagnaro et al. 2021).

In Santa Barbara County, fires and debris flows affected the area of the Sherpa Fire (2016) and Thomas Fire (December 2017–January 2018). In January 2017, a postfire debris flow triggered by an intense rainstorm (peak 15-minute rainfall intensity of 3 inches per hour) within the Sherpa Fire scar damaged local oil and gas facilities as well as El Capitan Canyon Resort (Schwartz et al. 2021). In 2018, the Montecito debris flows in the Santa Ynez Mountains killed 23 people, closed U.S. Highway 101 for 13 days, and caused more than \$1 billion in damage to a community and infrastructure just south of Santa Barbara (Lancaster et al. 2021).

The California Department of Transportation recently assessed the vulnerability of many highways in southern

California. It estimates that for a 10-year recurrence design storm, 0.6 percent of roads are vulnerable to postfire debris flows; for a 100-year storm, 0.5 percent of roads are vulnerable. Under a high greenhouse gas-emission scenario (Representative Concentration Pathway [RCP] projection 8.5—emissions will continue to rise) and 100-year event, up to 1.5 percent of the roads are vulnerable. The most vulnerable roads are in California Department of Transportation Districts 2, 7, and 11; Districts 7 and 11 incorporate portions of Angeles and Cleveland National Forests and San Bernardino National Forest (Chester and Li 2020).

The San Gabriel Fault Zone traverses the length of the southern part of Angeles National Forest. The San Andreas Fault is located along the northern side of the mountains, crossing Big Pines Highway and California State Route 2. Abundant landslides comprise widespread physiographic elements in the highly fractured rocks. The Crystal Lake, Cow Canyon, Manker Flat, and Coldwater Canyon landslides are some of the largest landslide deposits in southern California. The Heath Canyon landslide deposit above Wrightwood

produces material for debris flows that are a hazard for the community of Wrightwood. Besides Pelona Schist, other basement rocks commonly develop large, fast-moving rock avalanches on steep terrain. Large areas of the San Gabriel Mountains are subject to fast-moving debris flows during wet winters. Large landslides are infrequent but may occur more frequently in a warmer climate, increasing risk to development below unstable areas.

Landslides are common in the San Bernardino Mountains and include the Blackhawk landslide deposit, which traveled northward from the mountains almost 3 miles onto the desert floor by riding a layer of compressed air (Matti and Morton 2000). The Forest Falls area of Mill Creek has been the site of numerous debris flows, avalanches, and boulder falls that have been triggered by earthquakes and monsoonal rainfall.

Vulnerability Assessment Process

The vulnerability assessment in this chapter includes a synthesis of best available science using the following process:

1. Identify infrastructure at risk.
2. Quantify the level of risk relative to value, age, condition, and a combination of climatic exposure and sensitivity to exposure.
3. Summarize appropriate actions needed to minimize the risk. These actions help prioritize where funds are best invested and include adaptation measures to increase the resilience of infrastructure.

The vulnerability assessment has a significant geospatial component, complementing existing products such as a Sierra Nevada science synthesis (Long et al. 2014) and building on previous vulnerability assessments and adaptation options that focus on national forest resources (Halofsky et al. 2018, 2019, 2021). This assessment can help resource managers and engineers recognize vulnerabilities to climate change, assess risks to local infrastructure, and consider adaptation options that reduce risks. Box 4.1 summarizes fire and general climate change vulnerabilities, adaptation options, and on-the-ground actions for infrastructure.

Various agencies have vulnerability assessment processes, but most follow steps similar to those shown in box 4.2. The Federal Highway Administration uses the following comprehensive process:

1. Define the objectives and scope, including climate information, actions and products needed, and assets at risk.
2. Compile available data on assets, hydrology, and climate.
3. Assess vulnerability of assets, considering asset history and engineering information.
4. Develop and prioritize adaptation options.
5. Incorporate results into decision making (fig. 4.10) (USDOT FHWA 2017).

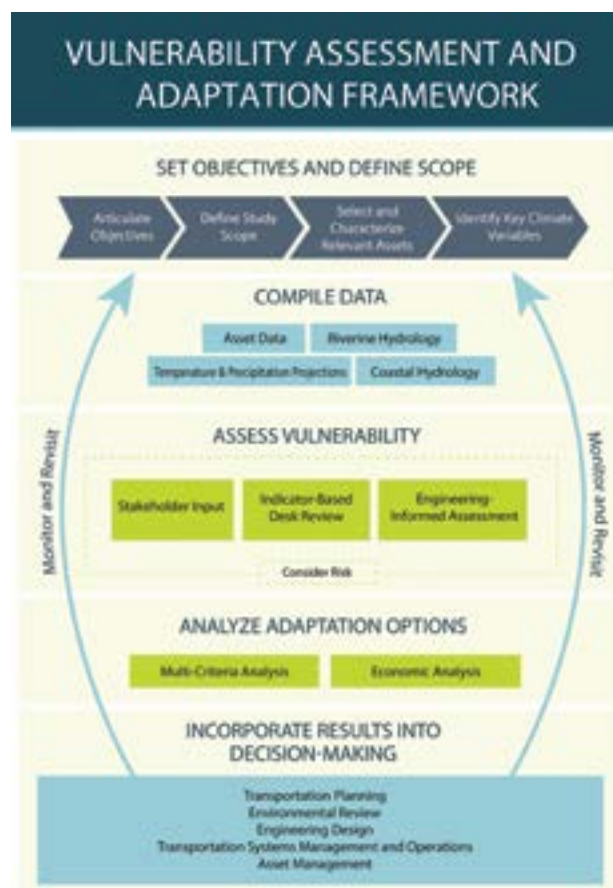


Figure 4.10—Federal Highway Administration framework for assessing the effects of climate change and extreme weather on infrastructure that can be used for both high-level planning and on-the-ground project implementation. This structured approach ensures thoroughness and consistency in designing and maintaining infrastructure in a changing climate (USDOT FHWA 2017).

Box 4.1**Summary of Infrastructure Types, Vulnerabilities, and Adaptation Actions****Fire vulnerabilities and adaptation actions**

Asset/issue	Vulnerability	Adaptation action
Roads	Heavy use during fire suppression Road damage and dust	Repair roads with U.S. Department of Agriculture, Forest Service, Burned Area Emergency Response actions Apply dust palliatives
Bridges and culverts	Damage by fire, particularly to wooden structures	Clear trees and brush near structures Build or replace structures with concrete or steel
Trails	Damage by fire to trail structures, walls, and bridges Slope ravel onto trail	Plan for trail maintenance after a fire
Buildings and facilities	Damage by fire, debris flows after a fire and rain	Create defensible space around structures Use fireproof materials Move facilities away from channels
Dams	Damage by fire to gate structures Root holes caused by burned vegetation	Remove vegetation on dams and around gates

General climate change vulnerabilities and adaptation actions

Asset/issue	Vulnerability	Adaptation action
Roads		
Maintenance	Lack of financial and human resources Demand for work after floods and fires Shifting timing of work	Inspect roads after storms Keep current on maintenance items Repair roads in problematic locations Increase flexibility in hiring personnel
Management	Lack of financial and human resources Lack of contracting flexibility Washouts and slope failures	Maintain adequate staff Maintain trained staff Decommission or close unneeded roads Move vulnerable sections of road
Surface drainage	Washouts Erosion/sedimentation Water quality degradation Gully formation	Remove water from road surface Outslope roads Use frequent rolling dips, cross drains, and leadoffs Armor pipe and dip outlets Armor eroding ditches
Culverts	Culvert failures Washout from poor installation Lack of capacity Plugging with debris, logs, and sediment	Keep channel clear Repair damaged culvert sections Add stream-diversion protection dips Add trash racks to trap debris Increase culvert capacity or use stream simulation designs
Low-water crossings	Structure washouts Additional traffic delays	Install only on noncritical routes Use vented fords to pass most of the flow
Bridges	Bridge failure Foundation scour Loss of freeboard or capacity Timber bridges burned by wildfire	Keep channel clear of debris and vegetation Armor foundations and areas with scour potential Redirect channel flow away from abutments Remove vegetation near bridges Remove aggradation deposits Increase freeboard
Streambank stabilization	Road-stream encroachment Road washouts Slope scour	Move the road Armor weak streambanks Redirect streamflow away from streambank

General climate change vulnerabilities and adaptation actions (continued)

Asset/issue	Vulnerability	Adaptation action
Erosion control	Slope erosion Sediment and soil loss Gully formation	Maintain adequate drainage Maintain adequate ground cover Plant grasses and deep-rooted vegetation Prepare soil to grow vegetation Add gully-control structures
Slope stabilization	Slope failures Rockfall Debris flows Accelerated erosion	Construct stable cut and fill slopes Add drainage and deep-rooted vegetation Add slope stabilization measures Pull back unstable sliver-fill slopes Add debris basins and check dams Use deep patch on settling fill slopes Remove loose rock and add rockfall protection
Other road issues	Lack of timely contracting Pavement freeze-thaw damage Fire support road damage Hazard tree danger Dust on dry, unsealed roads	Hire more contracting officers Use springtime road-use restrictions Designate fire-detour routes Have crews available to remove hazard trees Provide funding for dust palliatives
Trails	Trail closures and restricted use Trail damage Trail bridge damage	Promote trail partnerships Relocate vulnerable trail locations Modify trail bridge designs Strengthen trail maintenance capabilities
Facilities	Damage from fires, floods, and wind Aging structures Depleted water systems	Move vulnerable buildings and campgrounds Have storm- and fire-evacuation plans in place Use fire-resistant materials (e.g., metal roofs) Conduct forest thinning to create defensible space near structures Drill or deepen water wells
Dams	Lack of capacity during floods Overtopping or piping failures Inoperable gate and control structures Lack of available water during droughts	Clear, lower, or increase the size of marginal spillways Remove vegetation on embankments Repair inoperable control structures Plan for future major storms and droughts

Box 4.2

Potential Steps for a Vulnerability Assessment Process

Steps that can be used for an infrastructure vulnerability assessment are listed below. Note that the process is typically iterative as the process advances, and outputs depend on the skills and knowledge of participants.

1. Compile an asset inventory.
2. Form an interdisciplinary team.
3. Define assets at risk.
4. Examine site data and history.
5. Review relevant climate projections and climate-related stressors.
6. Summarize relevant hydrologic projections.
7. Conduct risk analysis.
8. Rank asset vulnerability.
9. Prioritize needed work and adaptation measures.

It is important to periodically monitor and evaluate the process and results.

The Forest Service has a similar process that includes (1) defining objectives and establishing an interdisciplinary team; (2) defining the scope of work relative to assets and climate stressors; (3) collecting asset information, climate data, and indicators; and (4) identifying and prioritizing asset vulnerabilities. These steps are followed by guidance and scoring tools for adaptation strategies for assets at risk (USDA FS 2018). Developing a clear approach minimizes data collection and analyses, streamlines the evaluation process for complex climate change issues, and saves money. The Canadian forest industry follows a similar process, developed by Engineers Canada (2016), which has been used in assessing vulnerability of forest roads (Partington et al. 2018).

The California Department of Transportation has developed climate change vulnerability assessment reports (and summary reports) as well as adaptation priorities reports for each of their districts, including District 5 in coastal central California (Caltrans 2019a, 2021), Districts 7 (Caltrans 2019b) and 8 (Caltrans 2019c) in the southern mountain regions, and Districts 11 (Caltrans 2019d) and 12 (Caltrans 2019e) in the extreme southern California border and coastal areas. Their reports address highway vulnerabilities, extreme weather effects and damage to district infrastructure, risk management, and adaptation designs that incorporate climate change into decision making. The California Department of Transportation Adaptation Framework

incorporates the important steps for asset vulnerability assessment. The framework considers factors, such as asset type, cost, site history, condition rating, traffic, and detour distance.

All processes that evaluate infrastructure vulnerability rely on good inventories of assets, such as the Forest Service Infra database or other asset management tools that include roads, culverts, bridges, buildings, and dams. Expertise is provided by an assessment or interdisciplinary team, consisting of personnel familiar with infrastructure and site history, local terrain sensitivity, climate data, and other relevant information.

Historical observations and future climate projections throughout southern California help establish exposure of infrastructure to potential climate stressors. Using asset data and history in conjunction with hydrologic data and projected climate data, a risk can be assessed for general or specific infrastructure assets. Ranking assets in the context of risk helps identify asset vulnerabilities and prioritize planning, funding, replacement, and maintenance activities.

Assessment and prioritization are critical because funding and resources are always limited. Identifying potentially problematic areas or sites before climate-related effects can help managers adequately consider potential consequences of damage. Table 4.1 presents a risk-rating matrix that considers (1) likelihood of an event causing damage or infrastructure failure, and (2) consequences of damage or failure, with risk subjectively rated from very high to very low for any given infrastructure asset (Keller and Ketcheson 2015).

Table 4.1—Risk rating matrix used to evaluate likelihood and consequences of climate change effects on infrastructure and other resources in the Southern California Adaptation Partnership assessment area

Likelihood of damage or loss	Magnitude of consequences		
	Major	Moderate	Minor
Very likely	Very high	Very high	Low
Likely	Very high	High	Low
Possible	High	Intermediate	Low
Unlikely	Intermediate	Low	Very low

Likelihood of damage or loss: very likely = nearly certain occurrence (>90 percent); likely = likely occurrence (50–90 percent); possible = possible occurrence (10–50 percent); unlikely = unlikely occurrence (<10 percent). Magnitude of consequences: major = loss of life or injury to humans, major road damage, irreversible damage to critical natural or cultural resources; moderate = possible injury to humans, likely long term but temporary road closure and lost use of major road or road systems, degradation of critical natural or cultural resources resulting in considerable or long-term effects; minor = minor road damage, little effect on natural or cultural resources that result in minimal, recoverable, or localized consequences. Risk and priority: very high and high risk = highest priority for risk reduction treatments; intermediate risk = treatments needed, may be incorporated in annual maintenance; low and very low risk = treatments may not be necessary.

For example, a bridge may have a moderate likelihood that it would fail in a major storm because of foundation scour, but the consequences of that failure are high if the bridge is the only access to an area and the road would be closed for a long time. Alternatively, a road segment may have high likelihood of closure from a landslide or culvert washout, but if the road is not a critical route or if there is alternate access, then the consequence of road closure is lower. Therefore, the overall risk might be assessed as low to moderate. Ideally, infrastructure determined to be high or very high risk would be given a high priority and either improved, closed, or relocated.

Duration of effectiveness is an important component of assessment, but both short- and long-term treatments

have value. Many adaptation treatments, both short and long term, are useful before a potentially damaging climate event. Channel cleaning and culvert maintenance are typically short-term treatments, whereas building an overflow channel to prevent stream diversion has long-term value. Some treatments are more cost effective than others. Vegetative erosion control treatments are particularly cost effective because they are inexpensive and are increasingly effective over time. Box 4.3 summarizes common adaptation treatments for roads, considering both short- and long-term value and cost-effectiveness. A more complete list of treatments and effectiveness is in Keller and Ketcheson (2015).

Box 4.3

Adaptation Treatments: Duration and Cost Effectiveness

Adaptation treatments	Duration		Cost effectiveness ^a	
	Short term	Long term	Low	High
Road maintenance				
Conduct grading, cleaning, and shaping maintenance	•			•
Road surface drainage				
Add rolling dips		•		•
Add ditch-relief culverts (cross-drains)		•		•
Add water bars	•			•
Implement ditch treatments, armoring, and check structures	•		•	
Add leadoff ditches	•			•
Implement cross-drain pipes, dips, ditch-outlet protection, and armoring	•		•	•
Culverts				
Maintain culverts	•			•
Remove minor channel debris or add trash racks	•			•
Provide diversion prevention and armored overflow protection for culverts		•		•
Bridge protection and improvement				
Maintain channels and clear debris and sediment around footings	•			•
Erosion prevention and control				
Implement physical erosion and control measures	•		•	
Vegetate barren areas with deep-rooted native plants		•		•
Prevent gullies by limiting water concentration		•		•
Slope stabilization measures				
Pull back side-cast fill and prevent sliver-fill failure		•		•
Add deep-patch slope treatments for failing slopes		•		•

^a Cost effectiveness differs, depending on treatment. Ratings are estimates based on the authors' experience.

Other Assessment Tools, Guidance, and Resiliency Efforts

The assessment information presented here builds on other climate change assessments and activities that have been conducted for federal lands (Furniss et al. 2013; Halofsky et al. 2018a, 2018b, 2021; Peterson et al. 2014; Vose et al. 2012, 2016, 2018), including those discussed above. The following help identify assets at risk and methods to assess the condition and vulnerability of those assets:

- Geospatial assessment tools and maps
- Work on transportation analysis and planning
- Watershed condition surveys and assessments
- Watershed improvement needs
- Best management practices (BMPs)
- Transportation resiliency guidebook (USDA FS 2018)
- Forest Service Burned Area Emergency Response (BAER) treatments catalog (Napper 2006)
- Emergency Relief for Federally Owned Roads (ERFO) program

Federal agencies can use these resources to complete local analyses (Furniss et al. 2018).

Geospatial Assessment Tools and Maps

Geospatial assessment can help assess risks to infrastructure, including maps of the following:

- Stream corridors, road-stream crossings, and locations where roads are near streams.
- Road systems with alternative routes to provide redundancy to key locations.
- Projected increase in stream bankfull width.
- Expected decrease in snowpack depth and duration.
- Fire intensity in conjunction with steep slopes and soil types susceptible to debris movement.

Maps can be generated using existing mapped information or geographic information system (GIS) databases. Different forests have different datasets, depending on which data are available and which have been entered for forest infrastructure. Where data are not available,

useful information may still be available, such as maps of critical maintenance areas, landslides, stream channels, sites with a history of storm damage, and materials sources for storm damage repairs. This information can help identify high-risk locations, future problem areas, and resources needed to facilitate repairs after significant effects occur.

Watershed Condition Assessments

In 2010, every national forest and grassland in the United States completed a watershed condition assessment at the subwatershed scale (HUC-6; 10,000–40,000 acres). This was conducted using a national Watershed Condition Framework model that rated various factors that influence watershed condition. The model is based on 12 watershed condition indicators, each comprised of various attributes (Potyondy and Geier 2011). Each attribute was rated as good, fair, or poor for each subwatershed based on standard quantitative and qualitative criteria. The attribute ratings were then integrated into a combined rating for each ecological process domain and then into an overall watershed condition score. In the watershed condition classification, road density, condition, and proximity to streams contributed significantly to the ratings.

In addition, 11 national forests throughout the United States that represent each of the nine Forest Service regions conducted pilot assessments of potential hydrologic change resulting from ongoing and expected climate warming (Furniss et al. 2013). Each national forest identified water resources that were important for that national forest, assessed climate change exposure and watershed sensitivity, and evaluated the relative vulnerabilities of watersheds to climate change. The assessments provided management options for responding to projected climate-hydrologic changes.

Transportation Analysis Process

Planning for transportation and access in national forests is included in national forest land management plans. The 2001 Road Management Rule (RMR 2001) requires national forests to use science-based analysis to identify a minimum road system that is ecologically and fiscally sustainable. The goals of transportation analyses are to assess the condition of existing roads, identify options for removing damaged or unnecessary roads, and

maintain and improve necessary roads without compromising environmental quality. Transportation analysis has several benefits:

- Identifies roads that need improvement or decommissioning.
- Establishes a framework to set annual maintenance work and costs.
- Improves agency ability to meet BMP requirements with regulatory agencies.

Consideration of climate change has generally not been a formal part of the analysis.

The Forest Service's Transportation Analysis Process (USDA FS 2008) helps reduce environmental effects and road mileage to levels that can be supported by available financial and human resources. Most infrastructure imposes some costs on the environment, and costs and transportation needs must be balanced to achieve a sustainable and suitable transportation system. This infrastructure assessment is best integrated with Transportation Analysis Process reports and updates as appropriate, including analyses identified in the Forest Service Travel Planning Handbook (USDA FS 2008). Outputs include the following:

- Map of the recommended minimum road system.
- List of unneeded roads.
- List of key issues.
- Prioritized list of risks and benefits associated with changing the part of the forest transportation system being analyzed.
- Prioritized list of opportunities for addressing risks and benefits.
- Prioritized list of actions or projects that would implement the minimum road system.
- List of proposed changes to current travel management designations, including proposed additions to or deletions from the forest transportation system.

This infrastructure assessment can be used to set priorities for improving roads to increase their resilience and reduce environmental effects. The Transportation Analysis Process should be interactive with the Watershed Condition Framework process (Potyondy and

Geier 2011) and vice versa. Most national forests have completed a travel analysis report that differentiates needed roads from those that are unneeded and recommended for decommissioning.

Best Management Practices

Implementing, monitoring, and improving practices for the management of water quality and watershed health are central to adapting to climate change. The publication *National Best Management Practices for Water Quality Management on National Forest System Lands, Volume 1: National Core BMP Technical Guide* provides BMPs for most aspects of forest management, including roads, trails, and recreation (USDA FS 2012). *Volume 2: National Core BMP Monitoring Technical Guide* (USDA FS, n.d.a) provides guidance on monitoring the effectiveness of BMP implementation. These technical guides, which also contain national directives and data management structures, are available for new planning efforts; National Environmental Policy Act analysis; and design, implementation, maintenance, and evaluation of proposed activities, particularly if projects affect water resources. In addition, local BMPs are developed and applied to address site-specific needs and requirements. The publication *Low-Volume Roads Engineering—Best Management Practices Field Guide* (Keller and Sherar 2003) summarizes key BMPs for engineering design and function of roads.

Road and Infrastructure Performance Monitoring

Considerable work has been done to repair forest roads and facilities throughout the West, including storm damage in Sierra Nevada national forests after the declared disasters of 1964, 1983, 1986, 1997, and 2017. Similarly, southern California forests have undergone extensive repair works after fire-related damage or storm events in 1997, 2003, 2011, 2017, 2019, 2020, and 2021. National BMPs require national forests to conduct detailed storm damage assessments to determine the location, extent of damage, cause, and cost estimate for repairs. In the past, these were primarily a paper exercise at a local level, but in recent years, surveys have been conducted using geospatial tools and mobile technology. Storm damage surveys recorded in GIS reveal how proximity to streams or certain geologic and topographic

Surveying roads during or soon after storms ensures timely detection of problems, such as insufficient drainage, unstable slopes, and vulnerable infrastructure. Observation of problems caused by storm runoff improves understanding of the causes of failure and of

designs and prescriptions that reduce the likelihood and consequences of future failures. Over time, this kind of monitoring illustrates how and where infrastructure can fail and informs the improvement of practices that reduce adverse effects on water quality and watershed function.

The Forest Service, with the help of the U.S. Department of Transportation, John A. Volpe National Transportation Systems Center, produced the *U.S. Forest Service Transportation Resiliency Guidebook: Addressing Climate Change Impacts on U.S. Forest Service Transportation Assets* (USDA FS 2018). The guidebook uses a conceptual framework for practitioners at

DSR+ DSR Supplemental Data Sheet (Replaces/Augments "Description of Damage" Block)	
DSR Reference _____ TYPE AND CAUSE OF FAILURE ☐ Stream crossing ☐ Plugged ☐ By wood ☐ By sediment ☐ By wood and sediment ☐ Too much water for culvert ☐ Fill erosion % of fill removed _____ ☐ Diversion of stream down road or ditch - Approx. length of diversion _____ ft. - Receiving feature ☐ Next crossing ☐ Cross-drain ☐ Hillslope ☐ Cross-drain ☐ Plugged ☐ Diverted ☐ Landslide from above ☐ Within 100 feet ☐ 100-1000 feet above ☐ > 1000 feet ☐ Landslide originating at road ☐ Cutslope failure ☐ Fill or sidecase failure ☐ Running surface slump ☐ Stream undercutting	☐ Gully ☐ Excessive road surface runoff ☐ Excessive ditch flow ☐ Cascading cross-drain failure ☐ Gully from above ☐ Other: _____ ESTIMATED VOLUME Estimated total volume of earth moved by the erosional event ☐ <10 yds ☐ 10-100 ☐ 100-1000 ☐ 1000-10,000 ☐ >10,000 ESTIMATED DELIVERY Estimated % of material that _____ Is on road _____ Is within 50 feet of a stream* _____ Was deposited within 50 of a stream _____ Was deposited in a stream Notes: _____
* Any stream, including draws and ephemeral streams. Does not need to be "live" or flowing at the time of inspection.	

Figure 4.11—A supplemental Damage Survey Report (DSR+) form used to complement the Federal Highway Administration DSR form by allowing for categorical analysis of roadway failures and documentation of damage.

a local level to consider climate change and prepare for effects on the transportation system. The guidebook can also be used to help communicate risk associated with climate change to decision makers. A high-level analysis, as outlined in the guidebook, allows practitioners to rapidly assess transportation vulnerabilities and prioritize high-risk areas. The guidebook highlights how a transportation system can be made more resilient to potential climate change effects when funding is available to support implementation.

Burned Area Emergency Response (BAER)

The objectives of the BAER program are to determine the need for and to prescribe and implement emergency treatments on federal lands to minimize threats to life or property resulting from wildfire effects, or to stabilize and prevent degradation to natural and cultural resources. In most cases, only a portion of the burned area is treated. Focal areas are severely burned areas; steep slopes; places where water runoff will be excessive; and fragile slopes above roads, trails, and campgrounds and other valuable facilities. The treatments must be installed as soon as possible, generally before the next damaging storm. Timely action is critical for effective treatments.

BAER efforts identify needed watershed and infrastructure measures for rehabilitation of burned areas after a wildfire, as well as measures to limit further resource damage. The BAER treatments catalog (Napper 2006) presents instructions, monitoring tools, and references that BAER assessment and implementation teams use to identify appropriate treatments. The catalog describes treatments for land, channels, roads and trails, and protection and safety. Readers learn the primary treatment use, the purpose and objective of the treatment, suitable locations for treatment implementation, and cost factors. Treatment effectiveness information includes benefits and limitations of treatments, although some of this information is limited or anecdotal. BAER teams need to validate specific treatment effectiveness in the affected area before recommending its use. BAER implementation team members can familiarize themselves with project design and implementation information as they review design considerations, tools and equipment, construction specifications, and safety considerations.

BAER teams can recommend a variety of emergency stabilization techniques. Reseeding of ground cover with fast-growing native (or in some cases nonnative) species and mulching with straw or chipped wood are common hillslope stabilization techniques. The team also assesses the need to modify road and trail drainage mechanisms by installing debris traps, modifying or removing culverts to allow drainage to flow freely, adding trash racks, or adding drainage dips and constructing emergency spillways to keep roads and bridges from washing out during floods. Refer to the BAER webpage (USDA FS, n.d.b) for more information about the BAER program.

Emergency Relief for Federally Owned Roads

The Emergency Relief for Federally Owned Roads Program (ERFO) was established to assist federal agencies with repair or reconstruction of tribal and federal lands transportation facilities, including federal roads that are open to public travel and have suffered serious damage from a natural disaster over a wide area or by a catastrophic failure (USDOT FHWA 2014). The intent of ERFO is to pay the unusually high costs of repair and reconstruction of eligible facilities, both emergency repairs and permanent repairs, with a minimum threshold of eligible repairs of \$700,000 for each event. Recent ERFO projects in southern California national forests were implemented in 2003, 2011, 2017, 2019, 2020, 2021, and 2022. During the past 15 years, ERFO expenditures on these forests have exceeded many millions of dollars.

Emergency repairs are those undertaken during or immediately after a disaster to restore essential traffic, minimize the extent of damage, or protect remaining facilities. Prior approval is not required for emergency repairs, but all other eligibility requirements of the program apply. Permanent repairs are those undertaken after a disaster to restore facilities to their predisaster conditions. Prior approval is required. ERFO assists federal agencies that are responsible for roads that meet the definition of “open to public travel.”

ERFO regulations require that damaged roads be repaired to restore traffic. In most circumstances, this limits repairs to a similar type of road in the same location, or replacement in kind. To incorporate climate-smart practices that improve transportation resiliency, the agency responsible for the damaged roads must provide

additional funding for the work. Although this limitation is frustrating to forest engineers with limited funds, this additional work may be essential in areas where a road is at risk to climate-induced changes in hydrologic regimes, including extreme events (e.g., floods, landslides). This is especially true for roads already in high-risk locations, such as floodplains or alluvial fans.

To reduce risk of future failure due to climate-induced changes, the Federal Highway Administration's Office of Federal Lands Highway can collaborate with other federal agencies to help develop best resiliency practices to incorporate improved climate-adaptation practices and specifications (USDA FS 2018). This can improve climate resilience, ensure durable investments, and

promote a sustainable transportation system on federal lands. Refer to the ERFO webpage (USDOT FHWA 2024) for more information about the ERFO program.

Other Considerations

Although experienced engineers and maintenance personnel may be knowledgeable about historical and current system patterns, future climate conditions are uncertain and may be underestimated. Local knowledge from specialists who have historical information about sites and trends can be particularly useful. Box 4.4 presents questions that can be addressed during an assessment process for specific design issues discussed below. By considering these questions, many of the infrastructure vulnerabilities and potential problems can be identified.

Box 4.4

Questions that Help Assess the Condition and Vulnerability of Infrastructure

Road maintenance:

- Does the road need maintenance?
- Are road ruts likely to concentrate water?
- Are culverts damaged, plugged, or in need of cleaning?
- Are rolling dips too worn to direct the water off the road?
- Do ditches need cleaning or armoring to prevent downcutting?

Road surface drainage:

- Is water draining from the road?
- Where is the water concentrated?
- Are the road-surface soils erodible?
- Which surface drainage measures will be most effective?
- Are the ditches stable, functioning properly, or in need of armoring?
- Are there enough cross drains or dips?
- Where can the water be reasonably discharged?

Culvert vulnerability:

- Does the culvert have a potential or history of plugging?
- Is the culvert damaged or known to be poorly installed?
- Does the structure have adequate capacity for anticipated future flood flows?
- Was there a recent fire or flood upstream of the culvert or stream crossing?
- Are trash racks or diversion prevention measures needed?
- Would a stream-simulation design be the best long-term solution?

Fords and low-water crossing setting and condition:

- Is the road a noncritical route or is there alternative access to the area?
- Is traffic use low and are occasional traffic delays acceptable?
- Is the channel ephemeral or does it have relatively low base flow?
- Does the watershed have large flow fluctuations or have a "flashy" response?
- Does the channel carry a large amount of debris or have debris immediately upstream of the crossing?
- Is the channel entrenched (broad and flat versus deep)?
- Is a low-water crossing the most cost-effective structure?

Bridge condition and needs:

- Is the channel near a bridge free of obstructions and vegetation?
- Is the stream channel aggrading or degrading?
- Is the channel subject to meander and likely to shift laterally?
- Does the bridge have adequate capacity and freeboard?
- Does the bridge have potential scour problems?
- Is there heavy vegetation around the structure?

Streambank stabilization:

- Is the road in a vulnerable location with respect to encroachment by a stream?
- Is the road in a channel migration zone? How much will future streamflows vary?
- Can the road be reasonably moved?
- Which roadway and streambank protective measures are reasonable?

Erosion prevention and erosion control:

- Is there concentrated waterflow across the soil?
- Are areas with erosive soil exposed and likely to erode?
- Do erosion-control measures need to be replaced?
- Does existing vegetation have shallow or deep roots?
- Are gullies starting to form where water leaves the road?

Slope stabilization and failure potential:

- Is the slope over-steepened, considering typical stable slope criteria?
- Does the slope have a history of instability, with large or small failures?
- Is the fill slope placed with “sidecast” construction on slopes over 60 percent?
- Are there signs of moisture or seepage on the slope?
- What is the risk of damage from a failure?

- Which stabilization options will be adequate and most cost effective?
- Do fires plus heavy rains have the potential to cause debris flows?

Trails:

- Will the timing of trail use change from traditional use periods?
- Is the trail surface hardened to accommodate early-season use?
- How will the trail be maintained after increased use?
- Does the trail surface concentrate water?
- Is the trail clear of hazard trees?
- Do trail bridges have adequate hydraulic capacity and scour protection?

Facilities:

- Will the facility withstand stronger storms and heavier rain?
- Is building insulation adequate to be comfortable with higher temperatures?
- Is clearing around facilities adequate to provide defensible space for fire suppression?
- Are fire-resistant materials used in construction?
- Are campgrounds located in safe locations from floods, debris flows, rockfalls, etc.?
- Are warning systems and evacuation routes identified for disasters?
- Are water systems likely to be depleted during drought periods?

Dams:

- Is there adequate “freeboard” on the dam?
- Are outlets functioning properly?
- Is the spillway clear and does it have adequate capacity?
- Is there heavy vegetation on the dam that can burn?
- For a high-hazard dam, does it have an emergency action plan distributed to all proper authorities?

Like natural resource categories (vegetation, wildlife, etc.), infrastructure can be analyzed in a structured, detailed manner based on vulnerability components: exposure, sensitivity, and adaptive capacity (IPCC 2014). Exposure is the potential for infrastructure to be subjected to climate stressors, such as flooding and wildfires. Sensitivity is the degree to which infrastructure would be affected by exposure to climate stressors. Adaptive capacity is the ability of infrastructure to adjust to potential effects from a climate stressor (Furniss et al. 2018), with the goal of resilience. Resilience enhances the capacity of ecosystems and infrastructure to withstand the effects of climate stressors without irreversible change or damage (Peterson et al. 2011).

Effects of Climate Change on Infrastructure

Climate change is expected to cause a significant increase in temperature and longer periods of drought (Pierce et al. 2018). Increased fire frequency and extent are likely to produce the greatest effects from climate change. Climate change in the SOCAAP assessment area is projected to cause the temperature to increase by 4 to 7 °F by the end of the 21st century (see chapter 2). The 10 warmest years of the 20th century occurred within its last 15 years. Also, models show at least a doubling of summer heat-wave days by mid-century in the Los Angeles area (USDI NPS 2011). A detailed discussion of climate change forecasts and effects for southern California is presented in chapter 2.

Higher temperatures and more droughts will likely increase the frequency and severity of wildfires, reducing or depleting some groundwater resources. Higher temperatures, higher evapotranspiration, and less available surface and subsurface moisture will likely reduce groundwater supplies and adversely affect water systems and dam management. Fewer water sources will likely be available for construction projects, fighting wildfires, and recreation sites and campgrounds (as well as domestic use), particularly in late summer and the fall. In addition, warmer, drier summers may increase dust problems for forest roads and facilities.

Total precipitation is expected to decrease slightly by mid-century. By the end of the 21st century, interior forests in southern California are projected to have a

slight decrease in precipitation, whereas coastal forests will likely have a slight increase in precipitation (depending on the global climate model and greenhouse gas emission scenario). However, precipitation intensity is anticipated to increase by about 7 percent per degree Celsius of warming, suggesting a potential increase in flash floods and debris flows (Prein et al. 2017). Dry periods and droughts will likely be exacerbated in a warmer climate. Overall, models predict up to 10–15 percent less precipitation in the Southwest (USDI NPS 2011). Higher temperatures will likely result in a higher proportion of precipitation as rainfall and less snowfall in the higher peaks of San Bernardino and Angeles National Forests.

Summaries of historical mean temperature and precipitation in southern California, as well as projected future values, are provided in chapter 2. Extreme events such as atmospheric river weather patterns, plus seasonal Santa Ana winds, will likely occur periodically, creating extreme events. Figure 4.12 shows the 24-hour heavy precipitation in southern California and the Los Angeles basin from a major storm in February 2019. Although individual storms may be larger, the time between storm events is expected to be longer (Polade et al. 2017).

Anticipated effects on infrastructure include periodic extreme flows and debris flows that will create stress on the current designs of culverts and old bridges. More intense rains will likely cause erosion and mobilize sediments, damaging local road cross-drain culverts and channels. Flood-damaged roads, combined with limited funding to repair them, will likely reduce agency capability to respond to wildfires and other large disturbances. Effects on infrastructure are projected to be more severe than in the past, both from floods and drought-related fires. Many damaging runoff events following fire have occurred in the SOCAAP assessment area following short-duration, high-intensity rainstorms associated with narrow cold-frontal rainbands, convective thunder cells, and monsoonal flows (Oakley et al. 2025). Global ocean warming and sea-level rise are expected to accelerate, and the latter may increase by 1.6 to 3.3 feet in height by 2100. This will likely affect coastal forest areas on the Los Padres National Forest and contribute to coastal erosion and associated instability problems as slopes become undermined or over-steepened. Additional slope stabilization expenses are likely.

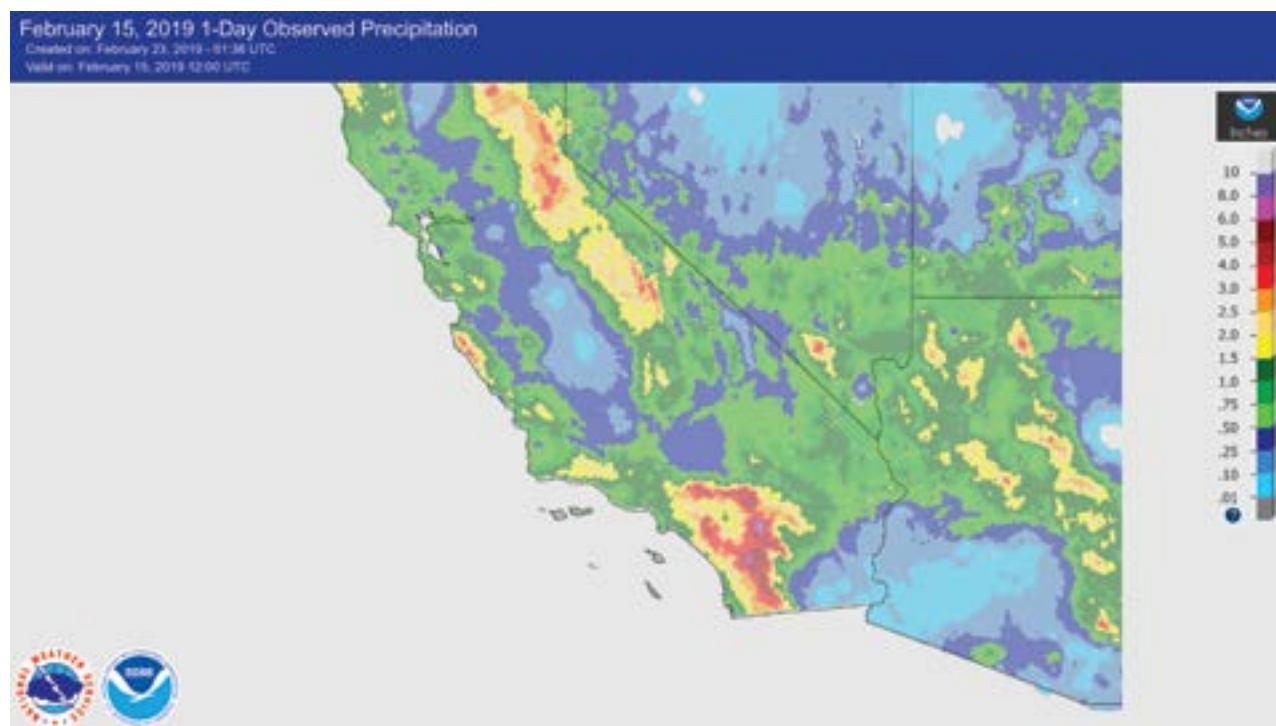


Figure 4.12—Observed 1-day (24-hour) heavy precipitation in southern California during a February 15, 2019 storm event. Source: U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Weather Service.

Potential benefits of milder winters and less rain or snowpack include lower costs for snow removal, a longer construction season for high-elevation projects, earlier access to mountain recreation areas on roads and trails, and less damage to paved and unpaved roads because of a dryer, stronger subgrade. Conversely, extreme heat from heat waves and fires may damage pavement asphalt binders. The disadvantages of climate change appear to greatly outweigh the advantages, but more flexibility will likely help many aspects of forest management adapt to uncertain climatic patterns.

Wildfire Effects, Fire Resilience, and Postfire Watershed Hydrology

Wildfires and associated effects are the greatest threat to infrastructure on federal lands in southern California. Fire suppression efforts demand a great deal of money and resources, and buildings, culverts, timber bridges, walls, signs, wooden structures, pavements, and campgrounds can suffer considerable damage. After a fire, erosion rates increase, sedimentation problems persist, and fires followed by intense storms create frequent

washouts, sediment-laden floods, debris flows, stream debris torrents, rockfall, and landslides (fig. 4.13). Most offsite damage downslope or downstream of a fire area occurs in the first few years after the fire and before the area can be revegetated. In some cases, hydrophobic soils initially accelerate erosion but regain their permeability with time.

In the past 40 years, more than 10,000 fires (more than 10 acres in size) have occurred in the SOCAAP assessment area. Although annual fire frequency has not increased in recent years, area burned has increased during a period of higher temperatures, longer periods of drought, and high fuel loads in forests. Steep, complex terrain combined with very dry fuels and strong Santa Ana winds produce some of the most severe fire weather and fire effects in the United States. Although southern California chaparral and forest ecosystems are fire adapted, climate change is projected to increase mean annual area burned by 42 percent in the San Gabriel Mountains (under RCP 8.5) (Wilder et al. 2020).

Significant recent fires in southern California include Old and Grand Prix Fires (2003), Cedar Fire (2003), Piru Fire (2003), Harris Fire (2007), Zaca Fire (2007), Witch



Figure 4.13—Postfire effects: as shown here, erosion rates increase, sedimentation problems persist, and fires followed by intense storms create frequent washouts, debris flows, stream debris torrents, rockfall, and landslides. Top photos by Joshua Direen, USDA Forest Service, San Bernardino National Forest; bottom photos by Allen King.

Fire (2007), Station Fire (2009), La Brea Fire (2009), Thomas Fire (2017–2018), Woolsey Fire (2018), Cranston Fire (2018), Holy Fire (2018), Saddle Ridge Fire (2019), Cave Fire (2019), Bobcat Fire (2020), Dolan Fire (2020), and Willow Fire (2021).

Many resiliency measures are available to reduce the risk of infrastructure damage by fires and to adapt to a warmer climate with more fires. Actions that can reduce infrastructure risk include reduction of fuel loads around structures (surface fuels and live vegetation), construction of defensible fuel profile zones, and shaded fuelbreaks. The National Fire Protection Association’s Firewise USA program (NFPA 2025) offers useful brochures, including *How to Prepare your Home for Wildfire*. These preparations include clearing around a structure, removing flammable material from the perimeter of the structure, sealing porches, sealing soffits and windows, and having flame-resistant siding and roofing materials.

Although many measures can reduce risk to structures, major modifications are often impractical because funding is lacking; modifications are most likely to

happen when a structure is replaced.² The publication *Recovering from Wildfire in Southern California Forests: A Guide for Forest Landowners* (Kocher et al. 2008) offers useful information on postfire assessment and wildfire recovery actions to minimize current and future damage. Measures include removing dead and dying vegetation, erosion and drainage control, addressing roadway needs, evaluating flood risk, and reforestation. Other specific onsite and offsite adaptation measures are discussed throughout this report.

Short-duration, high-intensity precipitation events can generate flash floods and runoff-induced debris flows after wildfires (Cannon et al. 2008, Kean et al. 2016). Postfire runoff will increase in both peak discharge and total volume, depending on the soil type, fire intensity, and vegetation and terrain characteristics. The effects of fire on runoff and sediment yield are illustrated by Quinn (2018). Lack of vegetation and unconsolidated soils lead

² **Globokar, D. 2023.** Personal communication. Chief facility manager, Santa Monica Mountains National Recreation Area, 26876 Mulholland Highway, Calabasas, CA 91302.

to increased sediment in drainages. The term “bulking” has been defined as increasing the water discharge to account for high concentrations of sediment in the flow. Mud and debris flows, which can significantly increase the volume of flow transported from a watershed, most often occur in mountainous areas subject to wildfires and subsequent soil erosion, and in arid regions near alluvial fans and other areas of geomorphic and geologic activity.

Waterflow may have suspended sediment concentrations of 5–10 percent sediment by volume. Hyperconcentrated flows such as mudflows and debris torrents can have a sediment concentration of 5–60 percent, and debris flows can have suspended sediment concentrations of more than 60 percent sediment by volume (Wilder 2020). Postfire peak streamflows can exceed unburned peak flows by one to two orders of magnitude caused by increased runoff and sediment bulking (Kean et al. 2016, Neary et al. 2003). Hydrologic changes after a high-intensity fire, particularly on steep terrain, can cause significant flooding and debris flows with a 1- to 2-year storm event. A relatively common postfire precipitation event with a return period of 1–10 years can produce a 1,000-year flood event (Fraser et al. 2020).

In addition to peak rainfall intensity and burn severity, watershed size and time after the fire influence streamflow rate per unit area. Peak hourly rainfall intensities more than 0.4 inches per hour can produce relatively large flows, whereas intensities that are more than 1.2–1.6 inches per hour can produce major flows and landslides. Because of the spatial heterogeneity of rainfall and variation in intensity over time, small watersheds (0.5–4 square miles), are most likely to have large magnitude runoff per unit area compared to larger watersheds (Wilder 2021).

For the design of facilities in areas that are prone to high sediment and debris concentrations, a bulking factor is often used. Application of a bulking factor can help determine flood risk and provide information to determine an adequate size for debris retention structures. Los Angeles County Department of Public Works’ *Sedimentation Manual* (LAC DPW 2006) and the *Sediment/Debris Bulking Factors and Post-fire Hydrology for Ventura County* (WEST Consultants, Inc. 2011) provide engineering designs for flood and sediment retention systems under different bulking and

watershed conditions. Equations, nomograms, and tables are provided for different design scenarios. The Federal Highway Administration publication *Debris Control Structures: Evaluation and Countermeasures* (Bradley et al. 2005) provides information on available debris control measures for bridges and culverts. The National Weather Service’s publication *Post-Wildfire Flash Flood and Debris Flow Guide* (USDC NOAA NWS 2015) offers postfire flooding advice on emergency preparedness and disaster supply kits as well as sources for current weather information.

Storm events that led to significant death and damage include the Old Fire and Grand Prix Fire in San Bernardino National Forest (2003), in which debris flows following a storm led to destruction of forest facilities and 15 deaths (Cannon and DeGraff 2009) (fig. 4.8). One month after the Thomas Fire in Los Padres National Forest (2017–2018), record rainfall produced debris flows that damaged 558 downslope structures and killed 23 people in Montecito and Carpinteria (Kean et al. 2019). Figure 4.14 shows the burned forest watershed from the Thomas Fire and damage to buildings and infrastructure in Montecito. The Dolan Fire in Los Padres National Forest (2020) produced a debris flow in the Rat Creek watershed that plugged a major culvert and closed California State Highway 1 along the Monterey coast (fig. 4.9).

BAER teams rapidly assess burned watersheds to determine emergency protection measures for affected watersheds, infrastructure, and nearby communities at risk from elevated peak flows or debris flows. Emergency protection measures include early warning systems, storm patrols, structure protection, channel clearing, installation of bollards and trash racks, debris retention structures, and road-stream crossing upgrades (fig. 4.15). To determine flood risk in affected watersheds, the 1949 RCS (Rowe, Countryman, and Storey) model—an empirical method that provides a rapid estimate of postfire streamflow—is often used. However, it has been shown to be inaccurate for small- to medium-sized watersheds because it lacks some key watershed and fire parameters. Recent efforts by the California Department of Forestry and Fire Protection, California Geological Survey, and others have used machine learning and data analysis of recent flood events to improve the forecasting (Wilder et al. 2020).

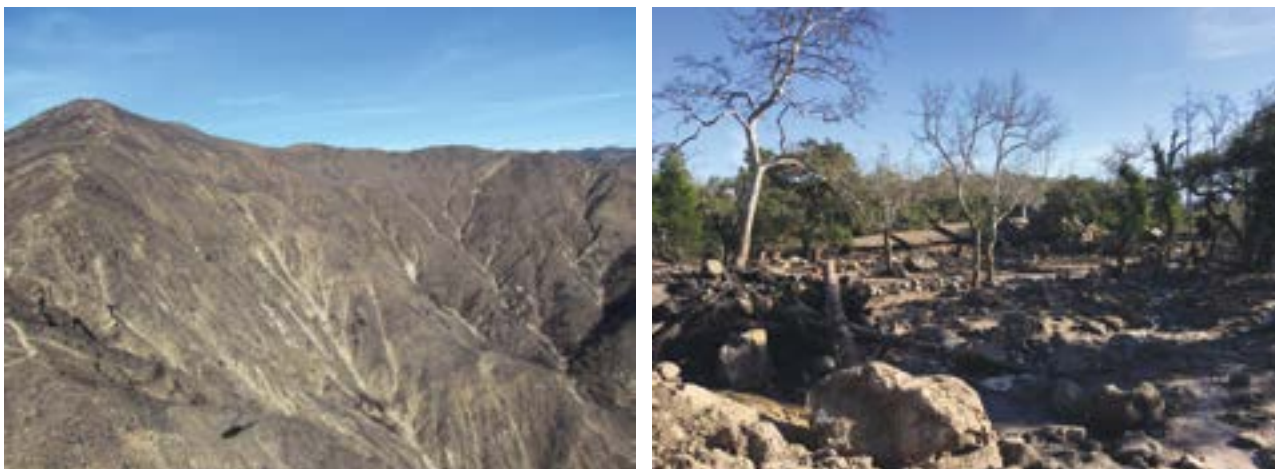


Figure 4.14—Burned upper watershed from the 2017–2018 Thomas Fire (left) and damage from a postfire debris flow downstream in Montecito, California (right). Note that rills, small gullies, and debris flows are beginning to form on the hillside in the watershed. Photos by Donald Lindsay.



Figure 4.15—Examples of debris-flow adaptation measures, including the installation of bollards (left) in a channel to trap large debris and a debris retention structure using a ring-net (right). Photos by Donald Lindsay.

The U.S. Geological Survey often assists federal agencies in landslide hazard mapping and identifying areas of high debris-flow risk after forest fires (Cannon and DeGraff 2009, DeGraff et al. 2011, Tillery and Matherne 2013). Figure 4.16 shows an example of debris-flow hazard mapping for a burned watershed, showing the percentage probability of a debris flow occurring under specific rainfall intensities and durations (often a peak 15-minute rainfall intensity of 1 inch per hour). Figure 4.17 is a detailed example of values (infrastructure) at risk because of debris-flow hazard.

Debris-flow hazard is a combination of the predicted likelihood (Staley et al. 2016) and volume (Gartner et al. 2014) of debris flow. For example, the most hazardous basins have both a high probability of occurrence and

an estimated large volume of material. The lowest relative hazard would be for basins that have low probabilities and the smallest volumes. Additional information on debris-flow hazard mitigation and adaptation measures is in the below section on “Slope Stabilization.”

Mitigation programs have a limited ability to respond to or prevent postfire flooding and debris-flow events. Damaging events are driven by multiple variables for drainage characteristics, topography, fire severity, rainfall timing and intensity, and climate change. Forecasting and modeling efforts have improved with time but still contain high uncertainty. However, a risk-based approach is still useful for identifying and prioritizing infrastructure vulnerabilities. Robust solutions include adapting the infrastructure to withstand an event with armoring



Figure 4.16—Example of a U.S. Geological Survey debris-flow hazard map with debris-flow probabilities for the 2019 Cave Fire, Los Padres National Forest.

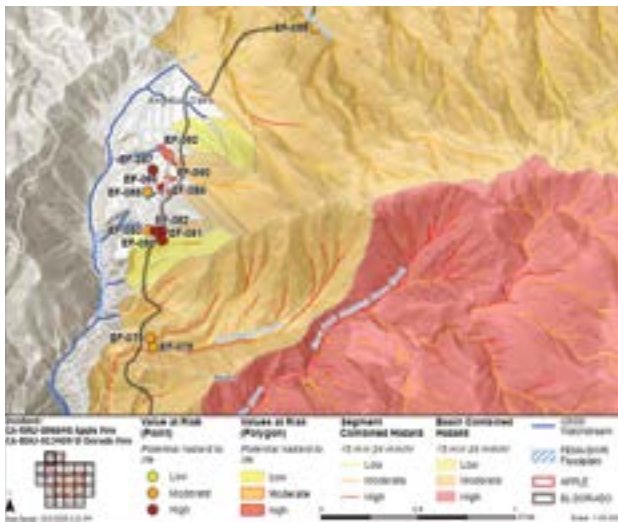


Figure 4.17—Example of a detailed debris-flow hazard map showing specific values at risk with debris-flow hazard ratings and specific values at risk (infrastructure buildings and California State Highway 38) relative to modeled combined hazard class by basin (polygons) and stream segments (lines). The combined hazard is defined by the U.S. Geological Survey and is a function of the predicted debris-flow likelihood coupled with the debris-flow volume. Figure by Donald Lindsay, California Geological Survey.

and strengthening structures or moving infrastructure to lower risk areas. Resilience-based engineering recognizes that fail-safe designs are unlikely, so in some cases, failures may need to be accepted and managed. Management and engineering strategies include redundant road systems, some infrastructure abandonment, and replaceable low-cost infrastructure use (Fraser et al. 2020).

Low-intensity wildfires can be beneficial for a healthy forest. In such cases, most leaves or needles remain on trees, only shrubs and young trees are burned, and the soil surface retains large woody debris. Damage to infrastructure is often minor, and watershed response is limited. High-intensity fires (typically crown fires) consume a large amount of foliage and other organic matter (including the forest canopy), and the intense heat can create a hydrophobic soil condition. Hydrophobicity occurs when accumulated duff on the forest floor burns and releases a waxy substance that penetrates into the top few inches of soil. The water repellency is a bit like covering the soil with a sheet of plastic. This hydrophobic condition reduces hydraulic conductivity and the capacity for soil to infiltrate rainwater, causing large runoff events (Larsen et al. 2009, Woods and Balfour 2010) and increasing the risk of extreme watershed responses and damaged infrastructure.

Adapting Transportation Infrastructure to the Effects of Climate Change

Roads, trails, bridges, and other infrastructure in the SOCAAP assessment area were developed over more than a century to provide access for mineral prospectors, loggers, hunters, and recreationists. Transportation infrastructure provides access that is largely determined by where these activities historically occurred in relation to land management objectives. National forests, national parks, and other federal lands are intended to protect water supply, timber and range resources, and wildlife and to provide multiple uses and enjoyment by the public. Access to public lands promotes use, stewardship, and appreciation of their value as a resource contributing to local quality of life (Louter 2006). Today, reliable and strategic access is critical for people to recreate, extract resources, monitor and manage resources, and respond to emergencies (Strauch et al. 2014).

The location of roads and trails can increase vulnerability of the transportation infrastructure to climate change. Many roads and trails were built on steep slopes because of the rugged topography in southern California, and cutslopes and side-cast material have created landslide hazards. Past resource extraction and development and their associated road network have contributed to the sensitivity of existing infrastructure by increasing storm runoff and peak flows that affect road-crossing structures (Croke and Hairsine 2006, Schmidt et al. 2001, Swanston 1971).

The four national forests in southern California contain 4,788 miles of roads (table 4.2) and 3,211 miles of trails (table 4.3), with the largest number of trails in Los Padres National Forest. Of the existing roads, 1,644 miles are suitable for passenger vehicles (typically gravel or paved surface), 2,802 miles are suitable for high-clearance

vehicles such as a pickup, and the remaining 342 miles are currently in storage and closed to vehicles. Roads are reasonably well distributed on all four forests.

Trail bridge data is from the Forest Service Infra database. Roads and trails cross many streams and drainages, and most road-stream crossings are culverts or bridges that were installed decades ago. Many roads and trails were constructed in valley bottoms near streams or on alluvial fan deposits to take advantage of gentle grades, but proximity to streams increases sensitivity to flooding, degrading aquatic resources, altering channel migration, increasing bank erosion, shifting the location of alluvial fans and debris cones, and increasing the risk of road damage. Most road-stream crossings use culverts rather than bridges, and culverts are generally more sensitive than bridges to increased flood peaks and associated debris

Table 4.2— Road miles and estimated road deferred maintenance and repair costs for passenger car systems for national forests in the Southern California Adaptation Partnership assessment area

National forest	Basic custodial care ^a	High-clearance vehicle system ^b	Passenger car system ^c	Total road system	Passenger car system cost ^d
MILES				DOLLARS	
Angeles	77	690	404	1,171	54,011,204
Cleveland	53	516	304	873	40,266,252
Los Padres	48	758	656	1,462	67,433,288
San Bernardino	164	838	280	1,282	59,130,968
Total	342	2,802	1,644	4,788	220,841,712

^a Roads placed in storage (>1 year) between intermittent uses. Basic custodial maintenance is performed. Road is closed to vehicles.

^b Open for use by high-clearance vehicles.

^c Open for and maintained for travel by a prudent driver in a standard passenger car.

^d Cost for passenger car, road-deferred maintenance is \$46,124 per mile based on data generated from a 2017 sample of the Forest Service passenger car system throughout the United States. This is not statistically valid at a regional scale but is adequate for estimation purposes. Cost per mile for high-clearance vehicle roads and basic custodial care cannot be estimated confidently and is therefore not included.

Table 4.3—Trail miles and trail bridges for national forests in the Southern California Adaptation Partnership assessment area

National forest	System trails	Motorized trails	Nonmotorized trails	Number of trail bridges
MILES				
Angeles	704	62	642	25
Cleveland	364	37	327	4
Los Padres	1,433	377	1,056	5
San Bernardino	710	75	635	10
Totals	3,211	551	2,660	44

(Furniss et al. 2018). Roads and transportation infrastructure are often the highest value built assets affected by climate stressors (Fraser et al. 2020). Fortunately, many vulnerability adaptation measures exist (box 4.1) that can be cost effective and effectively implemented to reduce the likelihood of storm damage and minimize adverse environmental effects. Cost-effectiveness varies among treatments. Many surface drainage measures and vegetative erosion control treatments are cost effective because of their low cost and long-term benefits (box 4.3).

Box 4.5 lists key references for adaptation measures that reduce the vulnerability of roads to storms. Inadequate road drainage facilities and practices are typically the highest priority for adaptation treatments, including road surface-drainage measures, drainage crossing structures, and channel problems that can lead to

structural failures and watershed damage. Relatively inexpensive road-surface drainage-improvement measures are particularly cost effective and can prevent significant road damage, hillslope erosion, and sediment delivery to streams. Drainage-crossing structures also need to be capable of handling increased flow volumes after fires from sediment loads and bulking when subject to debris torrents or debris flows. Box 4.6 shows a comparison of typical prefire and postfire runoff from a small watershed. The increase in runoff volume is caused by several factors, including more hillslope runoff, faster runoff, and a likely increase (statistically) in rainfall intensity because of the faster runoff (shorter time of concentration).

Transportation-infrastructure adaptation treatments, discussed in the following sections, are grouped as shown below. Each of these topics is significant in

Box 4.5

Key References for Road and Infrastructure Adaptation

Burned Area Emergency Response Treatments Catalog (Napper 2006)—This U.S. Department of Agriculture, Forest Service publication describes several drainage, channel, and erosion-control treatments for minimizing damage from storms after a wildfire. Treatments also apply to risk reduction of storm damage.

Climate Adaptation: Risk Management and Resilience Optimization for Vulnerable Road Access in Africa: Engineering Adaptation Guidelines (Le Roux et al. 2019)—This is a compilation of risk reduction methodologies developed in Africa.

Climate-Resilient Infrastructure: Adaptive Design and Risk Management (ASCE 2018)—This publication discusses methods for defining and dealing with climate change, monitoring, and adaptive design methods developed for infrastructure, particularly those dealing with floods.

Highways in the River Environment—Floodplains, Extreme Events, Risk, and Resilience (Kilgore et al. 2016)—This U.S. Department of Transportation, Federal Highway Administration publication offers technical guidance and methods for assessing the vulnerability of transportation facilities to extreme events and climate change in riverine environments.

Natural Disaster Reduction for Roads (PIARC 1999)—This World Roads Association publication outlines disaster prevention measures for infrastructure.

Storm Damage Risk Reduction Guide for Low-Volume Roads (Keller and Ketcheson 2015)—This U.S. Department of Agriculture, Forest Service publication discusses a range of options for nonrecurring treatments on existing or future low-volume roads that reduce the potential for resource impacts and damage resulting from storm events.

Synthesis of Approaches for Addressing Resilience in Project Development (Choate et al. 2017)—This U.S. Department of Transportation, Federal Highway Administration publication discusses many adaptation strategies and measures for roads and highways, both in a coastal and upland environment.

Box 4.6**Comparing Prefire and Postfire Runoff Using the Rational Method**

The Rational Method has long been used to calculate discharge from small watersheds (ideally 250 acres or less). The Rational Formula (using English units) is:

$$Q = C i A$$

where:

Q = peak flow (runoff); units are cubic feet per second

C = runoff coefficient, which reflects watershed characteristics such as topography, soil type, vegetation, and land use

i = mean rainfall intensity for a selected frequency and duration equal to the time of concentration; units are inches per hour

A = area of the watershed; units are acres

Under preburn conditions, the watershed drainage area (A), watershed characteristics (C), and a rainfall intensity (i) are selected. Rainfall intensity depends on the mean time of concentration for the unburned watershed and is based typically on years of rainfall intensity data, as shown in the typical rainfall intensity-duration-frequency (IDF) family of curves below.

The intensity of storms is projected to increase, so for any rainfall intensity used in the past for any return frequency, a higher value should be chosen today, or one can consider moving up one frequency curve (that is, from a 25-year curve to a 50-year curve).

Under postfire conditions, several factors change. The characteristics of the watershed change, so the runoff coefficient (C) changes. In an unburned forest watershed, the mean C might be 0.25. Once the vegetation is removed in a fire, C might increase to 0.60–0.80 because more rainfall will run off without vegetative cover, particularly if the fire has created a hydrophobic soil surface. C can exceed 1.0 because of sediment “bulking” following a fire (Kean et al. 2016).

The flow velocity will increase on a bare

slope, so the time of concentration of flow will decrease. Overland flow velocity might double for a barren slope compared to a well-vegetated slope (if velocity doubles, travel time will be one-half). As the time or duration (typically in minutes) decreases, the selected rainfall intensity increases (on any frequency curve [see below]). Thus, **an increased C and increased i lead to substantially higher runoff, or flows.**

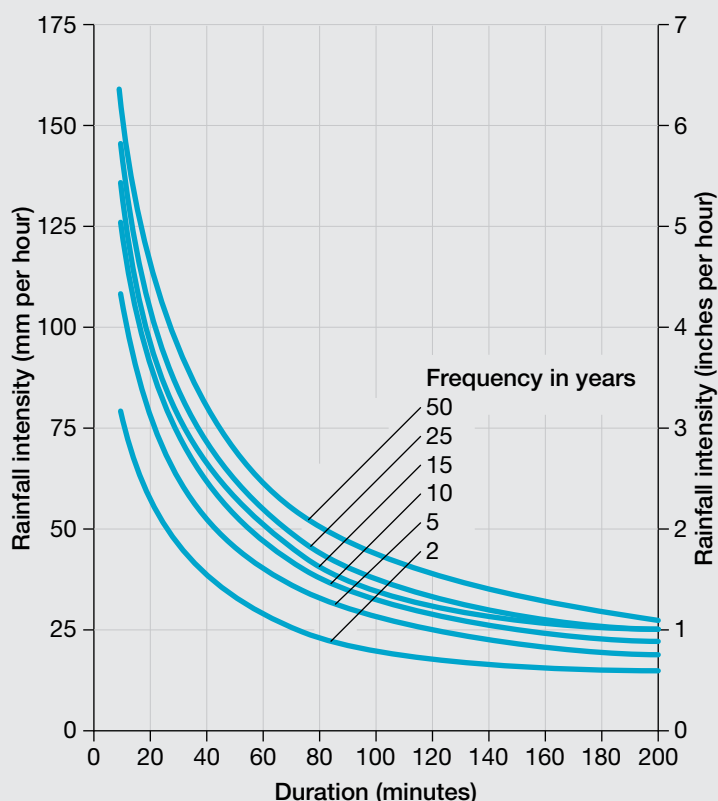
Prefire example

$$Q = C i A = 0.25 \times 3 \times 200 = 150 \text{ ft}^3 \text{ per second flow}$$

Postfire example (plus increased climate change rainfall intensity)

$$Q = C i A = 0.70 \times 4.5 \times 200 = 630 \text{ ft}^3 \text{ per second flow}$$

Therefore, **flow has increased by a factor of 4.** Note that this example does not consider bulking and increased sediment and debris in the flow.



A typical family of rainfall intensity-duration-frequency (IDF) curves (Source: Schall et al. 2008).

road and trail design and management, and each can be affected by climate change-induced droughts, fires, and floods:

- Road maintenance
- Road management
- Road-surface drainage
- Culverts
- Fords and low-water crossings
- Bridges
- Streambank stabilization
- Erosion prevention and erosion control
- Slope stabilization
- Other roads issues
- Trails

Each category has preventive measures that are relatively simple to implement or are cost effective (box 4.3). Other less common measures include structure replacement, road relocation, major rehabilitation, and structural improvements. These expensive actions need justification during the assessment process based on analysis of risk, potential damage, need, and cost-effectiveness. Many adaptation treatments are site specific, so field analysis and good judgment are needed for prescribing and designing on-the-ground treatments. An analysis team with knowledge of an entire road system must weigh the benefits of high-cost treatments at a few sites

versus treatment of a larger number of lower cost sites. However, given climate uncertainty, taking an incremental approach to implementing adaptation measures is realistic, especially given funding limitations, and may help reduce the risk of overspending (Choate et al. 2017).

Road Maintenance

Routine road maintenance protects the investment in the road and adjacent resources. It is important for roads to function properly any time of year, and particularly when large storms occur. Figure 4.18 shows roads badly in need of road maintenance and roads that are vulnerable to additional damage from a storm. When a large storm occurs, inspection and maintenance become critical, particularly for properly functioning road-surface drainage and stream-crossing structures. This applies to roads of all maintenance levels. That said, a common complaint from road managers in the southern California assessment area is frustration over doing only minimal road maintenance because of lack of funds.

Only about 20 percent of forest roads currently receive routine annual maintenance (USDA FS 2005). Unsurfaced roads are generally in variable condition, ranging from fair to poor. Lack of maintenance funds and other funding priorities preclude more routine maintenance work. Most work is done because of a specific project or with ERFO or BAER funding. Roads are kept passable and safe but not necessarily comfortable to drive. Keeping roads in a rough condition does enhance traffic safety because it ensures slower driving.



Figure 4.18—Ruts and erosion in the road surface due to lack of surface drainage and maintenance. These roads are particularly susceptible to damage from any storm when in this condition. Left photo courtesy of Joshua Direen; right photo courtesy of Vincent Barandino, USDA Forest Service, National Technology and Development Program.

Local individuals often have useful historical information on areas with soils subject to erosion, undersized culverts, and known problem areas. Documenting issues and developing a list of maintenance priorities allows a road manager to maximize the effectiveness of a maintenance budget. On occasion, maintenance of road surfaces and ditches can lead to increased sediment production following treatment (Luce and Black 2001). Therefore, road maintenance is best implemented only when needed to address the following (roughly in order of priority):

- Grade and shape the roadway surface to maintain a distinct inslope, outslope, or crown shape to move water rapidly off the road surface, keep the roadbed dry, and prevent concentration of water.
- Reshape surface drainage features (e.g., rolling dips, waterbars).
- Remove ruts in the road surface that trap and concentrate water.
- In areas damaged by fire, remove slope ravel material and rocks that end up on the road.
- Remove logs and debris from around the inlet area of culverts.
- Remove debris from the inlet area of ditch-relief, cross-drain culverts.
- Remove debris from trash racks upstream of culverts.
- Clean ditches to avoid blockage and ponding of water that can saturate the road subgrade and fill material.
- Replace missing riprap armor around inlet and outlet of culverts.
- Remove unwanted berms that have formed along the outside edge of the road or rebuild needed berms.
- Patch potholes and seal cracks in asphalt surfaces to prevent water intrusion and accelerated road damage.
- Compact the graded roadway surface to keep a hard driving surface and prevent loss of fine material.

Ditch cleaning exposes erodible soils and reinitiates existing outslope erosion processes, generating chronic sources of road sediment. As a result, light-touch ditch cleaning is generally advised. The result of less ditch cleaning over time can be vegetation encroachment and lower hydraulic efficiency. A balance is needed

between maintaining hydraulic efficiency and keeping a rough or armored surface or vegetative cover to reduce ditch erosion.

Ditches that are of greatest concern are those that are hydrologically connected to the stream system. Oversized ditches help maintain their hydraulic efficiency but allow for stabilization of the adjacent cutslopes so that adequate capacity is maintained in the absence of regular cleaning. Ditch enlargement is best implemented without undercutting cutslopes, which can create a new source of erosion and instability. Some sites may not be appropriate for oversized ditches and may require another technique, such as outsloping or insloping without a ditch and rolling the grade to manage water.

Additional road maintenance or improvement items that are useful for long-term prevention of damage include the following:

- Armor ditches in areas of particularly erodible soils or steep grades.
- Add more frequent ditch-relief cross drains, waterbars, or rolling dips.
- Convert an inslope section of road to an outslope drainage configuration.
- Install diversion-prevention dips at or downslope of stream-crossing culverts that have the potential to divert the stream down the road or ditch.
- Replace undersized culverts or bridges.
- Add riprap armor or soil bioengineering protection around the inlet of undersized culverts or bridges.
- Plant deep-rooted vegetation on over-steep cut and fill slopes or slopes with a history of movement.
- Install a deep-patch slope stabilization repair on chronically settling fills.

Despite the need for maintenance, particularly on open roads, inadequate funding results in most roads not receiving the maintenance they require to prevent chronic effects and storm damage. Stored roads receive minimal maintenance. Unneeded roads can be decommissioned, with no ongoing need for maintenance. Most roads that cannot be closed and will likely receive inadequate maintenance are likely to benefit from adaptation measures with good drainage and self-maintaining characteristics.

Road Management

Federal resource managers are examining tradeoffs between providing access and maintaining and operating a sustainable transportation system that is safe, affordable, and responsive to public needs, and that causes minimal environmental impact. Management actions being implemented to meet these objectives include developing more comprehensive access and travel management plans, reducing road maintenance levels, minimizing design standards, storm proofing roads, upgrading drainage structures and stream crossings, reconstructing and upgrading roads, relocating segments of roads, converting paved roads back to gravel roads, placing roads in storage, closing roads with decommissioning or obliteration, and converting some roads to trails. In fire-prone areas, it is often preferred to maintain redundant and alternative road systems and evacuation routes.

Temporary closure of roads and road-use restrictions have always been problematic. With shifting seasons for road use and less snowpack, the public will likely want access when roads, trails, and off-highway vehicle facilities are still saturated with water and not suitable for use. Waiting until soils are dry enough and strong enough to support traffic is a challenge. In extreme cases, road closure may be the best option.

Roads can be closed through **storage**, **decommissioning**, or **obliteration**. Each removes the road from use and makes it less vulnerable to storms. **Road storage** refers to measures to keep traffic off the road, but the basic road template is preserved. The national forests in the SOCAAP assessment area have a combined 342 miles of roads in storage. Closure can be for many years, but eventually the road may be reopened for land management activities. Closure devices such as gates, fences, earth berms, trees, brush piles, and boulders are used to prevent use of a road. These options provide flexibility to temporarily reduce costs and effects, while also considering social and economic factors. These roads can be reopened with a minimum of work during emergencies, such as access for firefighting equipment.

Permanent road closure occurs when a road is no longer needed to meet resource management objectives. Treatment options include reestablishing drainage patterns, stabilizing slopes, restoring vegetation, blocking

road entrances, installing waterbars, removing culverts, removing unstable fills, pulling back road shoulders, scattering slash on roadbeds, and eliminating roadbeds (Luce et al. 2001) (fig. 4.19). These measures can greatly reduce negative effects caused during storm events.

Decommissioning involves permanent measures, such as allowing natural reestablishment of vegetation and, if necessary, initiating restoration of ecological processes interrupted or adversely affected by the unneeded road. Decommissioning includes blocking the entrance, removing culverts, reestablishing natural drainage patterns via outsloping or frequent waterbars, pulling back road shoulders, and scarifying and seeding the road surface. **Obliteration** involves removal of the road template and reclamation or restoration of the land following resource production activities. This is typically the most rigorous, costly, and permanent option



Figure 4.19—Road closure options include decommissioning (top), complete roadway obliteration (bottom), and storm proofing with measures such as outsloping, frequent waterbars or dips, and other treatments such that maintenance is not needed to prevent damage. Photos by Gordon Keller.

for road decommissioning. Road closure issues are discussed in *Forest Service Manual 7700, chapter 7730—Transportation System Operation and Maintenance, 7734—Road Decommissioning* (USDA FS 2022).

Relocation of short segments of roads may sometimes be necessary when the road passes through a landslide zone or is directly affected by a large slide. Problematic areas such as unstable terrain should generally be avoided. Relocation is beneficial if there is a road-stream encroachment problem and the road is in an area that may flood or where the stream will eventually move (within a channel migration zone). Roads located along streams, in floodplains, and in or adjacent to channel migration zones are high-risk sites that are unsuitable. High-risk roads can be closed or relocated away from the channel or upslope on a hillside, outside a potential

channel migration zone. Although relocation may be costly and administratively and physically difficult, relocating roads away from streams, floodplains, and channel migration zones will likely eliminate future costly channel encroachment repairs and loss of road function for extended periods. In addition, channel functions can be better managed if road features do not interfere with natural stream processes. Figure 4.20 shows where existing main roads are within 164 feet of a stream. This issue has been a problem on many federal lands but has not been commonly perceived as a problem in southern California. If a road cannot be moved outside the channel migration zone, rock riprap can be used to armor the streambank (figs. 4.21, 4.22). Additional information on this issue and adaptation measures can be found in Halofsky et al. (2021).

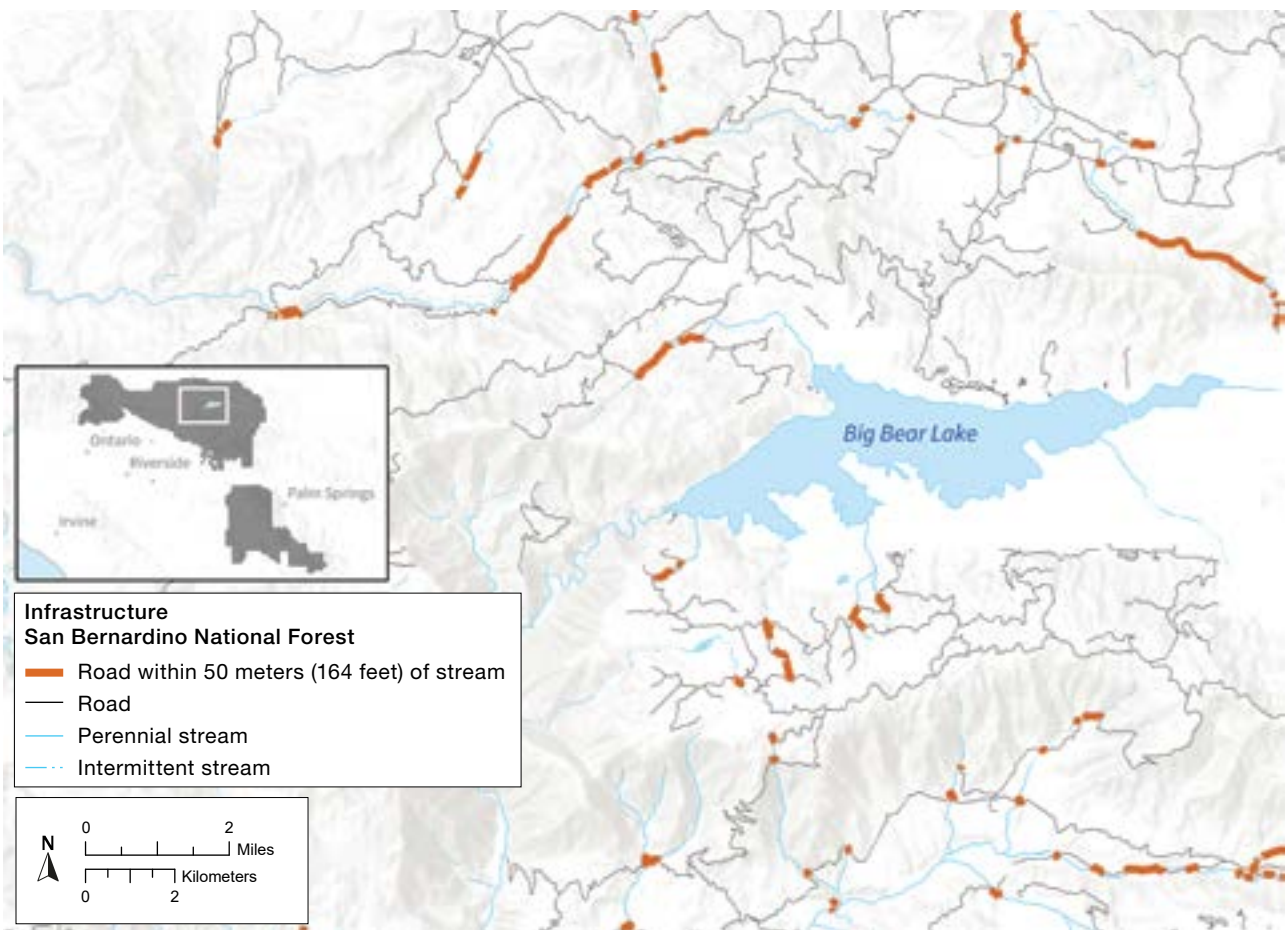


Figure 4.20—Forest Service Infra data showing locations where existing main roads are within 164 feet (50 meters) of a stream and may be vulnerable to increased streamflows, road-stream crossing failure, stream diversion, and channel migration.



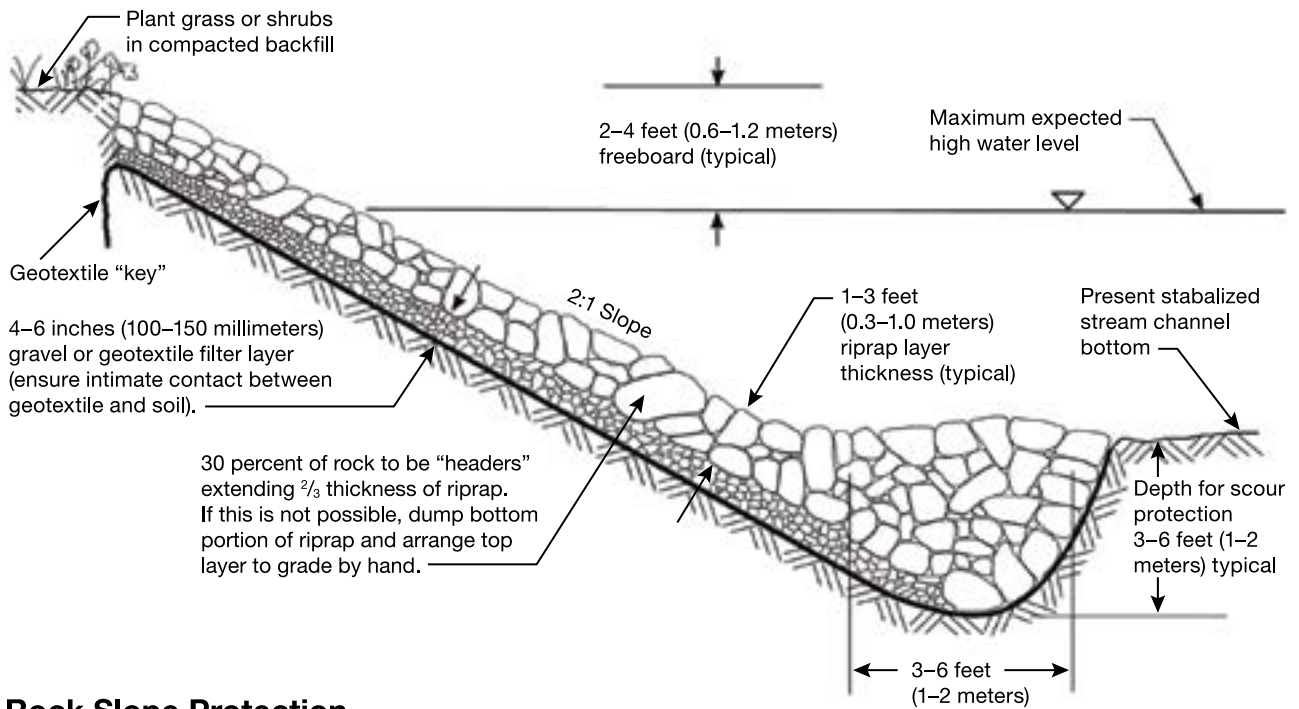
Figure 4.21—Common channel (right) and streambank (left) stabilization using rock riprap. Note where riprap has been washed away from a bridge abutment (yellow polygon) because the riprap rocks were too small. Left photo courtesy of Leslie Boak; right by Joshua Direen, USDA Forest Service, San Bernardino National Forest.

Road Surface Drainage

Road surface drainage in highly erodible soils can be difficult to resolve. Deciding whether to inslope or outslope a road requires careful consideration of the location, public safety, existing natural drainages, soil type, existing vegetation, and local experience. Although outsloping is a common forest road treatment to minimize concentration of water, many engineers in southern California prefer an inslope road template because of steep slopes and highly erosive soils. An inslope road requires frequent cross drains to remove the water and careful location or armoring of the drains to handle the concentrated flow.

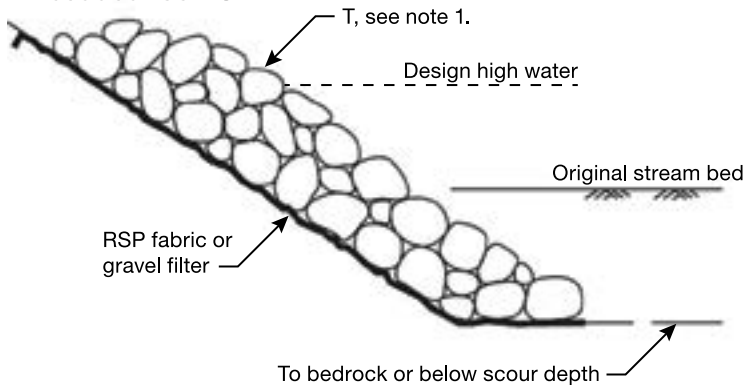
With traffic and time, ruts will form in most roads, necessitating periodic maintenance. In the absence of maintenance, the best road-drainage measures to prevent ruts are rolling grades, rolling dips or waterbars, and an inslope or outslope road. The following measures are used to construct and improve road drainage to prevent water concentration, move water rapidly off the road, facilitate water control, and prevent storm damage:

- Close or relocate/reconstruct road segments with excessively steep road grades. The steeper the road grade, the more difficult it is to achieve road-surface drainage. With steep grades, even roads with moderate cross-slopes keep water on the road surface for a long distance. Road grades less than 10 percent are easiest for control of surface flow. Grades less than 6 percent are helpful on roads receiving infrequent maintenance.
- Maintain positive surface drainage with an outslope, inslope, or crown roadway section (fig. 4.23). A cross-slope of 4–6 percent is typical; 6 percent may be ideal for drainage and requires the least maintenance. Two percent is typical for a hardened surface, such as a paved road and on flatter grades.
- Roll grades or undulate the road profile frequently to provide locations to disperse water off the road.
- Use frequently spaced leadoff ditches to prevent excessive water accumulation in roadway ditches.
- Use roadway cross-drain structures, such as rolling dips, pipe cross-drain culverts, open-top culvert flumes, or deflectors to both move water across and off the road surface, and to move water from inside the ditch across and off the road surface. Space the cross-drain structures frequently enough to remove all surface water without excessive water accumulation. Because these features are intended to cut off and discharge accumulated ditch water, cut to the bottom of the ditch, which may be relatively deep, and dam the ditch on the downgrade side.
- Protect cross-drain outlets with rock (riprap), brush, or logging slash to dissipate energy and prevent erosion, or locate the outlet of cross drains on stable, nonerodible soils, rock, or in well-vegetated areas. Use downspouts to move water down a fill slope to a stable outlet area. A stable outlet location is critical. The ideal cross-drain spacing depends on field conditions. Closer cross-drain spacing may eliminate the need for outlet armoring and minimize water concentration.

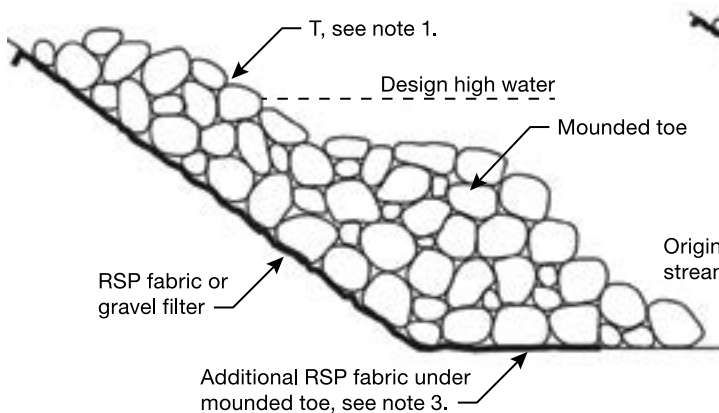


Rock Slope Protection

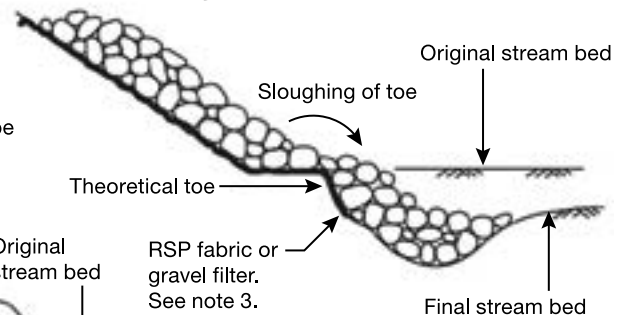
Embedded toe RSP



Mounded toe RSP (as constructed)



Mounded toe RSP (after launching of mounded toe)



1. Thickness “T” = 1.5 d50 or d100, whichever is greater.
2. Rock slope protection should extend above the projected level of maximum high water.
3. Rock slope protection (RSP) fabric not to extend more than 20 percent of the base width of the mounded toe past the theoretical toe.

Figure 4.22—Typical riprap installation details for streambank protection. Upper drawing from Keller and Ketcheson (2015); lower drawing adapted from Caltrans (2022).

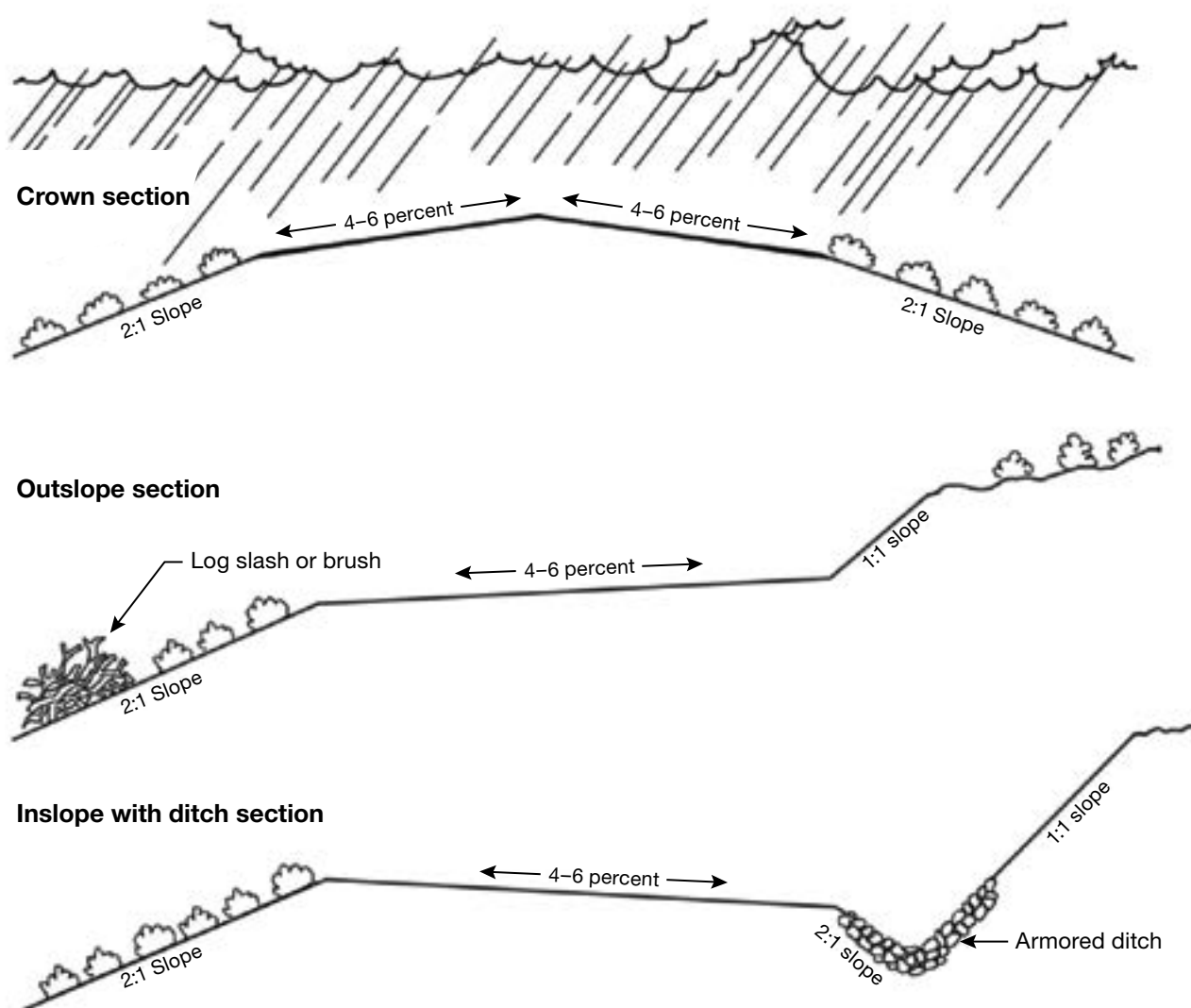


Figure 4.23—Basic road surface drainage options based on the shape of the road surface in cross-section: crown, outslope, and inslope sections. Source: Keller and Sherar (2003).

- Construct waterbars on infrequently used or closed roads to control surface runoff, and remove water from the road before it accumulates into an amount sufficient to cause erosion. Waterbars do not intercept the ditch and may redirect road-surface flow into in-board ditches on strongly insloped templates.
- Repair entrenched roads that are difficult to drain, otherwise a road may effectively become a canal. Ideally raise the road grade above the level of the adjacent terrain with fill material to be able to drain the road surface.
- Use catch-water ditches (intercept ditches) across the natural ground above a cutslope in areas with high-intensity rainfall and overland flow. These ditches are useful for capturing overland sheet

flow before it pours over the cutslope and erodes or destabilizes the cut. However, be aware that catch-water ditches that are not properly maintained can become counterproductive pools of water above slopes, increasing the probability of slope failure or gully erosion.

Note that many of the measures listed above may not be necessary if the waterflow is otherwise dispersed or reduced. If ditch erosion occurs or armor is needed at the outlet of a pipe, ditch, or dip, it is a sign of too much concentrated flow. Adding more cross drainage or leadoff ditches may reduce the flow in the problem area.

Spatial and terrain analysis tools developed to assess road risks, such as the Water Erosion Predictive Project model (Flanagan and Nearing 1995), Geographic Road Analysis and Inventory Package (Black et al. 2012,

Cissel et al. 2012a), and NetMap framework (Benda et al. 2007), are often used to identify hydrologic effects and guide management on projects needing drainage and erosion control. For example, an analysis on Umatilla National Forest determined that 12 percent of the road system contributes 90 percent of the sediment, which helps prioritize treatment plans focused on the most critical sites (Nelson et al. 2010). Similar findings have been observed with Geographic Road Analysis and Inventory Package modeling on other national forests (Furniss et al. 2018). Adequate drainage, as well as road-surface armoring, could prevent much of that sediment loss.

For all water-drainage applications on road surfaces, it is important to know the soil and hillslope conditions where water is discharged from the road onto the slope. Most mass slope failures below roads, as well as many gullies, result from excessive concentration of surface

water running off roads and saturation of marginally stable or unstable hillslopes. More detail on these drainage adaptation measures is in *Storm Damage Risk Reduction Guide for Low-Volume Roads* (Keller and Ketcheson 2015). Information on road surface drainage, road damage prevention, and water quality protection is available in the Forest Service, San Dimas Technology and Development Center's *Water/Road Interaction Technology Series* (USDA FS 2000).

Rolling Dips

Rolling dips (or broad-based dips) are designed to divert and remove water off the road surface and the roadway ditch while safely allowing for the passage of low-speed traffic (figs. 4.24, 4.25). They do not involve cross-drain culverts that often plug during major storm events. Rolling dips are a cross between a waterbar and a grade break. They have a reverse grade to direct water off the

Rolling dip profile detail

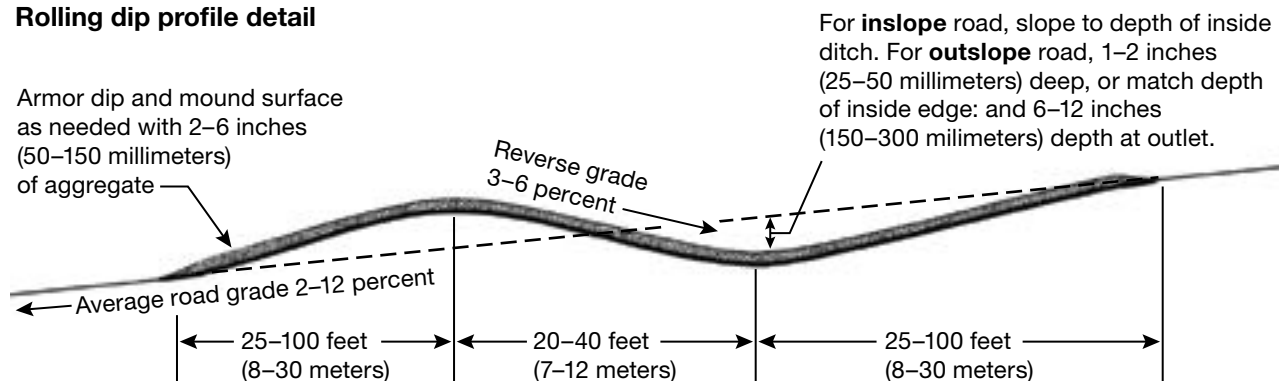


Figure 4.24—The form of a rolling dip with a mound and reverse grade to prevent water from going past the dip. Source: Keller and Ketcheson (2015).



Figure 4.25—Installation of typical rolling dip cross drains on roads. Rolling dips are commonly used on forest roads to remove water off the road surface. They can also be used as a dip to prevent stream diversion down the road and direct flow back into the natural drainage. Left photo by Joshua Direen, USDA Forest Service, San Bernardino National Forest; right photo by Gordon Keller.

road rather than down the road. Like waterbars, they rely on a mound or high point at the downhill side to reverse or change direction of the flow of water.

Rolling dips usually cost less, require less maintenance, and are less likely to plug and fail during a storm than culvert cross-drain pipes. The outlet area is often armored with rock to prevent erosion or the formation of a gully. Rolling dips are appropriate on low-volume, low- to moderate-speed roads (15–30 mph). Rolling dips are typically not constructed on road grades more than 8–10 percent, particularly for truck traffic. However, deep rolling dips have been constructed on considerably steeper grades.

Rolling dips are best constructed nearly perpendicular to the road, or ideally at a slight skew (25 degrees maximum) to minimize damage to truck frames driving through them while effectively changing the direction of waterflow. The bottom of the dip has a 2–5 percent outslope to ensure positive drainage. The entire structure is typically 75–200 feet long to ensure adequate length to comfortably pass vehicles and equipment. Armoring material may be needed in the bottom of the dip where it intercepts the road subgrade to prevent rutting in soft soils, and at the dip outlet. The mound and dip are armored with gravel or rock, particularly in soft soils, to maintain the shape of the rolling dip during traffic use. Ensuring operators understand the form and function of a dip will help ensure the dip is not damaged during maintenance with graders.

Inslope Versus Outslope Road Template

Inslope and outslope roads each have advantages and disadvantages, and either is likely better than a road with no cross-slope. An outslope road has long-term advantages to avoid any concentration of water and particularly to improve road resilience to storms if a road will receive minimal maintenance. However, in southern California forests, an inslope road with frequent cross-drain structures is generally needed. The highly erosive soils and fill-slope material, combined with dry conditions that make revegetation difficult, often lead to erosion problems. Thus, roads are commonly insloped with a berm and with frequently spaced cross-drain rolling dips, as mentioned earlier.

On an **outslope** road, the roadway template is relatively narrow (not requiring a ditch). As a result, there

is a small cut and fill, initial construction is inexpensive, and minimal maintenance is required. The dispersed flow avoids concentrating water, and the water is quickly moved off the road. Road-surface water typically does the least damage when it flows directly off the road and downslope, not down a roadway and into the ditch. Without a ditch, additional width and cutslope excavation are not needed. Because ruts and berms concentrate water on any road surface, an outslope road functions best when built in conjunction with rolling dips. Thus, an outslope road can be the most feasible roadway template to use if it suits the local conditions. On most roads, some combination of inslope and outslope exists to accommodate the terrain, drainage needs, and traffic safety. To function properly, ensure that maintenance on an outslope road does not build up any berm along the outside edge of the road.

An **inslope** road template is most appropriate where a significant amount of intercepted water from the cutslope occurs, or where a slippery, icy, or highly erodible road surface and fill slopes are a concern. Clay-rich soils, some silts, volcanic ash soils, highly fractured soft rock, and polished limestone rock all can be slippery when wet. Intercepted water in the cutbank may cause erosion or instability downslope. Drivers can feel unsafe, particularly on outslope curves and in steep terrain. In steep terrain and on steep grades where the road surface may be slippery or have snow and ice, it is safer to use an inslope road template. In some cases, an inside ditch may be used along with an outslope road template where there are seeps or springs in the cutbank.

Figure 4.26 shows the form and relative dimensions of an inslope versus an outslope road. Conversion of roads from an inslope template, typically with an inside ditch, to an outslope, involves a considerable amount of labor and earthwork and can be an expensive treatment. It requires removing some of the fill and road shoulder material and typically filling the ditch. New material may need to be imported to fill and raise the roadbed at the inside ditch line. Although roads with rolling dips or cross-drain pipes are common drainage measures, open-top culverts, small canals, and rubber deflectors have also been used. However, these other measures have limited effectiveness and require frequent maintenance, so they are not commonly recommended.

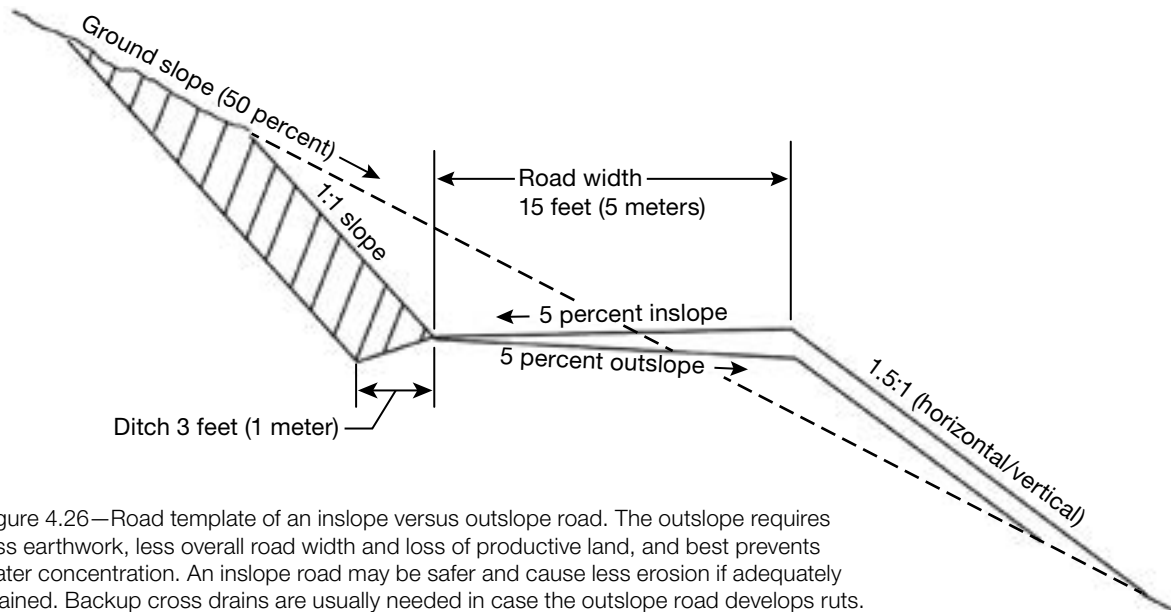


Figure 4.26—Road template of an inslope versus outslope road. The outslope requires less earthwork, less overall road width and loss of productive land, and best prevents water concentration. An inslope road may be safer and cause less erosion if adequately drained. Backup cross drains are usually needed in case the outslope road develops ruts. Source: Keller and Ketcheson (2015).

Cross-Drain Culverts

Cross-drain culverts (or ditch-relief culverts) are conduits buried beneath the road surface to discharge ditch runoff from the toe of the cut to the outside edge of the road. They are crucial on most inslope and crown roads to prevent excess concentration of water in the ditch. They are the most common type of ditch relief for road drainage and are particularly appropriate for high-standard roads where a smooth road-surface profile is desired. They are also common on low-standard roads anywhere a ditch is constructed. However, cross-drain pipes are expensive, and relatively small culvert pipes used for cross drains are susceptible to plugging during storms. During major storms, numerous small cross-drain culverts (such as 12- to 18-inch pipes) can plug and fail when intense rain mobilizes large amounts of sediment and debris. Therefore, rolling-dip cross drains are often used to minimize storm damage from plugged pipes.

Relief culverts are typically constructed with circular or arch pipes, or occasionally with rectangular concrete or wooden boxes. A minimum 18-inch-diameter round culvert is most often used for ditch relief to help prevent failure from debris blockage. Smaller pipes plug easily. In areas recently burned by wildfire, 24- to 30-inch-diameter pipes are often installed to accommodate the anticipated increased amount of sediment and debris moving off slopes. Additional cross-drain pipes reduce the spacing between pipes and thus reduce the discharge volume. Pipe size and

spacing can be calculated using the Rational Formula with small-road watersheds and local rainfall intensity-duration data. However, pipe size and spacing are more commonly based on local experience or on a recommended spacing from engineering tables and figures as discussed below. Plastic, high-density polyethylene pipes are sometimes used because of their light weight and ease of construction. However, they can burn and be destroyed in a fire, so their use on forest roads is typically limited.

Culvert ditch-relief, cross-drain pipe installation details are shown in figure 4.27. Culvert cross-drain pipes are installed with an angle of 15–30 degrees skew to the centerline of the road, using a minimum outslope of at least 2–3 percent. Both are important to move water efficiently into the pipe and to prevent plugging. In addition, the outslope is best at least 2 percent steeper than the ditch grade it is draining to reduce deposition at the inlet and prevent debris from plugging the pipe. A berm or ditch-block structure is usually needed in the ditch immediately beyond the cross drain to ensure that water turns and enters the pipe. This ditch-block should completely fill and span the ditch. An excavated inlet basin is also commonly used. The pipe should exit at ground level to prevent a waterfall and erosion. On steep ground, the pipe outlet area may need specific reinforcement, such as live stakes and riprap. If much significant outlet erosion is occurring, additional cross drains may be the best solution to reduce the quantity of water in each pipe.

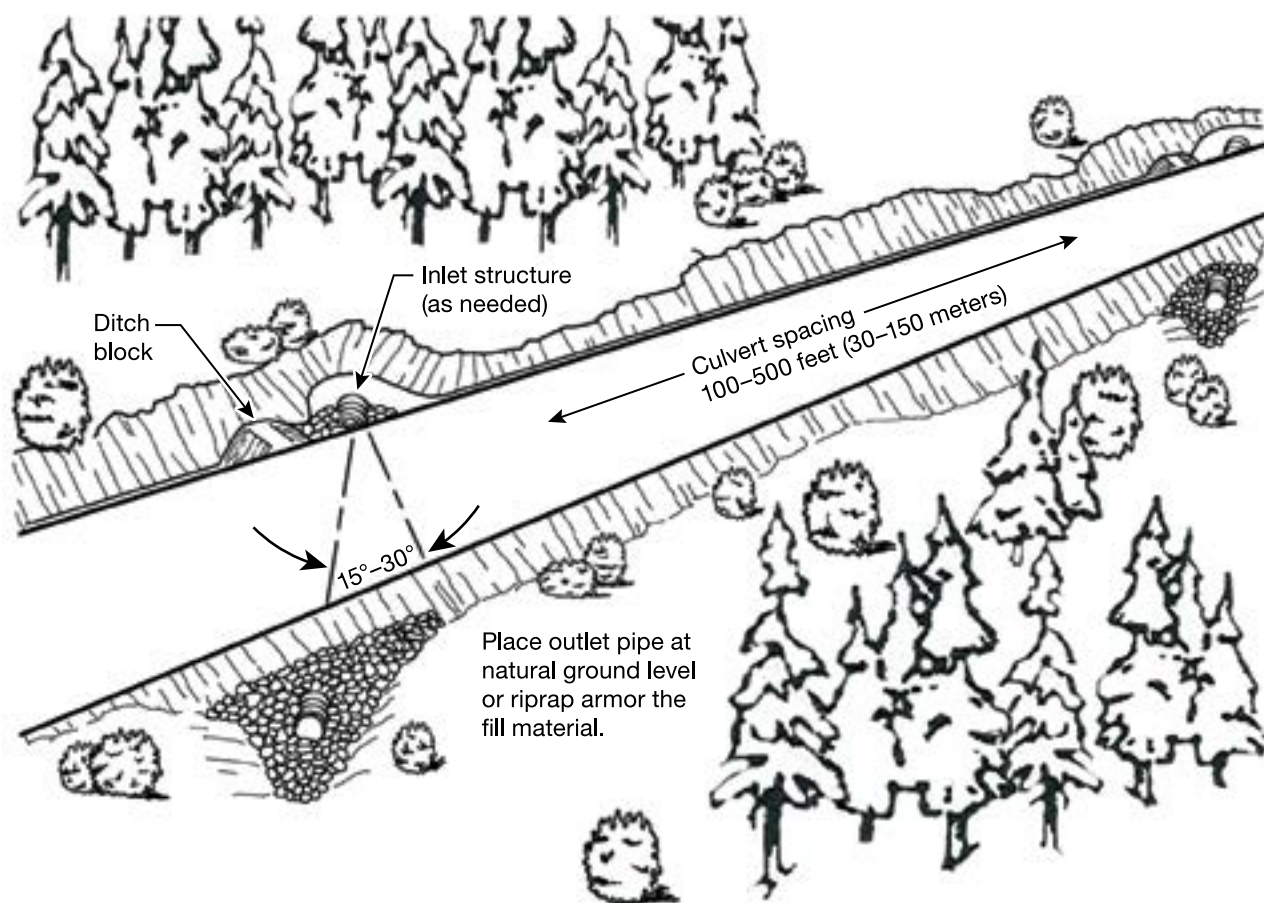
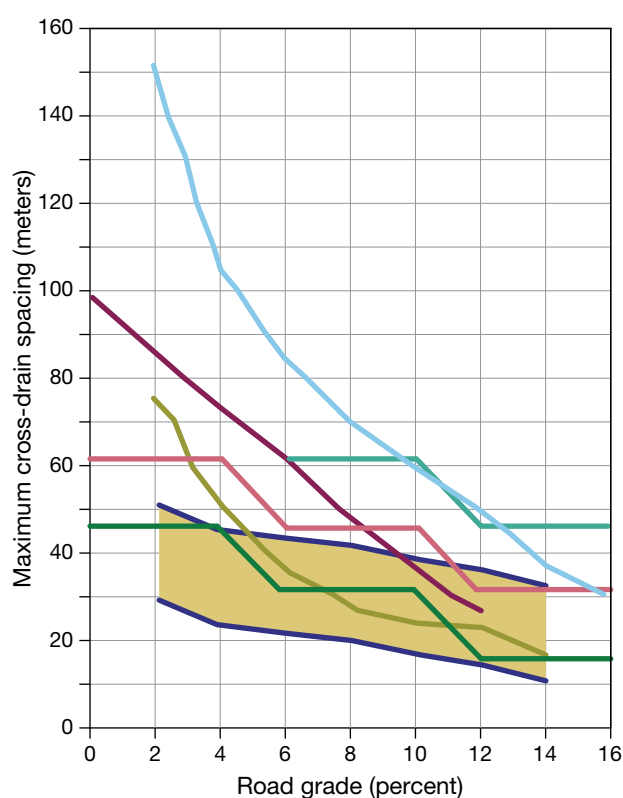


Figure 4.27—A typical culvert cross-drain installation that moves water from the ditch to the outside of the road. Source: Keller and Ketcheson (2015).



The recommended range of spacing of cross-drain culverts or rolling dips differs, depending on local conditions (fig. 4.28). Spacing for maximum distance between rolling dips or cross drains constructed on forest roads typically varies between 100 and 300 feet, but spacing is site specific and therefore adapted to projected climate conditions and existing soil and slope conditions (Copstead et al. 1998, Gonzales 1998). Tapping into local experience and judgment is beneficial when selecting

Aspect

- Broad-based dip (Swift 1985)
- Open-topped culvert (Haussman 1973)
- Waterbars (Haussman 1973)
- Silts and clays (Rothwell 1978)
- Silty sands/loams (Rothwell 1978)
- Rocky soils, sands, gravels (Rothwell 1978)
- Erosive to non-erosive soils (Packer and Christensen 1964)

Figure 4.28—Range of recommended cross-drain spacing as a function of road grade. Note: 1 meter = 3.28 feet. Source: Copstead et al. (1998).

appropriate spacing values, based on field performance, topographic location, location of natural drainages, soil type, road surfacing material, rainfall, traffic, approach grade, and other local conditions. In sensitive areas (e.g., near riparian zones), spacing might be much closer than in adjacent upland areas.

Ditches and Ditch Treatments

Ditches collect, move, and discharge water from the roadway. They are large enough to carry the anticipated accumulation of water, and ideally somewhat oversized to function during major storm events, especially when ditches have not been cleaned or maintained for a long time. They can also be a source of erosion if too much water flows in the ditch or water velocity is too high. Water is removed from the ditch with ditch-relief cross drains, rolling dips, and leadoff ditches. If water cannot be adequately dispersed or removed from the ditch, then the ditch can be armored (commonly with rock or vegetation), or the velocity can be reduced with small check-dam structures. Check dams are problematic and need attention to installation detail. If a ditch is armored or lined, it may need to be initially oversized to accommodate the armor and still have the needed flow capacity. Ditches with armoring or check dams can be difficult to maintain.

Leadoff ditches or turnout ditches are another way to discharge water and prevent accumulation of excess water in the roadway ditches (fig. 4.29). They are an inexpensive alternative to cross-drain culverts and should be used at every opportunity where the terrain is suitable. They usually do not use pipes that might plug in a storm.

They are used in flat terrain where there is no cutbank at approaching drainage crossings, and at fill areas across a swale or ravine. On flat terrain, a leadoff ditch may need to be quite long to daylight out into the forest and works best with an elevated roadway. They are also used at switchbacks where the road quickly changes direction across the slope to divide the waterflow. As with rolling dips or cross-drain culverts, they are discharged in nonerosive areas or use protected outlets to prevent erosion. If terrain or circumstances do not allow for the use of a leadoff ditch, it may be possible to discharge the ditch water into a sediment-catchment basin. To disconnect the road drainage from the stream, discharge the water into the forest or a vegetated area before the ditch reaches a stream channel (fig. 4.29).

Water that runs in the ditch can erode and move large quantities of soil and debris. Avoiding the need for a ditch is ideal, but when a ditch is necessary, frequent ditch-relief cross drainage is ideal to prevent water accumulation and reduce or prevent ditch erosion. However, this is not always possible where the ditch is deep or the road template is strongly insloped. When cross drains are not possible to construct, an eroding ditch can be armored with graded rock to decrease water velocity, prevent erosion and downcutting, and allow for sediment deposition (fig. 4.30). For slow velocities, a ditch armored with grass may have adequate lining. Small rock riprap is typically used, and for most ditches, graded 3- to 6-inch rock is ideal. A geotextile is sometimes placed under the rock as a filter to separate the rock from the soil and keep soil from washing out.



Figure 4.29—Leadoff ditches to allow for runoff discharge into the forest before it reaches a live stream or to avoid water concentration along the road. Photos by Gordon Keller.



Figure 4.30—A rock-armored ditch to prevent downcutting and erosion of the ditch. Photo by Gordon Keller.

Outlet Armoring for a Ditch, Rolling Dip, or Pipe

The accelerated velocity of water leaving a roadway ditch or culvert pipe can cause severe erosion or gullying if discharged directly onto erodible soils. Aligning and discharging culverts and cross-drain, dip-drainage structures at the natural ground level away from a live stream and into a stable, nonerodible soil area reduces erosion. When necessary, the pipe, dip, or drain-outlet area can be stabilized, and the energy of the water dissipated, by discharging the water onto a few cubic yards of graded rock riprap (fig. 4.31). Outlet erosion is a sign that closer cross-drain spacing is needed.

Other energy dissipation measures include stilling basins or settling ponds, reinforced splash aprons, gabion baskets, dense vegetation, forest slash and limbs, logs, boulders, and bedrock. When using slash, the material is pressed into good contact with the ground or mixed with varying sizes of debris to provide a ground-surface protection layer.

Drop Inlets and Culvert Cross-Drain Inlet Protection

Culvert inlet-control structures, or drop inlets, are occasionally placed in the inside ditch line at the location of a culvert cross drain. Drop inlets are commonly constructed with concrete or masonry boxes or from round metal or concrete pipe. They are consistent with the size of the ditch and pass the accumulated flow in the ditch. They are an alternative to a typical excavated culvert inlet basin (catch basin) and are typically used where the ditch carries large amounts of sediment or is eroding and downcutting. Figure 4.32 shows some drop-inlet types. Inlet structures are useful to change the direction of water flowing in the ditch into a cross-drain pipe, particularly on steep grades, and are particularly useful to stabilize the ditch elevation at the level of the inlet window before entering the culvert, thus preventing downcutting erosion in the ditch. Concrete and masonry box structures often have a bottom set below the cross-drain pipe elevation so that this area or reservoir serves as a trap for sediment (sand trap).

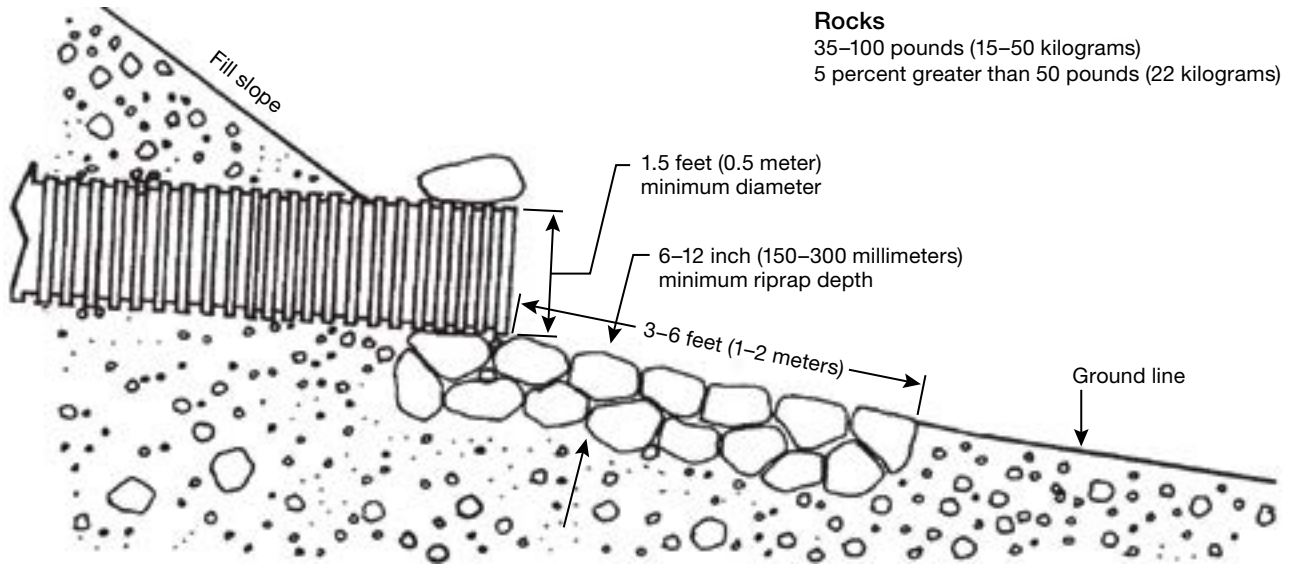


Figure 4.31—Detail of culvert-pipe outlet protection using small-rock riprap to prevent outlet erosion or scour. Keller and Sherar (2003)



Figure 4.32—A variety of culvert cross-drain drop-inlet structures used on forest roads. Left photo, USDA Forest Service, National Technology and Development Program; right photo courtesy of Gordon Keller.

Overside Drains and Downdrains

It can be challenging to move water off the road surface (from dips or cross-drain culverts) and down a steep slope in erosive soils. This problem is compounded during an intense rainstorm or after wildfires in southern California. Overside drains or downdrains are often built to at least move the water from the road edge, past the loose-fill slope material, and to solid, in-place soil or an existing drainage channel. U-shaped metal flumes are often used or occasionally round culvert pipes or concrete channels. They can all be used successfully if well placed, anchored, and compacted around the inlet to avoid an end run or piping under the inlet.

These structures can be problematic and have been damaged after fires. Fire can buckle the metal, or increased runoff after a fire can undermine or overtop the structure. Figure 4.33 shows damaged downdrains after fires. In some cases, the structures just need to be replaced. For an installation in erosive soils (such as decomposed granite), compaction of soil around the inlet is applied, or a nonerosive soil or soil-cement can be compacted in this area. To prevent washout of the road shoulder after a fire, an armored dip may be used that can then spill over a retaining structure used to stabilize the roadway (fig. 4.34).



Figure 4.33—Metal flume overside drains damaged by storms and the Cottonwood and Ojai Fires (top) and new installations of downdrains (bottom). Note the critical area at the inlet that often fails without proper installation and compaction. Left photos by Joshua Direen, USDA Forest Service, San Bernardino National Forest; right photos by Gordon Keller.



Figure 4.34—A washout on a forest road after a fire and storm event. The site was repaired with an armored dip, retaining wall, and grouted riprap below the wall. Photos by Joshua Direen, USDA Forest Service, San Bernardino National Forest.

Entrenchment Problems

Many roads become entrenched after years of road maintenance or erosion, effectively leaving the road in a condition like a canal. An outside berm can also prevent water from moving off a road. Water can only run down the road and not escape; in a flat location, water sits on the road, saturating the subgrade. In some circumstances and if not too entrenched, leadoff ditches can divert the water. The best adaptation measure for long-term protection of the road is to raise the road to a level

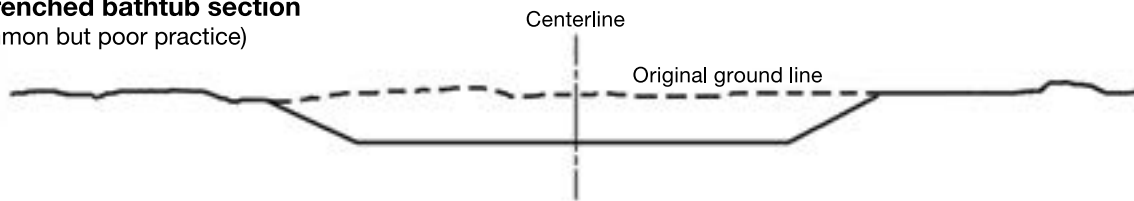
above adjacent terrain. Material can be imported or can be developed by excavating a ditch along the road, or both (fig. 4.35). Once the roadbed or trail surface is above the adjacent terrain, it can be drained to move water off the roadway surface.

Culverts

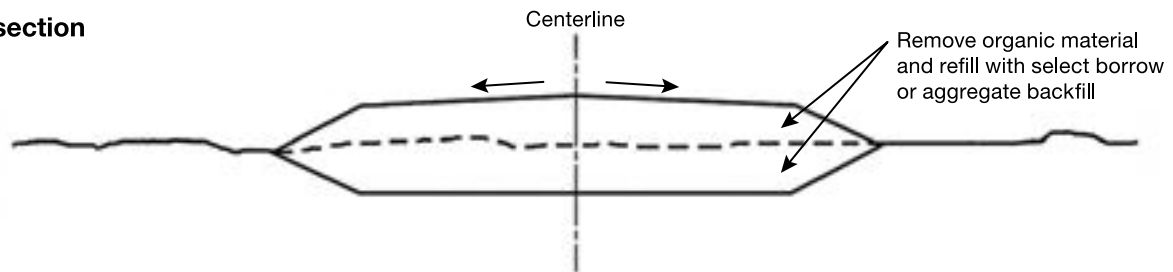
Roads constructed several decades ago often have culverts and bridges that are now at the end of their design life, making them more susceptible to damage



Entrenched bathtub section
(common but poor practice)



Fill section



Turnpike section

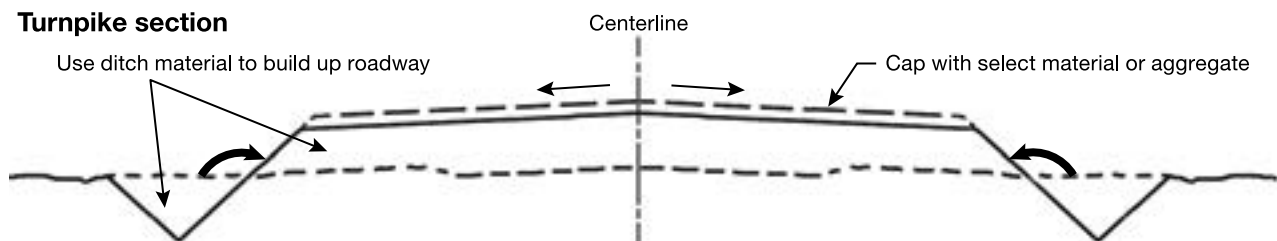


Figure 4.35—An entrenched road, a road with berms (photos), and road options for wet or flat terrain to elevate and drain the roadway surface (drawing). Note that berms may prevent erosion of a fill slope, but they also concentrate and channel water down the road. USDA Forest Service photos.

by extreme hydrologic events. Many stream crossings with culverts were designed to accommodate 25-year peak flows. Current standards typically require sizing for 100-year flows. Until recently, culvert sizing was generally expected to last only 25 years, representing a surprisingly high probability of failure. For example, the probability of exceedance is 56 percent over a 20-year design life, and 87 percent over 50 years (Furniss et al. 2018, Gucinski et al. 2001).

Because of age, undersizing of structures, and increased flows caused by climate change, culverts represent a vulnerable infrastructure feature—one that can cause road closures, high repair cost, and significant watershed effects. Figure 4.36 shows typical Forest Service Infra data identifying the location of 36-inch or larger culverts on a forest road system in San Bernardino National Forest. Pipes this size and larger are considered the most expensive and cause the most damage if they fail. Failure of numerous small culverts on forest roads also leads to cumulative watershed damage.

Culverts may need to be replaced, reinstalled, or realigned because of poor alignment, poor performance

(e.g., piping under the old culvert), plugging, or deterioration. Publications that provide insight into culvert failures during storms and provide information about reducing the likelihood of culvert failures are *Response of Road-Stream Crossings to Large Flood Events in Washington, Oregon, and Northern California* (Furniss et al. 1998), and *Designing Watercourse Crossings for Passage of 100-Year Flood Flows, Wood, and Sediment* (Cafferata et al. 2017). Examples of a problematic undermined culvert (culvert piping) and a partially plugged culvert, both with high risk of failure during storms, are shown in figure 4.37.

Historically, many relatively small culvert pipes have been installed because of lack of analysis, low cost, or availability of small pipes. However, small pipes tend to plug with sediment and debris, particularly in semiarid regions (e.g., southern California chaparral) where channels are typically dry but subject to periodic flash floods or debris torrents. Channels that transport large amounts of coarse sediments frequently plug culvert pipes. In these areas, relatively large box culverts or small bridges are preferred. Alternatively, simple unvented or vented fords/

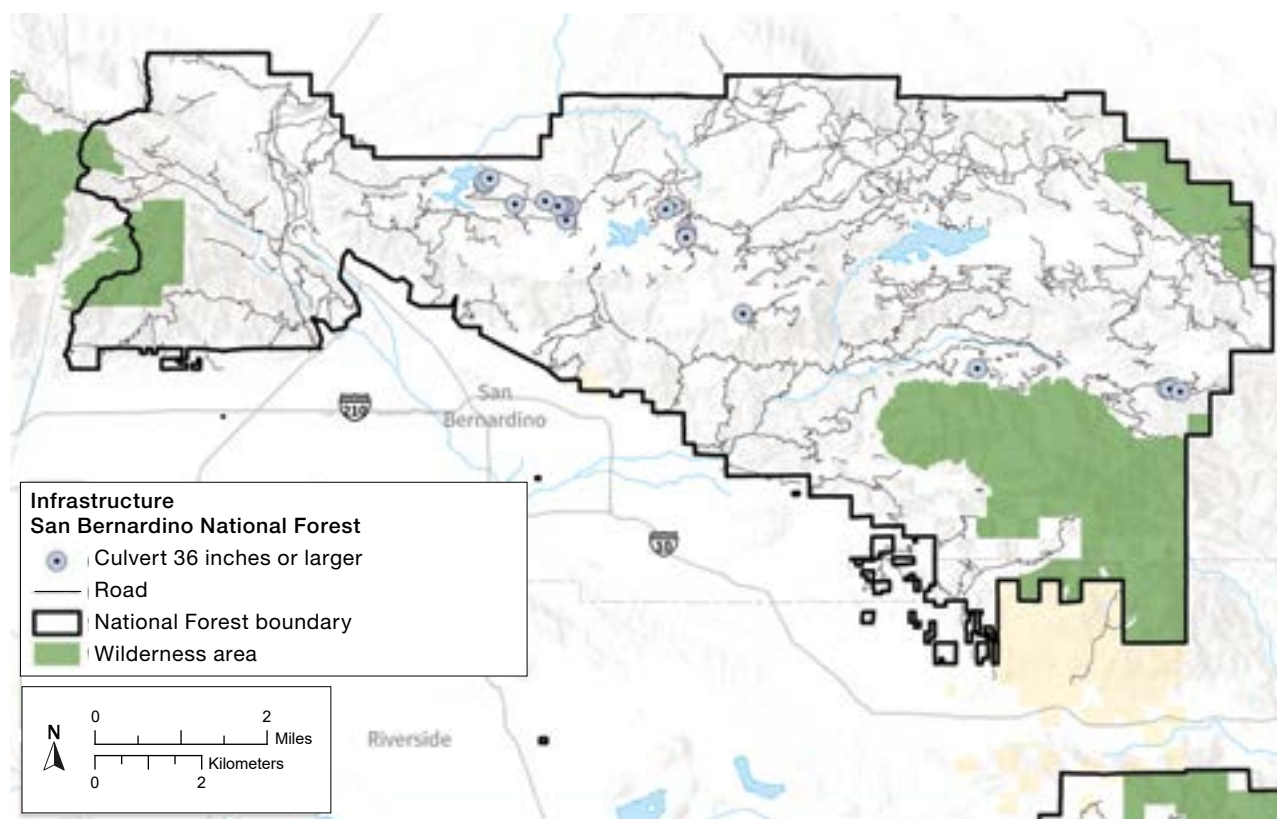


Figure 4.36—Example of Forest Service Infra data showing 36-inch or larger culverts on the road system in San Bernardino National Forest.



Figure 4.37—Problematic culverts as a result of piping under the structure (left) or loss of capacity from infilling with sediment. These culverts have a high risk of failure, particularly during major storms. Left photo by Gordon Keller, right photo by Donald Lindsay.

low-water crossings that pass a large amount of debris over the top of the structure may be most appropriate.

Culvert reinstallation and alignment considerations include the following:

- Minimize channel modifications.
- Avoid constriction of bankfull-flow channel width.
- Use a stream simulation design with a pipe width exceeding bankfull width.
- Maintain the natural channel grade and alignment.
- Use high-quality, well-compacted bedding and backfill material.
- Use inlet, outlet, and streambank protection measures.
- Prevent stream diversion.
- Add trash racks in channels that carry large amounts of debris.

Culverts are aligned as close as possible to the specific reach of the channel where they are being placed. Locations on channel bends are avoided, but if necessary, the culvert is fit into the bend as much as possible because of plugging and scour possibilities at the inlet and bank scour at the outlet. The pipe is set at the elevation of the natural stream-channel bottom, while considering the average channel thalweg elevation through that reach of the stream. A culvert set too low can fill with sediment, lose capacity, and possibly cause headward (upstream) channel erosion. A culvert set too high can create a waterfall at the outlet, causing downstream channel scour, undermining of the pipe, and possibly

preventing fish passage. Culverts specifically designed for aquatic organism passage may include oversizing the pipe and burying the bottom in stream substrate to simulate a natural channel bottom and stream characteristics.

Where aquatic organism passage and migration are needed, stream crossings are evaluated, designed, constructed, and maintained based on Forest Service guidance for assessment and design (Clarkin et al. 2005, Stream Simulation Working Group 2008). Stream simulation installations promote aquatic organism and fish passage and provide a design that is adapted for increased streamflows caused by climate change.

Design Flows for Culverts and Road-Stream Crossings

Determining the amount of flow expected during the life of a structure is the first step in designing culverts or other drainage-crossing structures. This involves a review of and application of hydrologic methods, including hydrologic and climate model projections (chapter 3). Taking into consideration the effects of climate change on design flows is also efficacious.

Pipe or structure design flows are determined for a 25-, 50-, or 100-year storm event (Q_{25} , Q_{50} , Q_{100}). Fortunately, many methods exist to determine streamflows, especially peak-design stormflows, using methods such as U.S. Geological Survey regression equations (Ries 2007), local stream-gauge data, or the Rational Method for small watersheds.

The U.S. Geological Survey has published state reports with regression equations for every state in the United States (Turnipseed and Ries 2007). Updated state information is available via the online National Streamflow

Statistics Application (Newson and Jacobsen 2021). In addition, the U.S. Geological Survey StreamStats Web application (USDI USGS, n.d.) allows users to choose a location in most states and determine hydrologic data for a particular site. Finally, summaries of useful hydrologic methods can be found in *Highway Hydrology* (McCuen et al. 2002), *Highway Drainage Guidelines* (AASHTO 2007), and *Designing Watercourse Crossings for Passage of 100-Year Flood Flows, Wood, and Sediment* (Cafferata et al. 2017).

For culverts in small watersheds and for ditch-relief cross-drain culverts, the Rational Method may be most appropriate. The Rational Method relies on rainfall intensity data (as well as watershed area and terrain runoff characteristics). It can be used to estimate current watershed discharge when the characteristics of the watershed have changed since the original design of a culvert, such as after a fire or recent development. These watershed changes affect the value of the runoff coefficient, time of concentration, and rainfall intensity entered in the calculation (box 4.6). Rainfall intensity can be quite local, but information on rainfall intensities is generally available in all areas of the United States, including southern California stations. One of the best sources of data for rainfall intensity, duration, and frequency is the U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Weather Service's Precipitation Frequency Data Server (USDC NOAA NWS 2023).

Comparing different hydrologic methods is helpful because each method has advantages and limitations, such as period of record, consideration of climate change, and changes in watershed characteristics. Note that most hydrologic methods do not consider debris loading in a channel, so expert judgment and local experience are needed to assess plugging potential from vegetation and sediment (fine sediment, boulders, and rocky debris). Once a design flow is determined, pipe dimension that will pass that flow can be determined using the U.S. Department of Transportation, Federal Highway Administration's pipe capacity nomographs (Normann et al. 2005). These nomographs are for water and do not reflect the addition of debris and sediment.

Several methods have been suggested for determining an increased design flow to reflect climate change. Wilhere et al. (2016) offers a methodology for sizing

culverts based on climate models and projected streamflows in the Pacific Northwest. Recommended culvert designs are then based on expected increases in bankfull width, cost considerations, risks, and analysis uncertainties. A stream simulation design methodology is often used. Some simple estimates from Europe increase or adjust design flows by 15–30 percent. Others have suggested moving up one recurrence frequency on local rainfall intensity-duration-frequency curves (e.g., use a 100-year recurrence frequency rather than a 50-year frequency) (Devkota and Gyawali 2015). The Pacific Climate Impacts Consortium and Environment and Climate Change Canada have examined a “temperature scaling” methodology of increasing rainfall intensity based on the mean increase (change) in temperature for a given area and timeframe based on the assumption that warmer air can hold more moisture (ECCC 2018–2025).

Culvert and Channel Maintenance

Culvert maintenance and periodic cleaning of the pipe and channel near the inlet to the pipe are critical to proper function. Lack of maintenance contributes to many culvert failures (fig. 4.38). Ideally, pipes will receive maintenance before any major storm, although that can be guaranteed only by performing maintenance routinely and after the last major storm. Common culvert maintenance includes the following:

- Keep the inlet clear of wood, sediment buildup, rocks, and vegetation.
- Ensure that headwalls are in good condition.
- Reline worn culvert barrels or replace the pipe.
- Replace damaged or missing splash aprons or riprap.
- Bend back damaged metal blocking the entrance.

Culvert Diversion Prevention and Overflow Protection

Stream diversion at culverts is a significant problem in many upland watersheds and can cause significant damage when water is diverted down the road. Diversion potential exists on roads that have a continuous climbing grade across a stream crossing or where a road slopes downward away from a stream crossing in at least one direction. Diversion prevention is a cost-effective adaptation treatment for culverts at risk of overtopping and washing down the road. The physical consequences of



Figure 4.38—Culverts needing maintenance or repair and with a high risk of failure from plugging because of logs across the inlet and damage to the inlet. Left photo by Donald Lindsay, right photo by Gordon Keller.

exceeding the capacity of a stream-crossing structure usually depend on the degree of exceedance, volume of fill at the crossing, characteristics of fill and soil, and flow path of the overflowing stream discharge. When the structure capacity is exceeded, or if the culvert pipe plugs with debris, the stream backs up behind the fill. If the low point of the crossing is the ditch line, the water will divert down the road rather than flow directly over the road fill and back into the natural channel. At some point, the water will leave the road and erode fill and the hillside all the way to a channel (fig. 4.39: a–c).

If the low point is over a pipe, or an armored dip is constructed in the roadway near a structure, water will flow across the road and return quickly to the channel (fig. 4.39). Armoring the dip or low point prevents erosion, downcutting, and additional damage to the road and fill. Also, in fire areas where considerable sediment and debris are mobilized and risk of culvert plugging is high, the entire fill embankment can be armored with geosynthetics, turf reinforcing mats, shotcrete, gabion mattresses, or rock riprap for protection against overtopping (fig. 4.39: a–c). Rock armoring is commonly used for embankments and has been successfully used on non-fish-bearing crossings prone to high debris loads (Cafferata et al. 2017). A comprehensive discussion of roadway-embankment overflow protection is found in *Minimizing Roadway Embankment Damage from Flooding: A Synthesis of Highway Practice* (Briaud and Maddah 2016).

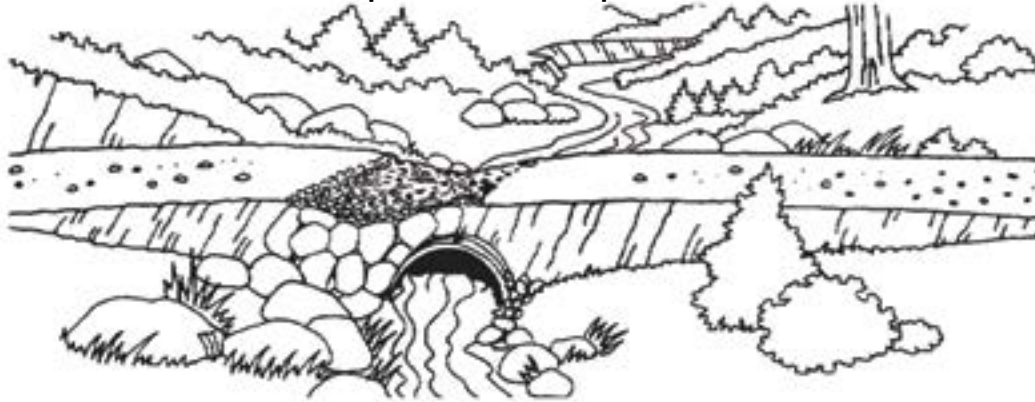
The cost of an overflow dip, fill armoring, or designed failure point is small compared to the cost of replacing

the entire fill and repairing damage to the road, or the resource cost of the large, persistent gullies that diversions usually cause. *Diversion Potential at Road-Stream Crossings* (Furniss et al. 1997) discusses the physical effects of diversion potential and provides design considerations for remediation of existing crossings with diversion potential.

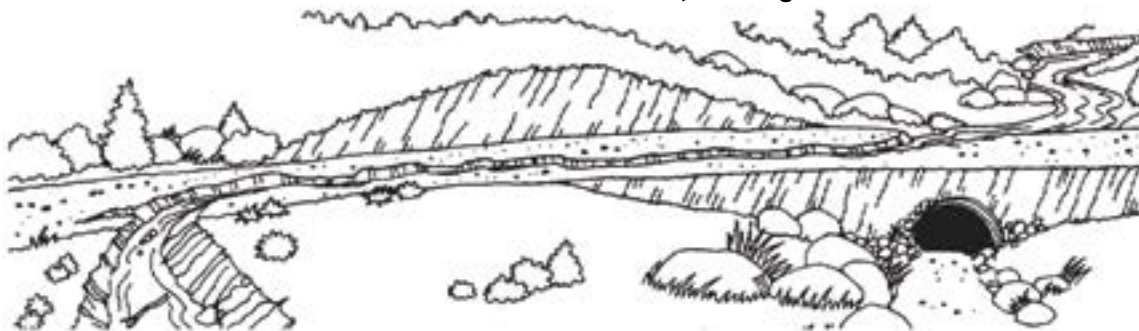
Trash Racks

In forest environments, a common mode of failure is culvert plugging with organic debris, sediment, and rock, as opposed to failure due to lack of flow capacity. Storm damage studies in the Pacific Northwest have determined that plugging—from woody debris, sediment slugs, or debris torrents—caused more than 80 percent of culvert failures (Furniss et al. 1998). Southern California forest culverts are prone to plugging from the high volume of sediment moving off steep, erosive slopes after fires and floods. Trash racks (sometimes called debris racks, debris fences, debris-straining structures, grizzlies, or bollards) are effective in preventing pipe plugging in channels with significant amounts of organic debris (fig. 4.40). Trash racks are also commonly placed in drainages that may be subject to debris flows after a high-intensity burn. Trash racks are placed upstream of a pipe in an accessible location, or in some cases, placed immediately at the inlet of the culvert. Large debris racks are also occasionally placed in channels upstream of bridges and across drainages prone to debris flows. If a trash rack is placed upstream of a pipe or bridge, access is needed for periodic cleaning.

A. Good installation: armored dip over a low fill to prevent stream diversion.



B. Poor installation: a stream diverted down the road, forming a new channel.



C. Consequence of stream diversion out of its natural channel.

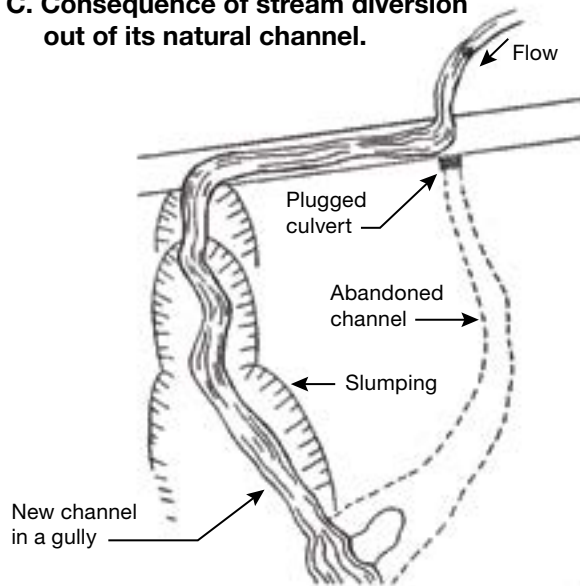


Figure 4.39—(A) Undersized culvert fitted with armored overflow dip to pass water without stream diversion or fill washout. (B) Stream diversion due to a plugged culvert crossing, sending water down the road instead of its natural channel and (C) causing considerable offsite damage. (D) Gabion mattress, (E) turf-reinforcing mats, and (F) rock riprap used to protect an embankment from overflow damage. Drawing adapted from Furniss et al. (1997). Upper photos by Mark Russell, USDA Forest Service, National Technology and Development Program; lower photo by Donald Lindsay.

Trash racks are limited to stream crossings where culverts are undersized or prone to plugging because they require periodic maintenance. The coarse-grained debris must be removed from behind the trash rack on a regular basis for them to remain effective. Better solutions include installing a larger pipe, using an overflow pipe or dip in case of plugging, and modifying the site to use a low-water crossing or bridge.

Before installing trash racks at a crossing, careful evaluation of the site and the conditions under which debris accumulation will occur is needed. Design considerations for debris-flow mitigation include the anticipated magnitude or volume of debris, likely path of debris, size and gradation of material or sediment, and impact force. Trash racks can potentially cause bank scour as water tries to flow around the structure and can create barriers to fish passage. Trash racks can become a liability if not maintained and need to be cleaned before storm events.

Trash racks have been constructed with many materials and in several configurations, including railroad rails, steel rebar, structural steel sections (e.g., I-beams),

concrete beams, wooden lumber, and logs (figs. 4.40, 4.41). The objective is to have a structure that passes normal waterflow and stream bedload but stop (trap) coarse debris and boulders. Spacing of the bars on a trash rack depends on the material moving through the channel; that spacing ranges from the diameter of the culvert to half the diameter of the culvert. Bollards, or vertical posts (often concrete or steel H-piles) are one of the most effective trash racks used in large channels or to mitigate debris flows (fig. 4.41). Spacing is typically relatively wide (2–4 feet) because the objective is to stop large boulders and logs while letting smaller material pass through the bollards (VanDine 1996).

A slanted trash rack over a culvert inlet is self-maintaining because organic debris will slide up the rack, keeping the entrance to the culvert free. However, the inlet capacity of the culvert is diminished because of the change in entrance hydraulics. It is important to consider the altered inlet hydraulics in sizing the pipe. Figure 4.41 shows trash racks before and after storm events, indicating the need for maintenance and cleaning



Figure 4.40—A variety of trash racks used in California forests to prevent culvert plugging from upstream sediment and debris. Upper left photo by Allen King, upper right photo by Donald Lindsay, lower left photo by Gordon Keller, lower right photo by Vincent Barandino, USDA Forest Service, National Technology and Development Program.



Figure 4.41—Bollard-type trash racks placed in channels or upstream of culverts before storms (left) and full of debris after major storms (right). Note that trash racks need to be cleaned periodically and maintained. Upper left photo by Allen King, upper right photo by Alan Yamada, lower photos by Gordon Keller.

of the structures after a storm. Flared inlet sections on pipes or wingwalls help turn debris and funnel it through the pipe. A trash rack may be the least preferred way to prevent long-term pipe plugging, but it is a simple and inexpensive option that increases the resilience of existing pipes.

In areas where wildfires have recently burned, large quantities of fine sediment, ash, and debris can be mobilized. A riser pipe with trash rack is commonly placed on small culvert pipes (18–36 inches) where debris or sediment movement could plug the pipe (fig. 4.42).

Stream Simulation and Aquatic Organism Passage

In the past 15 years, to improve aquatic organism passage and stream function, many culverts have been replaced with open-bottomed arch structures or bridges that are less constricted during high flows and that can accommodate fish passage at a range of flows (fig. 4.43). Natural channel design techniques that mimic natural

stream-channel condition upstream and downstream of the crossing are being used at these crossings. In addition, culverts on non-fish-bearing streams but in critical locations are being upgraded to make them more storm resilient as funding and opportunities allow. Many structures built or replaced today need to ensure aquatic organism passage and accommodate a 100-year storm event. The concept of stream simulation promotes these objectives and offers a means of adapting culvert crossings to climate change. Both bridges and large, multiplate steel culverts (also called buried bridges) are ideal for stream simulation because they can typically exceed the bankfull channel width, maintaining or creating a natural stream channel bottom through the structure.

Although the Forest Service Aquatic Organism Passage Program implements projects on streams more commonly in the Pacific Northwest, aquatic organism passage projects also occur in streams in the SOCAAP assessment area (fig. 4.44). Many of the streams are



Figure 4.42—Culverts with plugging potential (top) and trash racks to prevent plugging (bottom) that have been designed with different trash rack risers in areas where wildfire has occurred. Upper photos by Joshua Direen, USDA Forest Service, San Bernardino National Forest; lower photos by Gordon Keller.

ephemeral, but headwater reaches are perennial. Thus, resident fish populations benefit from aquatic organism passage projects, which also enhance habitat and remove barriers in streams to increase seasonal habitat. Several aquatic organism passage improvement projects have been built in the Trabuco Ranger District of Cleveland National Forest (box 4.7), improving aquatic organism habitat and stream and structure resilience against storms.

Several habitat restoration projects have been undertaken in Los Padres National Forest (Davy Brown Creek and Munch Creek restoration projects) to remove barriers and reestablish connectivity for historical steelhead trout (*Oncorhynchus mykiss*) runs. Bridges have replaced other structures for stream restoration, and another major project benefit is the resilient nature of bridges that are at relatively low risk of failure during storms (see bridge discussion below).

The stream simulation approach for designing road-stream crossing structures is a pragmatic and sustainable solution to maintain passage for aquatic organisms at all life stages, while meeting vehicle transportation and climate resilience objectives. The stream simulation design process integrates fluvial geomorphology with engineering principles to create a natural and dynamic channel through the road-stream crossing structure. The premise of stream simulation is that the creation of channel dimensions and characteristics, such as those in the adjacent natural channel, will enable fish and other aquatic organisms to experience no greater difficulty moving through the structure than if there were no crossing structure. Stream simulation channels are designed to adjust laterally and vertically to a wide range of floods and sediment or wood inputs without compromising the movement needs of fish and other aquatic organisms or the hydraulic capacity of the structure. Figure 4.45 shows



Figure 4.43—Stream simulation design and function moving through a culvert (top left, figure from Keller and Ketcheson [2015]) and various stream simulation installations. Upper right and lower left photos by Gordon Keller, lower right photo by Jonathan Berry.



Figure 4.44—Examples of stream restoration projects for aquatic organism passage on Trabuco Creek, Cleveland National Forest (top), and Davy Brown Creek, Los Padres National Forest (bottom). Left photos show the previous barriers to fish passage, and right photos show the bridges constructed to promote fish passage. The bridges are also more resilient to major stormflows. Upper photos courtesy of Kirsten Winter, lower photos courtesy of Kristie Klose.

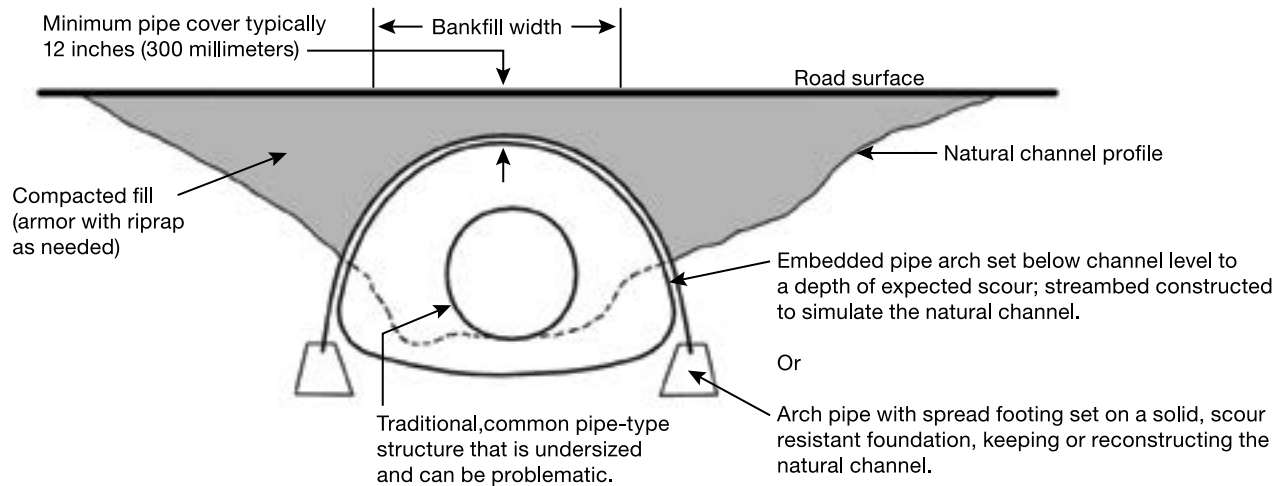


Figure 4.45—An improved or stream simulation culvert design compared to that of a traditional culvert installation. Source: Keller and Ketcheson (2015).

Box 4.7

Trabuco Creek Restoration for Watershed Health, Aquatic Organism Passage, and Climate Resilience

The Trabuco Creek project provides insight on how watershed health, aquatic organism passage, and climate resilience can be achieved through a stream restoration project. Trabuco Creek (Trabuco Ranger District, Cleveland National Forest) is in the Santa Ana Mountains. Nine concrete fords and 115 small dams were constructed of native rock and mortar on Trabuco Creek and other local creeks (Upper San Juan, Holy Jim, and Silverado Creeks) between the 1930s and 1970s. They

were built to create pools for trout fishery, water conservation, and water supplies for fire suppression. Up to 30 of the structures have washed out or failed during rainstorms (Winter 2022). Some of the remaining dams and fords have created jump heights of up to 10 feet, making the stream impassable to most fish and other aquatic organisms (see photos below).

A stream restoration program is currently underway to help restore stream health, watershed function, and habitat for species such as the steelhead trout (southern distinct population segment) which historically ranged from central California to Mexico. The Forest Service and others are removing old dams and low-water crossings (fords) and replacing some of them with bridges.



Old ford and dam structures that have been damaged periodically and created barriers to fish and other aquatic organisms. Photos show the Trabuco Creek old ford (left) and Silverado Creek Dam #7 (right) before removal.

Seven concrete fords have been or will be replaced with bridges or bottomless arch culverts. On Trabuco Creek, one ford was replaced with a bridge in 2017, and three other bridges are being designed. On Holy Jim Creek, two concrete fords were replaced with bridges in 2019. Similar projects are being undertaken on Davy Brown Creek and Munch Creek in Los Padres National Forest to improve habitat for steelhead trout (Klose 2022).

To date, removal of structures on the creeks has provided unobstructed fish passage on about 10 miles of streams, and the streams have been able to establish natural contours and streambed features. Caltrans, Federal Highway Administration, Orange County, California Department of Fish and Game, and other agencies are

also planning and supporting the removal of other structures on these drainages.

These project improvements have successfully contributed to climate resilience. Bridges and stream-simulation bottomless-arch culverts (see photos) have both been resilient to major storms (Gillespie et al. 2014). In-kind replacement of the old structures that were damaged in 1978, 1980, and 2005 continued to fail. Improved structures such as the bridges have fared well in storms after the Holy Fire (2018). The new Trabuco Canyon Road Bridge successfully passed both the storm-flows in December 2018 and large debris-laden flood flows caused by the fire-flood sequences associated with the two storms in February 2019.



Newly constructed bridges and bottomless-arch culverts that have enhanced fisheries habitat and demonstrated to be resilient to flooding and debris flows. Photos show the Trabuco Creek crossing #3 after bridge construction (left) and Holy Jim #1 with a new bottomless arch (right).

the hydraulic design of a traditional culvert compared to a design that can achieve stream simulation.

Properly designed stream simulation projects for aquatic organism passage typically function well during major storms, particularly where the structure width is equal to or greater than the natural channel bankfull width. Several stream simulation culvert projects were evaluated in Green Mountain National Forest (Vermont) in September 2011 following Hurricane Irene when flows exceeded the 100-year flood quantity. Each structure

survived with minimal problems and performed flawlessly, maintaining aquatic organism passage at each site. Only some movement of the bed material was observed (Gillespie et al. 2014, Gubernick 2011). Many other conventional culverts and bridges in the region were damaged or destroyed. For a comprehensive discussion on stream simulation and aquatic organism passage, see *Stream Simulation: An Ecological Approach to Providing Passage for Aquatic Organisms at Road-Stream Crossings* (Stream Simulation Working Group 2008).

Fords and Low-Water Crossings

Numerous fords and low-water crossings are found in the SOCAAP assessment area. They offer an alternative to culverts and bridges for stream-crossing repairs or replacement on low-volume roads where road use, streamflow conditions, and topographic setting are appropriate. Their construction or repair may be simple or somewhat complicated, requiring specific site considerations; high- and low-flow information; and soils, hydraulic, and biotic analyses. Conversion to or selection of a ford is particularly useful if a culvert pipe has a history of plugging from channel debris, or if a site is difficult to drive through or generates excessive sediment. Fords, particularly vented fords, can be an effective adaptation strategy for road-stream crossings that have failed.

Low-water crossings may have a simple rock reinforced (armored) driving surface, or an improved, hardened surface such as gabions or a concrete slab (fig. 4.46). Vented fords combine the use of culvert pipes, box culverts, or open bottoms to pass low flows and a reinforced driving surface over the culverts to support traffic and keep

traffic out of the water most of the time. The reinforced driving surface over the vents resists erosion during overtopping at high waterflows. The entire wetted perimeter of the structure should have a “U” shape and be protected to a level above the anticipated design high-water elevation.

The main advantages for using low-water crossings or fords are outlined below. Many of these considerations reflect the uncertainty and potential effects of climate change, thus making fords a preferred adaptation solution.

- Fords are relatively low-cost hydraulic structures, particularly when compared to bridges. Initial cost can be moderately high, but they require minimal maintenance and repairs if properly designed.
- Fords are generally more forgiving than large culvert structures. If flow data are unreliable, a ford can be designed to protect the wetted flow area and allow for uncertainty in peak flow.
- Fords, and particularly vented fords (fords with pipes or box culverts under the roadway surface), can be used with minimal delays most of the time without



Figure 4.46—An old, unimproved ford (top left) and a new concrete slab ford (top right) on Deer Creek, San Bernardino National Forest. Bottom photos show two other armored fords. Top photos by Joshua Direen, USDA Forest Service, San Bernardino National Forest; bottom photos by Vincent Barandino, USDA Forest Service, National Technology and Development Program.

the cost of larger structures, such as bridges, which need to span the peak-flow limits.

- Fords can easily accommodate low normal flows and occasional high peak flows.
- Fords are not susceptible to plugging failures because the design involves most or all of the flow over the top of the structure, particularly during a flood. With vented fords, the driving surface over the vent may be removable, such as with a cattle guard, permitting debris to be cleared after a large flow event. Thus, they are good designs in drainages that are subject to debris torrents or in drainages that carry large amounts of debris.

The main disadvantage of fords is that the road is occasionally closed or subject to traffic delay when flow over the structure is too deep to drive through. Fords can also be dangerous if a vehicle enters deep water and is swept downstream, so it is important to post warning signs regarding the danger. Although the design of fords can be simple, fords are often damaged if they are not well constructed. Undermining and downstream scour are common problems (fig. 4.47). Upstream and downstream cutoff walls several feet deep are typically needed to keep the slab in place and avoid undermining.

Fords and low-water crossings are often effective for storm resilience, but they can be a barrier to fish passage and aquatic organisms, particularly if the crossing forms a waterfall at the downstream edge of the structure. On alluvial fans, commonly found in the SOCAAP

assessment area, a ford can be an attractive alternative to a bridge. During storm events, stream channels on fans often move, or the flow changes to a new channel. Thus, any structure on the old channel may become useless. Under these circumstances, installation of relatively low-cost structures that may be abandoned is likely preferable.

Low-water crossings or vented fords can be constructed to pass large flows and large amounts of debris and provide suitable aquatic organism passage (fig. 4.48). They are designed to be overtopped; even if the vents plug with debris, a large waterway open area is provided, and the natural substrate material is maintained through the structure for aquatic organism passage. Alternatively, a bridge can be built for ideal aquatic organism passage conditions, but bridges are typically much more expensive than a low-water crossing. For additional technical information, see *Low-Water Crossings: Geomorphic, Biological, and Engineering Design Considerations* (Clarkin et al. 2006).

Bridges

There are 41 Forest Service-managed bridges in southern California national forests that are regularly inspected per Federal Highway Administration criteria. Most are in reasonably good condition, and none are structurally deficient, but all need routine or ongoing maintenance work (table 4.4). The concrete and steel bridges have a relatively long lifespan (75–100 years), and they were generally designed adequately for the anticipated flows. New Forest Service bridges



Figure 4.47—A ford damaged over time on Trabuco Creek, Cleveland National Forest, from downstream scour, or structure undermining. Upstream and downstream cutoff walls are typically needed to protect the structure. Photos courtesy of Kirsten Winter.



Figure 4.48—Large, vented fords that are resilient and have a predominantly natural stream channel bottom, ideal for aquatic organism passage. High flows can pass readily over the structure, while the natural channel bottom enables aquatic organism and fish movement. Left photo courtesy of Kim Clarkin, right photo courtesy of Terry Warhol.

Table 4.4—Condition of national forest bridges in the Southern California Adaptation Partnership assessment area

National forest	Adequate	Structurally deficient	Total
NUMBER			
Angeles	19	0	19
Cleveland	3	0	3
Los Padres	9	0	9
San Bernardino	10	0	10
Totals	41	0	41

and bridge replacements are designed in accordance with the agency’s stream simulation guide for aquatic organism passage (Stream Simulation Working Group 2008), making bridges more resilient to climate change (Furniss et al. 2018).

Data include major culverts with a >20-foot span. Bridges are a major investment, requiring protection to prevent failures. It is important to build good bridge design and bridge-scour protection measures into the initial design. However, changes over time can affect the hydrology of the watershed and thus increase storm-flows, putting older bridges at risk. Watershed characteristics may change because of new land uses or wildfires. Climate change will likely contribute to more intense storms or occasional longer duration storms. Thus, old bridges may have marginal hydraulic capacity for storm runoff. Some bridge protection may be needed over time

and added for scour protection to prevent undermining of foundation piers or abutments. Bridges are costly, so scour prevention measures are a high priority. These include the following:

- Foundation repairs and grouting.
- Channel clearing of trees and debris.
- Riprap placement around piers or abutments.
- Channel lining with riprap or gabions.
- Flow redirection with barbs or rock jetties.

Bridge work is facilitated by an interdisciplinary team, including hydrologists, geomorphologists, earth scientists, engineers, and fish biologists.

Figure 4.49 shows a flooded bridge approach, a failed bridge, and a bridge that has minimal freeboard—the distance between the expected high-water level and the bottom of the superstructure (beams or girders)—and is at risk of failure from a 2005 major storm event in Angeles National Forest. In some cases, an overflow dip can be built into approach fills, particularly fills that block a historical floodplain, to provide a controlled failure point that can be repaired rather than losing the bridge structure. Channel maintenance can also increase bridge flow capacity and reduce plugging or blockage during a storm.

Many changes can occur over time at a bridge site and in the watershed upstream of a bridge. Climate change and variability in hydrologic dynamics can increase peak flows and the amount of sediment transported



Figure 4.49—A failed bridge and road approach closed during the Angeles National Forest major 2005 storm event (top). A bridge with minimal freeboard (bottom) runs the risk of failure, particularly if a debris flow hits the bridge. Photos courtesy of Alan Yamada.

through the stream system. Thus, it is important to carefully evaluate bridges for increased storm damage risks that were not anticipated at the time of construction. Understanding the processes at work in the watershed upstream and downstream of a bridge site is critical for determining the most cost-effective treatment. *Stream Instability, Bridge Scour, and Countermeasures: A Field Guide for Bridge Inspectors* (USDOT FHWA NHI 2009) has useful insights on bridge instability problems and appropriate responses.

Channel Maintenance and Debris and Sediment Clearing

Channel debris and vegetation may cause scour problems or plugging for bridges. Common countermeasures for an existing bridge with debris problems include the following:

- Monitor debris buildup for prompt removal.
- Clear upstream debris and vegetation.
- Install debris catchers, bollards, or deflectors (structures that require maintenance).
- Remove sediment or areas of aggradation that decrease channel capacity.

Channel clearing and maintenance help maintain flow capacity. Some recurring debris and sediment problems may be the result of natural stream and riparian processes or altered processes caused by the presence of the structure itself, an encroaching roadway, or land use upstream. Most treatments are only temporary and will require occasional new clearing of debris and vegetation. The best long-term solution is often the replacement of the bridge with a longer, higher structure, or relocation of the structure to a less susceptible site.

Figure 4.50 shows vegetation encroaching on a channel as well as aggradation with sediment after a storm event. Removing some of this material would reduce potential for channel blockage during a flood. Removing unwanted vegetation and debris channels is often controversial because it can disturb the channel, but it is an effective method for maximizing the structure flow capacity and reducing the risk of blocking a bridge. An interdisciplinary process is helpful for identifying the counterproductive vegetation for removal versus which vegetation to leave for channel stability and ecological benefits.

Aggradation in the channel can reduce the cross-sectional area of a bridge and thus reduce flow capacity. This tends to occur on a river bend where a point bar develops on the inside of the bend. Some channel



Figure 4.50—Stream channels under bridges occasionally need clearing and tree or sediment removal to maintain channel capacity and prevent blocking and diverting flows and plugging the bridge. Point bars (right) will repeatedly build up with time, creating a continual maintenance problem at bridge sites. Bends are often poor locations for bridge sites because of persistent sediment deposition and channel changes. Photos by Gordon Keller.

deposits need to be periodically removed to maintain bridge flow capacity. This material is typically sandy gravel, so it may be useful as fill or surfacing material in another area. Some gravel and boulders are needed in the channel to provide bed material for fish spawning.

Increasing Freeboard

Lack of freeboard may be due to a lack of design-flow capacity. It may cause a bridge failure by catching floating debris that can push the superstructure off its abutments. Stream channels in areas of aggradation, on alluvial fans, and carrying significant amounts of large woody debris have the potential to plug a bridge. In these areas, evaluating bridges for their freeboard can reveal potential risks. At minimum, freeboard is several feet, depending on conditions in the upper watershed.

Solutions to lack of freeboard are not simple. The structure can be replaced with a longer span to increase

the waterway open area of the structure, or the superstructure (girders and deck) can be raised. For structures with a marginal flow capacity, the superstructure can be raised to increase freeboard. The success of these measures depends on the shape of the topography around the bridge. Raising the bridge deck in flat terrain may accomplish nothing if the flood waters spread out across a floodplain, but a longer structure could be more useful. Figure 4.51 shows a Bailey bridge superstructure with marginal freeboard and debris stuck in the superstructure after a flood. The problem was solved by adding height to the abutments and piers, thus raising the deck and placing a new concrete superstructure across the span. Alternatively, some channel clearing may be warranted (after considering potential adverse environmental effects).



Figure 4.51—Bridge with flood debris in the superstructure and marginal freeboard (left). Bridge abutments, piers, and deck were raised (right) to add freeboard and flow capacity. Photos by Gordon Keller.

Bridge Scour and Protection

Bridge foundation scour is one of the most common causes of bridge damage or failure during storm events. Common forms of scour at bridge sites are contraction scour, general channel scour, and local scour around piers and abutments (fig. 4.52). The depth of scour and amount of potential bedload movement need to be evaluated at bridge sites, particularly if a site has historical scour problems. In coarse, rocky channels with boulders, scour depth may be less than 2 feet; in gravel channels with cobbles, scour may be several feet deep; and in fine sandy river channels, scour more than 50 feet deep has been observed.

Determining scour depth requires knowledge of the hydraulic conditions and an evaluation of the channel and bed material characteristics. U.S. Army Corps of Engineers programs have developed methods for determining scour depth. Bridges that are classified as “scour critical” in the National Bridge Inventory System are potentially vulnerable, high-risk structures that are given priority for adaptation measures. Figure 4.53 shows a bridge failure caused by scour of the right pier and abutment; riprap was used around bridge abutments for scour protection. Common mitigation measures for protecting bridges against scour include the following:

- Locate a structure foundation on materials that are not scour susceptible (e.g., coarse rock, bedrock).
- Widen a structure to avoid constricting the flow channel, thus avoiding flow acceleration.

- Armor the entire channel with scour-resistant materials (grouted gabions, riprap, concrete, etc.).
- Protect the channel, streambanks, and abutments against local scour using vegetation, root wads and logs, riprap, sack concrete, articulated concrete blocks, vegetated turf reinforcing mats, or gabions.
- Redirect stream channel flow with barbs, spur dikes, weirs, cross vanes, etc.
- Install deep foundations, placed below the anticipated scour level, such as relatively deep spread footings, or drilled or driven piles, or caissons.
- Add shallow scour-cutoff walls, gabion or concrete splash aprons, plunge pools, or a riprap layer along the downstream edge of an in-channel structure.
- Install deep cutoff walls or deep sheet piles below the depth of scour or to scour-resistant material (e.g., bedrock).

For additional technical information on scour, refer to Kattell and Eriksson (1998), Richardson and Davis (2001), and Lagasse et al. (2009).

Stream channels are dynamic and tend to meander or shift laterally, longitudinally, and vertically over time, particularly in low-gradient environments or on debris fans. They can change flow direction during flood events and may reoccupy some historical floodplain deposits. Alluvial fans are also problematic because the active

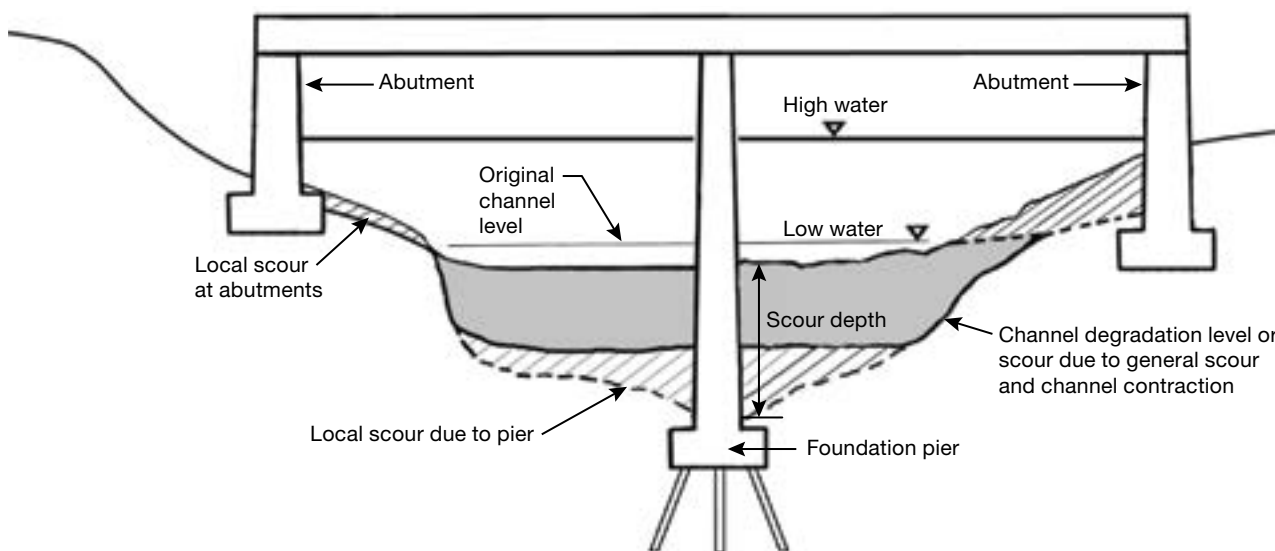


Figure 4.52—Scour types and common scour problem areas around a bridge. Adapted from Neill (1973), courtesy of the Transportation Association of Canada.



Figure 4.53—A bridge that failed as a result of scour around its right pier and abutment (note the leaning pier) (top), and bridges with scour protection provided by rock riprap around the abutments (bottom). Protection is essential for bridges that are constructed on stream bends. Upper photo by Alan Yamada, lower left photo by Kirsten Winter, lower right photo by Gordon Keller.

channel may shift with time and during a significant storm event. Examination of historical flow patterns or old aerial photos can inform projections of channel migration and aid bridge resilience. Solutions can involve a longer bridge span, although spans long enough to accommodate stream meander are often impractical. Alternatively, a sacrificial low-cost ford may be preferable if there is a high risk of the channel shifting location or of structural loss.

Streambank Stabilization

Roads located near streams are often inundated or are washed out by streambank erosion and scour. This may occur more frequently in a warmer climate as streamflows increase and carry increased sediment loads. If

streamflow velocities exceed the threshold velocities of the materials for movement (shear stresses), erosion and scour will result. These problems often occur where a structure has confined or redirected the flow of the channel, where flows have increased in the channel, or where natural protection such as vegetation has been removed from the channel or around a structure. Therefore, measures are needed to reduce flow velocities, redirect the flow, dissipate the energy of the flow, provide scour resistance below the likely depth of scour, and armor areas with materials that can resist the flow.

Several stabilization treatments are available to minimize the susceptibility of structures or streambanks to disturbance-caused erosion processes. Engineered grade-stabilization structures or vegetation-oriented remedies

range from conventional plantings to a combination of biological and engineering elements, such as soil bioengineering (McCullah and Gray 2005). Measures include the use of rock riprap, gabions, concrete slabs, cabled concrete blocks, turf-reinforcing mats, vegetation, and various biotechnical treatments. River training structures include spur dikes, vanes, J-hooks, weirs, and drop structures. River engineering is an evolving field, and consultation with engineers and geomorphologists can be essential to success. Additional local and systemic problems can be created through improper design and implementation of river engineering techniques.

Rock riprap is a commonly used, but often misused, erosion- and scour-protection measure (figs. 4.21, 4.22). It confers resistance to high stream velocities when properly installed, and is widely available, relatively low cost, durable, and adaptable to many sites. Vegetation can grow through riprap with use of live stakes driven through the riprap, and riprap can tolerate some movement because of the self-healing behavior of loose rock. It can move to some degree, deform, conform to scour areas, and still provide erosion or scour protection. Riprap can effectively armor an entire channel cross section (above and under water), streambanks to the expected high-water level, and plunge pools or stilling basins. Riprap can be placed at the outlet of pipes, along the downstream edge of a structure, in a scour hole, or around and along channel protrusions, such as bridge piers. Although riprap is widely used, it is adding “artificial hardening” to a local area and can transfer problems downstream. If flow velocities are relatively low, other techniques using vegetation or logs plus boulders may be preferable.

The two most common reasons for riprap failure are improper sizing and poor installation. The most rigorous sizing criteria are based on shear stresses or tractive forces exerted by flowing water and sediment moving along the rock surface. The Federal Highway Administration’s publication *Design of Riprap Revetments* (Brown and Clyde 1989) provides a comprehensive design process for riprap sizing, permissible tractive forces and velocity, and design examples. *Bridge Scour and Stream Instability Countermeasures* (Lagasse et al. 2009) also discusses riprap design.

Design and installation options for riprap include the following (also see fig. 4.22):

- Use well-graded riprap to provide a dense armoring layer, ensuring that the riprap layer is at least as thick as the maximum rock size, preferably 1.5 times the maximum size.
- Use hard, durable, and angular rock.
- Place riprap on a filter layer of either gravel or geotextile. The filter allows water to drain from the soil while preventing soil-particle movement behind or beneath the riprap. In critical applications, a multiple filter layer may be beneficial. A sand cushion over geotextile can prevent damage to the geotextile.
- Install riprap around the layer’s perimeter, particularly along the toe of an armored slope and at the upstream and downstream ends of the rock layer so that scour will not undermine the whole structure, or make an end run behind the structure. Extend the protection through a curve or beyond the area where fast or turbulent flow is expected. Excavate the toe to below the depth of expected scour, or to at least several feet deep.
- Place riprap with an excavator or by hand to help achieve interlocking of the individual pieces. Dumped riprap may result in an uneven layer thickness and an unstable structure overall.
- Add more rock or an extra length of gabions at the toe of the protected area to help prevent scour and undermining the structure.

Other solutions for streambank instability often involve a combination of physical and soil bioengineering techniques. Also, the force of water can be reduced by river-training structures, such as spur dikes, groins, vanes, J-hooks, jetties, barbs, weirs, drop structures, and in-channel logs (large woody debris) and boulders, as well as by increasing channel sinuosity and vegetating floodways. Streambank stabilization measures are often needed at road-stream crossings where a road fill may encroach on the stream; a culvert fill is placed across the stream, where a flow constriction accelerates streamflow velocity or where a road is constructed along a stream.

Many streambank stabilization techniques useful in adaptation to stormflows and to protect structures are discussed in more detail in the *Storm Damage Risk Reduction Guide for Low-Volume Roads* (Keller and Ketcheson 2015). The U.S. Department of Agriculture,

Natural Resources Conservation Service's *Streambank and Shoreline Protection* (USDA NRCS 1996) emphasizes use of vegetation, soil bioengineering, and biotechnical methods, as well as traditional structural streambank stabilization methods. *Environmentally Sensitive Channel and Bank Protection Measures* (McCullah and Gray 2005) also discusses many of these techniques.

Erosion Prevention and Erosion Control

Erosion prevention on roads, the entire road prism, and disturbed areas conserves topsoil and protects water quality. Road and trail surfaces, roadway cut and fill slopes, and disturbed developed areas contribute to accelerated erosion. More intense storms and increased runoff promote soil movement, erosion, and sedimentation to local watercourses, so prevention of erosion is an important adaptation strategy. Sediment in drainages that is mobilized during intense storms creates debris torrents and debris flows.

The main causes of erosion are concentration of flowing water and lack of ground cover over the soil. From a climate resilience standpoint, maintaining adequate vegetative ground cover is one of the best treatments to prevent erosion during storms. After a wildfire, quickly reestablishing a vegetative ground cover minimizes erosion and instability. Effective hillslope treatments include those that increase infiltration and use a combination of seeding, mulching, and log erosion barriers. The recovery period for vegetation on slopes in southern California is typically 2–7 years (Wilder et al. 2020).

Many mountains in southern California have very high erosion rates because of steep canyons, young sedimentary deposits, and fractured fault zones. High erosion risk is prominent in the Santa Ynez, Santa Ana, San Jacinto, and Laguna Mountains of the Peninsula Ranges, and parts of the San Gabriel Mountains. After intense fires on steep slopes, dry ravel increases and much of it is delivered to channels, resulting in increased sediment yield as well as erosion (USDA FS 2005, Wilder et al. 2020). Figure 4.54 shows examples of typical soil erosion and potential erosion on roads.

Erosion control measures are necessary immediately following construction and often after fire disturbs an area. This is especially important before the first winter period following construction or ground disturbance and before a major storm event. In construction areas,

ground cover is often difficult to establish, so sediment is typically trapped around the site. Good planning can help reduce the area disturbed by construction, and the site can be progressively rehabilitated.

Concentration of waterflow can be prevented, and eroding channels can be armored or stabilized to reduce erosion. Trapping sediment before it enters natural drainage channels is critical, but it is most effective to place treatments at the erosion source. Bare ground can be covered with matting or mulch to reduce initial erosion and promote vegetation growth.

Surface erosion from road surfaces, shoulders, cuts, and fills is significant (Gucinski et al. 2001). Movement of sediment can occur during and after road construction, after road maintenance, during logging or mining activities, if a road is closed but not stabilized, or from poor land-management practices near the road. Mass-erosion rates from roads are typically one to several orders of magnitude higher than from other land uses (Gucinski et al. 2001). Much of that erosion occurs during storm events and during the first year after construction or a fire.

Erosion control requires prevention of short-term erosion from bare or exposed soil and control of long-term erosion through establishment of vegetation. In steep or severe erosion conditions, a retaining wall, rock ground armor, or a gully plug can be effective. Good erosion control treatments typically promote germination and growth of plants, encouraging natural recruitment from the surrounding native vegetation. Conserving native topsoil and resspreading it over an area helps promote plant growth.

An erosion control plan describes local conditions, possible problems, possible solutions, and costs for control. This plan is useful for construction projects, vulnerability reduction measures, and site repairs and can include an evaluation of the most effective physical, vegetative, and biotechnical treatments. Short- and long-term measures can be planned, as well as an evaluation of needs such as fertilizers, irrigation, and protection measures (Keller and Ketcheson 2015).

Erosion Control Treatment Selection Guide (Rivas 2006) and *Erosion and Sediment Control Practices for Forest Roads and Stream Crossings—A Practical Operations Guide* (Gillies 2007) describe erosion control principles, treatments, and treatment selection by engineers and other specialists.



Figure 4.54—Common soil erosion problems and potential erosion along roads. Photos by Vincent Barandino, USDA Forest Service, National Technology and Development Program; except lower left photo by Allen King.

Where Erosion Occurs Along Roads

Most disturbed road areas, including the road surface; road fills; and some road cuts, shoulders, and drainage ditches, are exposed to erosion at some time. Other associated areas, such as log landings, skid roads, construction staging and storage areas, and borrow pits and quarries can erode and produce sediment. Common types of road erosion include sheet and rill erosion on the cutbank (and fill slopes), ditch and road surface erosion, and gully erosion when water becomes concentrated (fig. 4.55). Erosion can be prevented with physical, vegetative, soil bioengineering, and biotechnical methods. Effective erosion control requires assessment of the situation, attention to detail, inspection and quality control during installation, and post-project maintenance.

Physical Methods for Erosion Control

Drainage control and ground cover are the key elements for controlling erosion. Water concentration is prevented by dispersing the flow or by controlling the water. Concentrated, fast-flowing water has a large amount of energy and can therefore scour, erode, and form gullies. Many erosion-control measures are used to help disperse or control the flow of water (e.g., armored ditches, berms, check dams, turf reinforcing mats). Other measures that disperse and control surface drainage (e.g., rolling dips, road shaping, use of ditch-relief culverts and leadoffs) are discussed above.

Physical methods include materials that provide protective ground cover, such as mats and netting, straw, wattles, silt fences, turf reinforcing mats, slash and

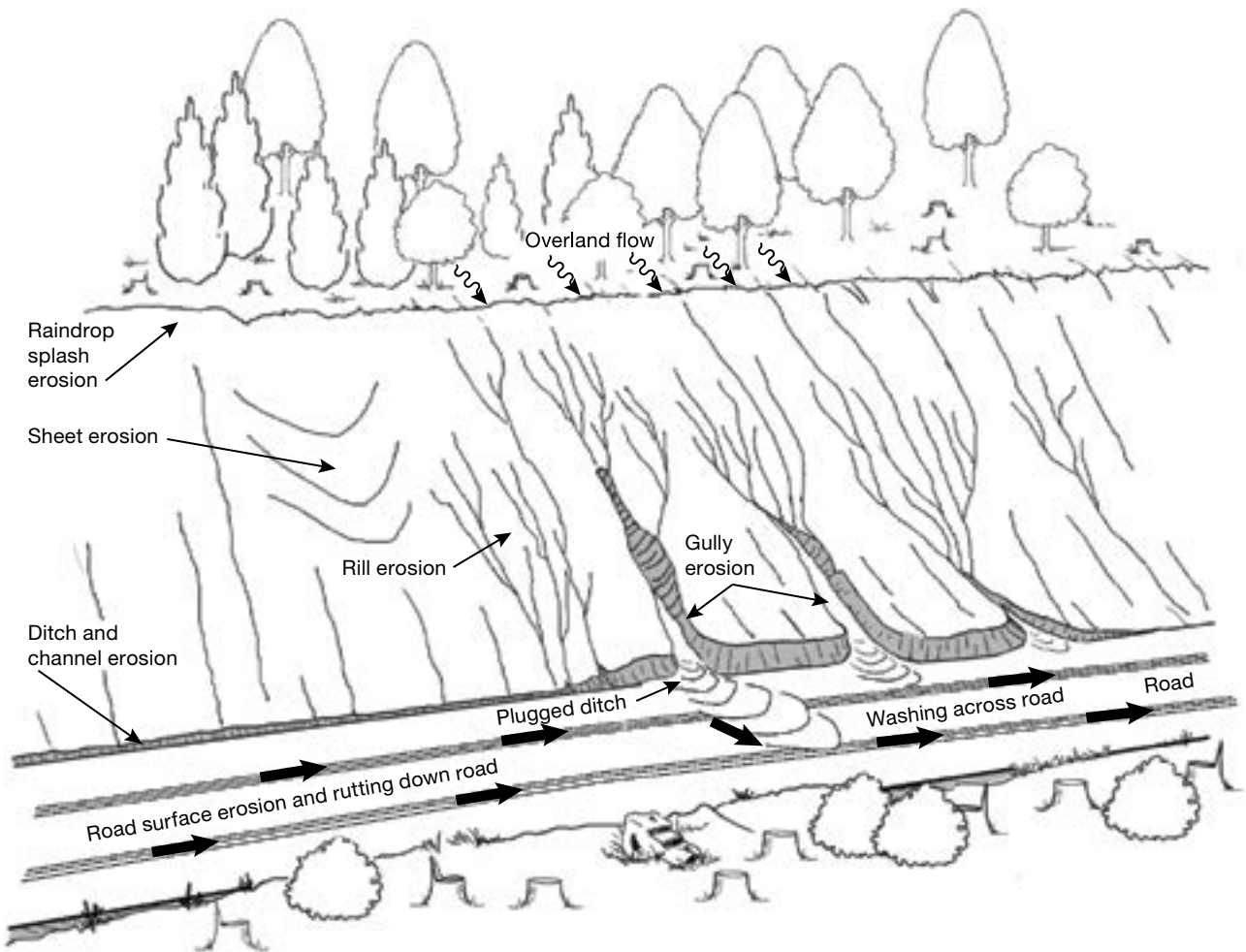


Figure 4.55—Common types and sources of erosion along a road. Keller et al. (2011).

mulches, bonded fiber matrix, rock, and concrete (fig. 4.56). Mulch is occasionally applied over recently burned areas, but it has limited effectiveness, so applications are reserved for specific situations. Additional physical methods include the following:

- Berms to control and direct waterflow, or berm removal to disperse runoff.
- Walls, barriers, and sinks or sediment basins to trap sediment.
- Mulch and soft ground cover with straw, woodchips, slash, leaves, bark, shredded paper, mats, bonded fiber matrices, etc. to temporarily protect the ground surface against erosion.
- Hard armor or ground cover using rocks, riprap, articulated concrete blocks, geocells, gabions, etc. for permanent ground cover.
- Rocking on the roadway surface, particularly on steep road grades, erodible soils, areas of concentrated waterflow, and hydrologically connected roads at approaches to stream crossings.
- Rolled erosion control products (erosion control and revegetation blankets) and mats to provide ground cover and promote vegetation. Mats and blankets need to have good contact with the soil and be pinned down according to manufacturer recommendations.
- Turf reinforcement mats to armor high-flow channels.
- Silt or sediment fences to trap sediment, particularly around worksites.
- Stabilizers and tackifiers to modify the soil surface to make it more resistant to erosion.
- Hydromulching and hydroseeding.

- Modified soil surfaces (terracing, roughening, etc.) to control runoff and aid revegetation.
- Waterbars, rolling dips, and other cross-drain structures to disperse and divert water from the road surface and ditches.
- Check dams and rock armor used in ditches to reduce velocity and prevent downcutting and erosion.

Vegetative Methods

Vegetation is the most preferable type of long-term ground cover in forest and range settings. However, it can be difficult to establish vegetation on semiarid landscapes and erosive soils, so there is a general reliance on native vegetation. Vegetation, when established, provides the following benefits:

- Reduces raindrop effect via top growth and leaf litter.
- Reduces runoff velocity via increased roughness from growing plants and leaf litter.
- Provides structural integrity (reinforcement) of the soil via the root system.
- Filters chemical pollutants and sediments from runoff.
- Increases water infiltration into the soil, and percolation and lateral movement of water through the soil.
- Increases evapotranspiration (vertical movement of water to the air through plant tissues).

Vegetative methods use grasses, shrubs, and trees for ground cover, root strength, and soil protection (fig. 4.56: bottom photos). Drought-tolerant native species of vegetation are carefully selected to ensure survival in the semiarid climate in most of southern California.

Good soil preparation improves the long-term success of vegetative treatments. The texture and fertility of the soil affect its productivity and ability to support vegetation growth. Compacted soils can be loosened with scarification or subsoiling, and the addition of organic material. Low-fertility soils may need amendments to promote growth. Other chemicals or minerals in soil may retard growth and need mitigation. Netting can be used to initially protect seeds and promote germination. Vegetation must be capable of providing dense ground cover, and deep roots for slope stabilization, with local native species being preferable. Nonnative annual grass

is discouraged but may be needed to protect disturbed areas against surface erosion for the first few years. The erosion control plan and consultation with local botanists and native plant guides are important before prescribing vegetative treatments. *Roadside Revegetation: An Integrated Approach to Establishing Native Plants* (Steinfeld et al. 2007) describes issues associated with establishing native vegetation.

Use of Deep-Rooted, Native Vegetation

Type and source of vegetation are carefully chosen to best accomplish the specific objective. Information such as topography, aspect, climate and microclimate, soil type, fertility, time of planting, and subsequent land use are needed to develop the final design. Local botanists, soil scientists, and native plant specialists can provide input for vegetative treatments. Vegetation with deep root systems is typically resistant to drought and helps stabilize slopes. Many grasses provide dense ground cover, but if they have shallow roots, shallow mass failures can occur on steep slopes when the soil is saturated (fig. 4.57).

Soil Bioengineering and Biotechnical Erosion Control Methods

Soil bioengineering and biotechnical treatments and their costs vary, depending on site conditions and values at risk, and most are labor intensive. Soil bioengineering uses an integrated approach to assess, design, construct, and maintain living vegetation to repair damage caused by erosion and slope failures (Gray and Sotir 1996, Sotir 2001). Biotechnical treatments combine the use of vegetation with physical structures, such as vegetated gabions or vegetated reinforced soil slopes (Gray and Leiser 1982). Biotechnical stabilization is a specialized field, and consultation with experts and other guides is highly recommended. Common soil bioengineering and biotechnical treatments include the following:

- Live stakes (willow and others) embedded in the face of the slope.
- Fascines/bundles/wattles—bundles of branches that are laid in a trench along contour lines that sprout and grow.
- Brush laid onto terraces in the slope, covered with moist soil and compacted.
- Vegetated reinforced soil slopes (geosynthetic reinforced soil slopes with brush placed on each lift with the reinforcement).



Figure 4.56—Common erosion control measures: (top) physical measures using straw mulch and netting (left), and application of woodchips and straw wattles (right) for ground cover and surface stabilization until vegetation grows. (Bottom) typical vegetative erosion control measures using grasses on a closed road (left) and deep-rooted shrubs and trees, as well as grass on a cutslope (right). Photos by Gordon Keller.



Figure 4.57—Slope failures from shallow rooted vegetation, such as some grasses. Photos by Gordon Keller.

- Vegetated gabions and walls (retaining structures interplanted with live vegetation cuttings).
- Live cribwalls (wooden cribwalls with material that will sprout or that are constructed with vegetation layers).

Lewis (2000) and USDA NRCS (1992) describe bioengineering techniques, soil bioengineering concepts, and examples of vegetative methods that stabilize upland roadsides. Additional information regarding soil bioengineering and biotechnical slope stabilization are discussed below.

Gullies and Gully Prevention

Gullies are a specific form of severe erosion that is typically caused by concentrated waterflow on erodible soils. Gullies can have major effects on an area by taking land out of production and by lowering the groundwater table, as well as by being a major source of sediment. They can be caused by concentrated water flowing off roads or can affect roads by creating another drainage crossing (fig. 4.58). Gullies often form and enlarge with each high-intensity rainfall event. If a gully can be prevented by diverting or dividing a concentrated flow of water, a great deal of damage can typically be prevented.

Gullies can often be prevented by **investigating and removing the water source causing the gully**. Gully

formation at the outlet of cross-drain structures or road drainage points is a common problem. Gully formation, or gully initiation along a road, is a function of the contributing area, road length and type, and the ground slope over which the water runs (or hillslope gradient). These relate to the volume of water accumulated and the energy that causes erosion. Resistance to gully formation is a function of soil and vegetation characteristics in which the water exits onto the slope, so drain exit location is important. Thus, the spacing of road drainage features is particularly important to prevent the formation of gullies.

Gully formation is a concern on steep slopes, particularly when a pipe discharges onto an unprotected hillslope (especially after 200-feet downslope). If the outlet discharges onto forest litter, initiation of a gully will require a longer distance; with an energy dissipator below the outlet, the initiation distance may be 1,000–2,000 feet. Gully initiation is likely on shorter segments of road with an inslope because of the more concentrated flow at the outlets. Controlling the road length draining to the culvert effectively controls the contributing area and the amount and velocity of water, thus preventing gully initiation.

Figure 4.59 depicts gully initiation as a function of contributing road length and hillslope for soil with three levels of erodibility. The low soil-erodibility data were collected in volcanic soils in central Oregon, the medium



Figure 4.58—Gully formation below a road where excessive water was discharged from a ditch-relief cross-drain culvert (left) and in a ditch line below a wildfire area after a thunderstorm (right). Illustration by Heather Ross, photo by Donald Lindsay.

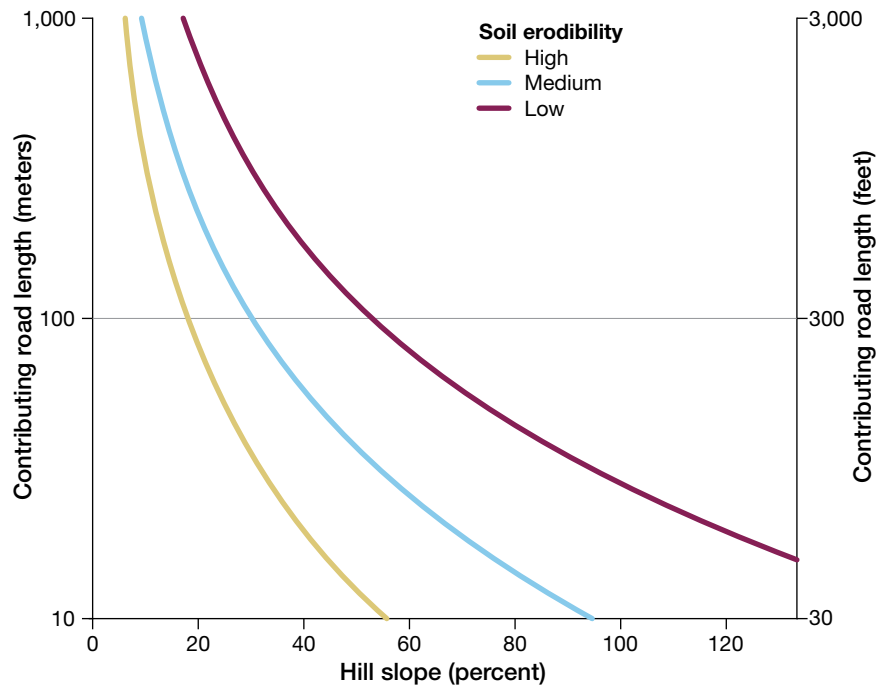


Figure 4.59—Gully initiation data from the contributing road length as a function of hillslope for various soil erodibility categories. Adapted from Cissel et al. (2012b).

soil-erodibility data were collected from granitic soils in the Idaho batholith, and the high soil-erodibility data were collected from young basalt and glacial deposits on the Olympic Peninsula, Washington (Cissel et al. 2012b).

Gully Stabilization

Stabilization of gullies begins with removing or reducing the source of water flowing to and through the gully. Gully stabilization structures are not usually preferred on natural stream channels. However, they are occasionally used in natural drainages to correct severe problems but only after careful study. For gully formation or gully formation below the road, the best solution is likely to add more frequent drainage features to reduce the concentrated water volume.

A gully can typically be stabilized with vegetation or refilled with dikes or small dams built at intervals along the gully. Stabilization of the base of the gully is often necessary to allow side slopes to be stable enough to become revegetated. Reshaping and stabilization of the over-steepened gully sides may also be needed as well as some treatment on the headcut area. Gully stabilization can require a lot of work and expense, and efforts frequently fail. Note that gully formation and stabilization in natural stream channels is different than gullies formed from local concentrated road runoff; treatments for natural stream channels are beyond the scope of this chapter.

Check-dam structures for gully stabilization are typically constructed of rock, gabions, logs, wood stakes with wire or brush, bamboo stakes, rock and brush, and vegetation. Loose rock structures are somewhat forgiving and can deform a bit and still function (fig. 4.60). The rock should be well graded, but it will still be porous, detaining water temporarily and then attenuating the runoff water. Gabions are commonly used but can be problematic and need extra care for installation. They are subject to settlement, piping through the rock, and flow diversion around or under the structure. A geosynthetic filter material can be placed behind and under the structure to provide a soil filter and prevent piping. A headcut structure is also typically needed to stabilize the upslope or top-most portion of the gully and prevent additional headward movement. Design details for successful gully stabilization structures (fig. 4.61) include the following:

- Design a weir or a notched or U-shaped spillway for the peak flow capacity to keep the waterflow concentrated in the middle of the channel.
- Key the structure into the adjacent banks tightly and far enough to prevent erosion **around** the ends of the structures.
- Bury the structures deep enough in the channel to prevent flow under the structure.



Figure 4.60—Gully stabilization structures made from logs (left) and of loose rock (right). Photos by Gordon Keller.

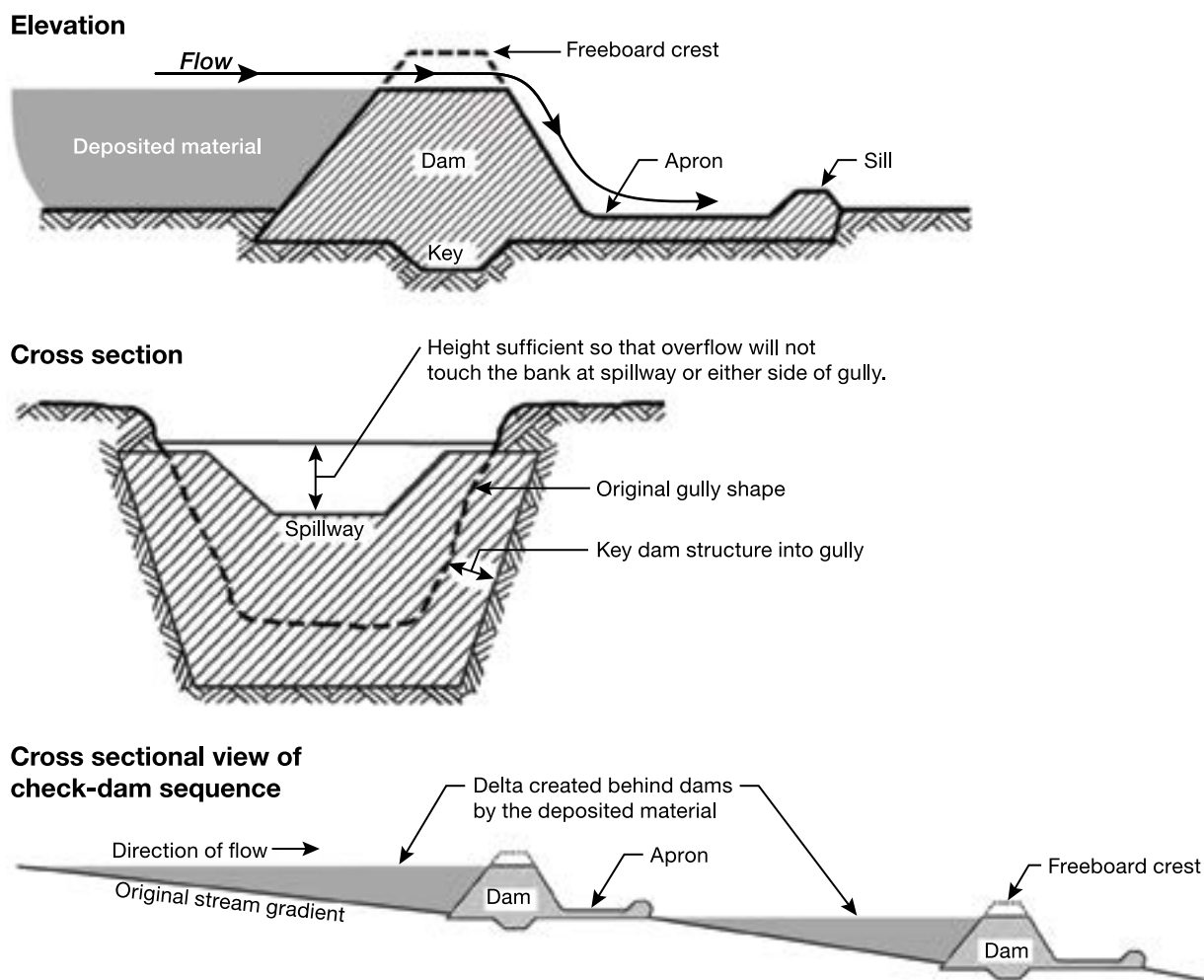


Figure 4.61—Check-dam design used to control or stabilize a gully. Note the important design details of keying the structure into the gully—having a U-shaped weir and protecting the toe area against scour with other downslope structures. Adapted from Keller and Ketcheson (2015).

- Spill the water over the structure onto a splash apron (protective layer of rock), or into a pool of water to prevent scour and undermining the structure.
- Space the structures close enough so that flow over the structure spills into backwater caused by the next structure downstream.
- If rock-check dams are used, well-graded rock will make the structure relatively impermeable. Combining vegetation with the rock will add integrity to the structure.

Slope Stabilization

Landslides and slope instability are common problems in many areas of the southern California mountains because of complex geology, frequent faulting, and steep terrain. A slope failure has the potential to either block the road with debris piled on it or cause a section of the road to detach from the slope. Twenty-nine percent of the system roads for passenger vehicles in SOCAAP assessment area national forests are in slope zones classified as high to extreme slope hazard. Nearly 50 percent of the road miles in Angeles National Forest are in high- to extreme-hazard areas, so this forest is susceptible to slope failures during storm events. The San Gabriel Fault Zone, along the southern part of Angeles National Forest, and the San Andreas Fault, on the northern side of the mountains, have produced highly fractured rocks that contain abundant landslides. Portions of Los Padres National Forest that contain Franciscan Formation marine sediments with clays and shale commonly have landslides. Sedimentary and volcanic rock units in the Santa Ana Mountains of Cleveland National Forest also have frequent landslides. The Peninsula Ranges in San Bernardino and Cleveland National Forests have relatively few landslides (USDA FS 2005).

Many types of instability occur in the SOCAAP assessment area, including shallow slumps, massive earthflows, cutslope failures, debris slides, debris flows, and rockfall (fig. 4.62). Debris slides are common in forest terrain after heavy rains but are typically more local and less destructive than debris flows. They commonly occur on slopes of more than 60 percent, particularly in pockets of colluvial soil or shallow soils over a bedrock contact. Slope stabilization measures can be used, as discussed above. Debris flows are addressed separately below.

Slide stabilization measures are important climate adaptation tools. Techniques, such as vegetation establishment, drainage management, and road surface maintenance are simple and inexpensive and can prevent slope failures caused by storms. Removing loose, settling, high-risk fill material can also reduce storm damage. A deep patch repair can also be implemented. Slope stabilization measures, such as buttresses, retaining structures, and horizontal drains are effective but expensive. Therefore, these treatments are typically implemented only after a slide has occurred or after signs of potential instability. Slope stabilization techniques include road relocation, drainage measures, use of vegetation, flattening slopes, removing slide material, slope terracing, buttresses, retaining walls, reinforced fills, biotechnical structures, soil nails, and deep-patch reinforcement. Implementation of slope stabilization treatments ideally are based on local experience, occasional subsurface investigation and analysis, and site investigation by geotechnical or engineering geology personnel. Prellwitz and Steward (1994), Turner and Schuster (1996), Keller et al. (2011), and Fay et al. (2012) describe slope stabilization techniques that are cost effective and sustainable.

Cutslopes and Fill Slopes

Cutslopes and fill slopes are routinely constructed in new construction or road reconstruction and repair projects. Over-steep cutslopes and fill slopes are a hazard during storm events and are at risk for failure. Failed slopes typically need to be repaired or removed. They usually do not involve analysis but rather are constructed at slope angles thought to be stable, based on local experience and general guidelines focused on producing stable slopes. If a specific problematic, unstable, or wet area is encountered, the road can be realigned near the area, or various stabilization treatments can be used. Table 4.5 presents stable slope ratios for cuts and fills in various soil and rock types. Existing slopes steeper than these values are at risk for failure during storms.

For most cutslopes, typical slope angles are based on the general soil or rock type and field observations. For most rocky, silty to sandy soils in the Western United States, cutslopes of 1:1 or $\frac{3}{4}$:1 (horizontal to vertical) are used. In rock cuts and rocky or cemented soils, near-vertical cutslopes can be used, and a $\frac{1}{4}$:1 slope is commonly used. In clay-rich, fine-grained soils



Figure 4.62—Examples of the variety of slope instability types seen on national forests in southern California, ranging from large earthflows and landslides to local rockfall and road cut slumps. Top, middle, and bottom left photos by Allen King; bottom right photo by Gordon Keller.

Table 4.5—Common stable slope ratios for different soil and rock conditions

Soil/rock condition	Slope ratio (horizontal: vertical) ^a
Cuts	¼:1 to ½:1
Most rock	¼:1 to ½:1
Very well-cemented soils	¾:1 to 1:1
Most in-place soils	1:1 to 1½:1
Very fractured rock	1½:1
Heavy clay soils, volcanic ash	2:1 to 3:1
Soft clay-rich zones or wet seepage areas	2:1 to 3:1
Fills	
Fills of most soils	1½:1 to 2:1
Fills of hard, angular rock	1½:1
Low cuts and fills (less than 7–10 feet)	2:1 or flatter (for revegetation)

^a While slope ratios shown here are horizontal to vertical, current Federal Highway Administration FP03 specifications use a vertical-to-horizontal designation.

or zones of saturation, flatter slopes such as 2:1 or 3:1 may be required for stability. **Cutslopes are designed for specific soil, weather, and groundwater conditions, and local experience is needed to determine the appropriate angle.**

For fill slopes, a slope of 1½:1 to 2:1 is used for most soils. Rock fills can be stable on slopes as steep as 1½:1 or even 1:1 with angular rock and careful placement. The fill material is compacted, ideally in thin layers (lifts), to increase density and strength. To achieve good vegetative stabilization on a constructed fill slope, the slope is 2:1 or flatter, especially for low fills. On ground slopes steeper than 30–40 percent, the base of the fill is placed on a terraced surface to key the fill into the slope and prevent a failure along the plane of contact between the fill and natural ground. The foundation is critical for stability of the fill. **On slopes that are more than 50–65 percent, a full-bench road is constructed without fill.**

In gentle terrain with slopes less than 50 percent, a balanced cut-and-fill design is used, and material excavated from the cutslope is placed into the adjacent fill embankment (fig. 4.63). On slopes of 50–65 percent,

the suitability and stability of balancing the cut-and-fill material is carefully evaluated, depending on local soils. On steeper slopes, a steep full-bench cutslope is typically used with no fill slope.

Thin sliver fills are a common problem on old roads where construction was done by sidecasting the fill material on steep slopes, with no compaction of the fill material. The material may only be 2–4 feet wide at the road surface. These slopes commonly have failures or problems with settlement, particularly during major storms. These sites can be repaired by pulling back the fill material with an excavator. The resulting road will be narrower but have a stable platform. The road can also be widened by excavating and shifting into the hillside or implementing a “deep-patch” reinforcement repair.

Increasing Stability with Structures

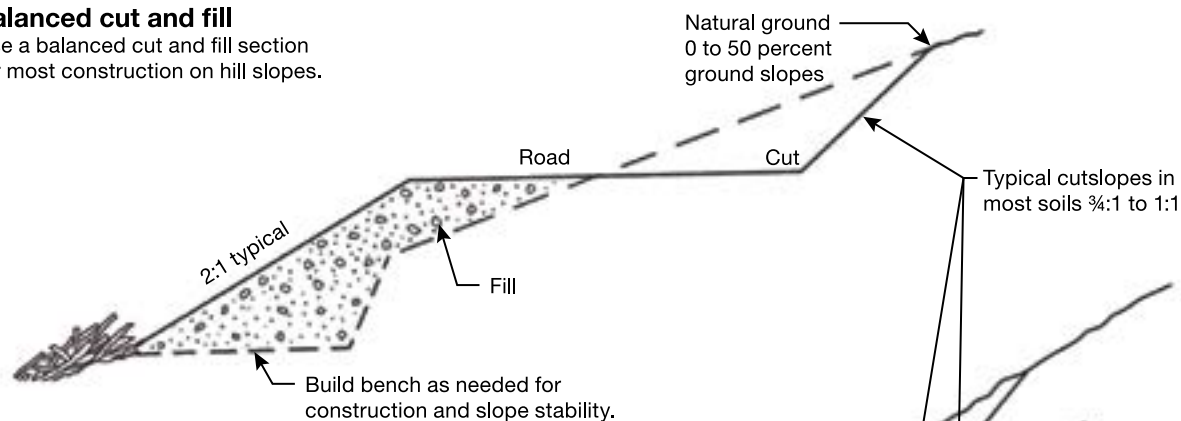
Retention structures are used in many applications with roads. They resolve a space constraint in steep ground by using a wall to support the roadway, thus avoiding a large cut or fill. They are also used to rebuild the roadway where fills fail to avoid a slide area; support a roadway across a narrow saddle; buttress a marginally stable or failed slope; and provide vertical, low-profile abutments for bridges. Mohny (1994) describes the use, selection, and design of retaining walls.

Retaining walls are expensive structures and are not routinely used to reduce vulnerability. They are not used without considering road relocation, cutting into the hillside to place the road prism on a full bench, or using a reinforced or rock fill. However, when needed, walls and buttresses effectively support the roadway (fig. 4.64). Their use can reduce future slope stability problems, avoid long fill slopes that may be erodible or unstable, and keep the toe of fills out of drainages.

Walls constructed into cutslopes are designed to allow ditch cleaning without undermining the wall or damaging its facing. Walls are designed and constructed in the context of an existing or potential failure plane of any slide and the depth of failure. The size and height of the wall are based on geological investigation and slope stability analysis to ensure that the structure will have enough mass to resist the driving forces of the slide or slope. A wall needs to

Balanced cut and fill

Use a balanced cut and fill section for most construction on hill slopes.



Full-bench cut

Use full-bench cuts when the ground slopes exceed 50 to 65 percent.

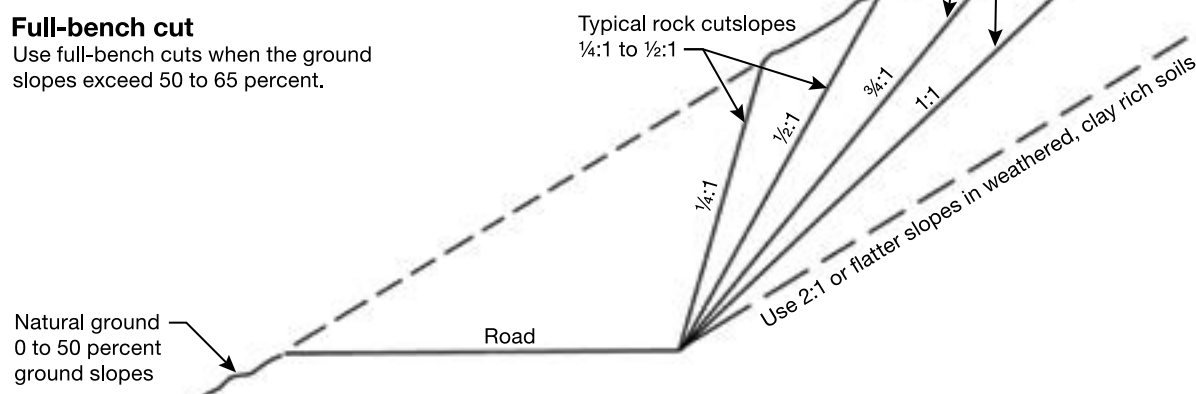


Figure 4.63—A balanced cut and fill, slopes, and commonly used stable cutslope and fill slope angles. Keller et al. (2011)



Figure 4.64—Slope stabilization structure types: a rock buttress (left) and an old masonry rock retaining wall (right). Left photo by Gordon Keller; right photo by Joshua Direen, USDA Forest Service, San Bernardino National Forest.

be deep (tall) enough to have its base placed on firm, in-place material (ideally bedrock) below the depth of slide movement or a slide plane. Walls are built with a subsurface drain behind the structure. In some cases, a lightweight structure constructed with sawdust,

shredded tires, or geofoam can be designed to minimize the driving forces if the wall is placed on a slide or on marginal foundation material. A geotechnical or geological engineer is consulted when selecting and designing retaining structures.

Gravity structures are typically made of reinforced concrete, cellular bins, gabions, masonry, dry rock walls, or large rocks. Structure size depends on the height of the wall needed to fit the site and provide the desired roadway width and elevation. Other design factors include loading conditions on the wall, and allowable foundation conditions. Gravity structures are commonly built up to 25 feet high. Above this height, gravity structures become difficult and expensive to build, so reinforced soil structures are commonly used. For simple gravity structures, the base width is typically 0.6–0.7 times the height to achieve a stable design for simple loading conditions. With traffic loading, the base-to-height ratio is 0.6–0.8. For a hillslope immediately above the wall, the base-to-height ratio is 0.7–1.0. Some structures may require a wider base for unusual conditions, such as a soft foundation, high lateral loads, or seismic loads. Any structure is set onto firm, in-place materials.

Earth-reinforced systems, reinforced soils, geosynthetic reinforced/confined soils, and mechanically stabilized earth (MSE) walls are an economical and effective alternative to gravity-type structures for most wall heights and applications. Following a landslide in 1972, the first MSE wall in the United States was built on California State Highway 39 in Angeles National Forest (fig. 4.65). For walls more than roughly 15 feet high, MSE walls offer significant cost advantages over gravity structures. In the case of rural or low-volume roads, where access may be difficult and when budget is limited, prefabricated or lightweight materials, combined with local soils, are generally recommended.

MSE walls use many facing materials, including tires, wood beams, straw bales, modular concrete blocks, gabions, concrete panels, geotextile or turf reinforcing mats, and other facings. Geotextile and geogrid layers are used to reinforce soils, although welded wire,



Figure 4.65—Mechanically stabilized earth (MSE) walls: (top) reinforced earth system wall built on the Angeles Crest Highway, Angeles National Forest, in 1972; (bottom left) welded wire MSE wall; and (bottom right) geotextile wall. All were used because they are relatively low cost and easy to construct. Upper photos courtesy of The Reinforced Earth Company; lower left photo by Joshua Direen, USDA Forest Service, San Bernardino National Forest; lower right photo by Gordon Keller.

chain-link fencing, metal bars, and metal strips are also used. Welded wire and geotextile walls are commonly used and simple to design (fig. 4.65). Soil-reinforced gabions have a typical basket forming the face and gabion wire mats reinforcing the backfill. Reinforcing spacing is typically 3 feet (the height of a basket). The length of reinforcement is a function of the wall height and loading conditions, similar to other MSE designs. A reinforcement spacing of 8–12 inches is ideal for most MSE or geosynthetic-reinforced soil walls. Berg et al. (2009a, 2009b) describe MSE wall design and construction.

Drainage Improvements

Wet areas, clay-rich or deeply weathered soil pockets, and shear or fault zones require relatively flat cutslopes to reduce the risk of failure. Seeps, springs, and wet areas require special consideration and drainage. In any excavation, the water table remains below the exposed surface (where practical) to prevent instability. If an excavation opens a wet area, or a fill is placed on a wet area, extra measures are taken to drain the slope, flatten the slope more than normal, or buttress the toe of the slope. A stable, wet slope angle may be roughly half the angle of the same stable, dry slope.

Drainage measures, including cut-off trenches or underdrains, toe drains, drainage blankets, filter blankets, and horizontal drains are used to remove water and lower pore-water pressures within the slope. Any reduction in the water table or pore pressures in the slope will improve slope stability. Underdrains are commonly placed along roads in wet cutslope and seepage areas to remove the water.

Deep-Patch Shoulder Strengthening

Uncompacted fills on steep slopes often progressively settle, are a maintenance problem, and are at risk of failure. Grading does not stop the settlement but starts a long-term commitment to continual roadway repair. A deep patch reduces or stops the continual settlement, thus decreasing road maintenance costs. It can improve the site from a marginally unstable site to a stable site. Deep patches can reduce or stop surface movement on sections of roads crossing areas of large-scale slope settlement.

The deep-patch design is a shallow road-fill slope repair by which the upper 3–6 feet of the subsiding section of roadway is excavated, the fill material is replaced with compacted select backfill, and several

layers of geogrid or geotextile are installed (fig. 4.66). Wilson-Musser and Denning (2005) and Cuelho et al. (2012) contain additional information about this technique and design methods.

Soil Bioengineering and Biotechnical Slope Stabilization

Biotechnical slope stabilization (combining structures with vegetation) is cost effective for stabilizing slopes and producing a natural looking structure, particularly for shallow failures. Although planting is labor intensive, vegetation use is typically inexpensive and improves slope stability through root strength. However, because the dry climate in much of southern California can reduce the effectiveness of vegetation in some situations, drought-tolerant vegetation is nearly always required.

Deep-rooted shrub and tree species are preferred over shallow-rooted grasses for most applications (fig. 4.67). Advantages of biotechnical measures are low initial cost, a visually pleasing result using biological systems, and minimal maintenance. Vegetative stabilization is not used by itself for stabilizing large, deep-seated slides.

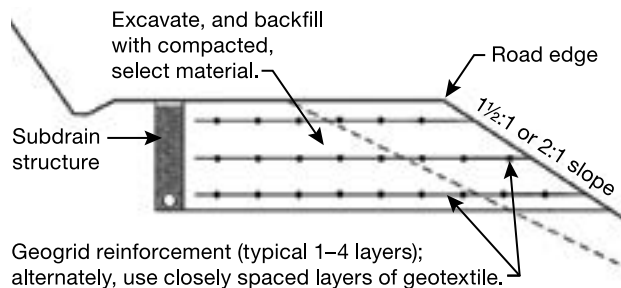


Figure 4.66—Instillation (top) and a cross-section diagram (Keller et al. 2011) of a typical deep-patch, road-embankment repair. Photo by Gordon Keller.



Figure 4.67—A shallow failure at the depth of shallow-rooted grasses (left) and a deep-rooted system from pine tree vegetation (soil bioengineering) that provides deeper stabilization to the slopes (right). Left photo by Gordon Keller, right photo by Donald Gray.

Sidecast Fill Pullback for Slope Stabilization

Sidecast fill material, or loose material placed on top of native soil on a slope, can absorb water and fail at the base of sidecast material. These old, thin, poorly compacted fills commonly fail, particularly on steep slopes. Newer roads do not use as much sidecast construction, and excess material can be hauled to a flatter area or disposal site. However, some fill slopes exhibit instability and warrant treatment because of an excessively steep slope, rotting logs in the fill, local groundwater conditions, and climate stressors.

On steep natural slopes (steeper than 50–60 percent), a road-fill failure can trigger a debris slide downslope of the road fill. These debris slides can travel for long distances, increasing the volume of material involved in the slide and damaging the hillslope itself, particularly if infrastructure is at the bottom of the slope. Most fill failures that cause such an event are identifiable and preventable. Small scarps and curved cracks in the road surface, particularly on the outside half of the road, indicate fill settlement or incipient failure.

In addition to deep-patch repairs, sidecast fill pullback, or removal of high-risk fill material can reduce the risk of failure (fig. 4.68). However, just pulling back sidecast fill (and hauling it to a stable disposal site) can narrow the roadway. In some cases, a roadway ditch can be eliminated to gain road width, which may require additional cutting into the hillside or changing the road grade or alignment. Collins (2007) discusses detection and mitigation measures.

Slope Ravel

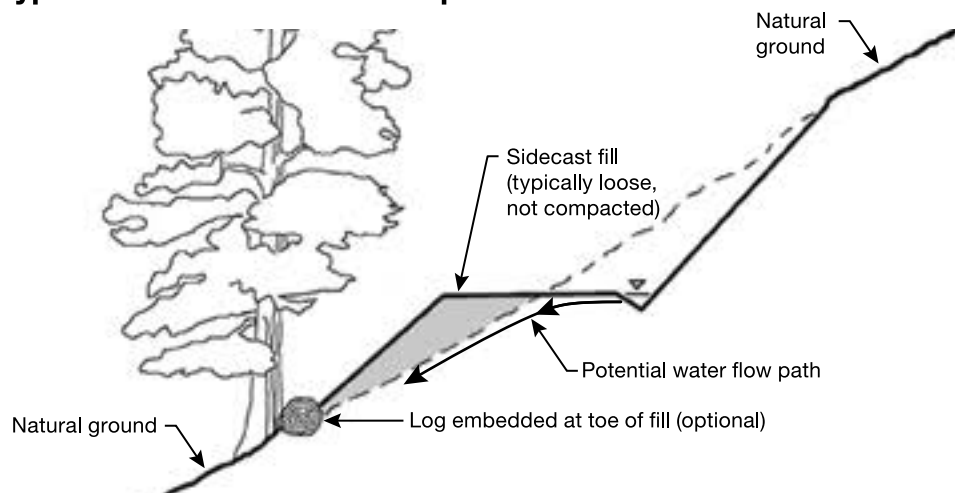
Continual raveling of slopes often occurs after wildfires in southern California (fig. 4.69). This is both an erosion-control problem and a slope-stability problem. Slope ravel occurs because of the loss of vegetation on steep slopes and in soils that are already erodible or contain highly fractured rock. Slope ravel is hard to prevent, but the problem can be anticipated and equipment kept available to remove the material from roadways. In addition, small retention structures can be built to retain the material and keep it off the roadway and out of cross-drain culverts or watercourses.

Debris Flow/Debris Torrent Adaptation Measures

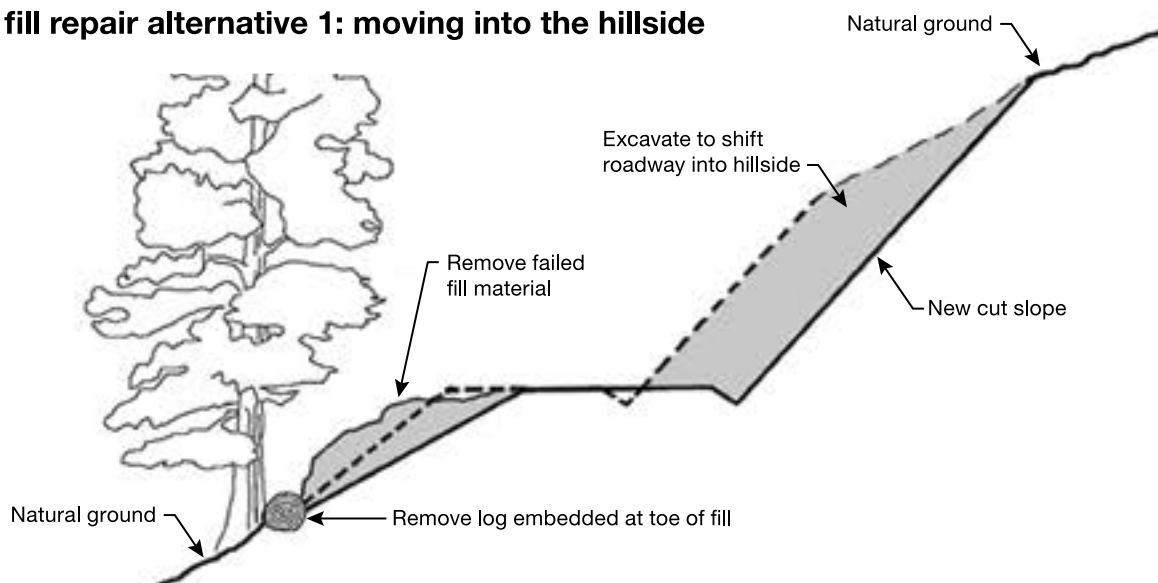
Debris flows are common in southern California on steep terrain following wildfire and after intense rain and may occur more frequently in a warmer climate. A debris flow is a mass movement of mud, rocks, and logs down a channel. It starts as sheet flow on a slope, often accelerated by hydrophobic soils that increase runoff, eventually concentrating the flow and then causing erosion and rilling that initiate sediment transport. The transported soil and water eventually concentrate in the main channels (fig. 4.70).

Sediment-laden flow increases shear at the interface with the channel bed, causing downcutting and transport of increasingly larger material. Note that most of the material in a debris flow comes from channel erosion, not hillslope erosion (Santi et al. 2006). Large amounts of material (rock, sediment, woody debris) can be mobilized in a semiliquid, concrete-like slurry, moving down channels with high energy. Along with all the rock and sediment comes the down woody debris from both the fire and

Typical view of a sidecast fill prior to failure



Failed fill repair alternative 1: moving into the hillside



Failed fill repair alternative 2: eliminate the ditch and narrow the road

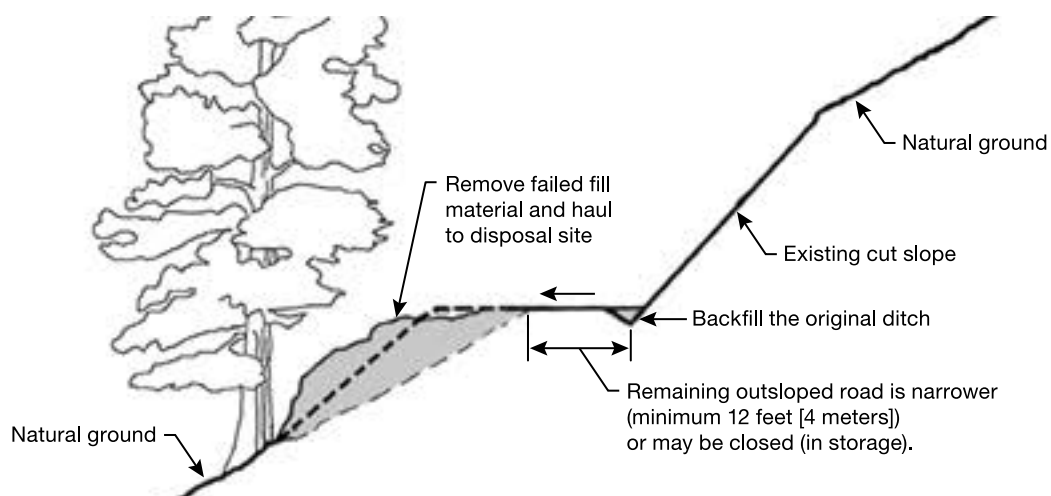
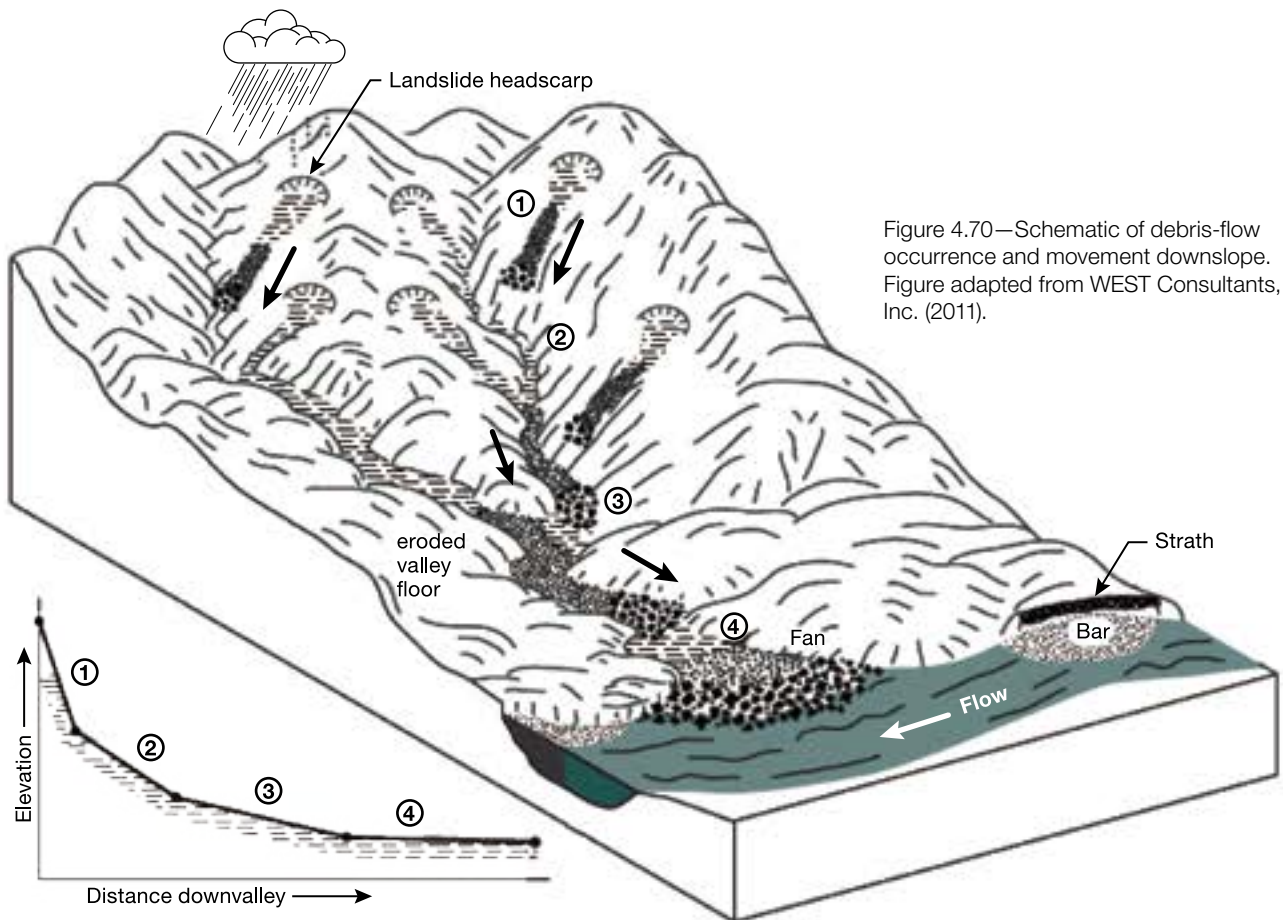


Figure 4.68—Road-fill failure repaired by pulling back or removing loose sidecast shoulder and fill material and shifting into the hillside, possibly narrowing the road. Adapted from Keller and Ketcheson (2015).



Figure 4.69—Examples of slope ravel from steep slopes and erosive soils or fractured rock, particularly after a fire where vegetation is burned off. Bottom right photo shows a wood retaining structure (which is burned) used to catch slope ravel and rockfall. Top photos by Gordon Keller, lower left photo by Donald Lindsay, lower right photo by Allen King.



historical slope deposition. Debris flows can damage or destroy large infrastructure in their path and are dangerous to people. Figure 4.71 shows the source area of debris flows on a steep slope, damage to roads and culverts, and the types of material moving in debris flows. Note the quantity of large boulders being moved in each debris flow.

The U.S. Geological Survey, in collaboration with the Forest Service, often maps debris-flow risk—a function of fire intensity, slope, soil type, and rainfall intensity (Cannon and DeGraff 2009, Cannon et al. 2008). The best adaptation treatment is usually to move or close any infrastructure in a location determined to be at high risk of damage from a debris flow. However, this is difficult to do in a suburban setting or with fixed buildings, highways, and other infrastructure. The following management and physical adaptation measures can be used to protect areas at high risk (fig. 4.72):

- Move vehicle trailers and close vulnerable facilities and campgrounds when heavy rains are forecast.
- Replant upper watershed areas with grasses and deep-rooted shrubs so they will mature before heavy rainfall.
- Disperse drainage on headwater roads with outsloping or frequent cross drains to minimize the concentration of water in drainages that can lead to debris flows.
- Build debris retention structures. This can include gabion walls; porous, open check dams and slotted concrete dams; bollard debris racks; debris-flow netting; and ring nets to trap sediment, boulders, and logs. Basins for large debris and sediment have been used at the mouth of several canyons coming out of Angeles and San Bernardino National Forests. Small debris-retention structures have been built in many drainages in Angeles National Forest. Most are currently filled with sediment.
- Build deflection structures to modify the direction of debris flows away from infrastructure.
- Place local K-rails and concrete barriers to stop or deflect small debris flows.
- Construct angled ramp structures to deflect debris away from bridge piers.
- Clean and reshape drainage channels to reduce debris loading and improve hydraulic capacity.

Because most facilities and infrastructure cannot be moved easily, trapping sediment and debris is a common solution. The challenge is to construct a debris-retention basin or structures large enough to hold the volume of material. Multiple gabion structures are often used to construct a series of retention areas in a drainage prone to debris flows. Care must be taken to avoid building structures that simply force the flow around the structure. Ring nets can be used to catch small potential debris flows with a volume of less than 1,000 cubic yards. They are best used high in the watershed to trap small slides before they build up too much volume and energy. Unfortunately, ring nets can be difficult to install and hard to clean out once they have filled with debris. Larger structures, debris-catchment basins, and debris-retention basins are typically built lower in the watershed, such as at the mouth of a canyon (typically not on Forest Service land).

Bollard debris racks, often using H-piles, are used in debris-prone channels to trap larger debris but allow smaller material to pass through. Debris-flow deflection structures (e.g., berms and barriers) are constructed at critical locations upslope of infrastructure to deflect material away from the infrastructure. Debris-flow mechanics, effects, and mitigation measures are well documented (Chen 1997, Chester and Li 2020, Kean et al. 2016, Piton 2016, Piton et al. 2022, Santi et al. 2006).

Rockfall Prevention

Rockfall refers to quantities of rock falling freely from a cliff face. A rockfall is a fragment of rock (a block) detached by sliding, toppling, or falling, that moves along a vertical or subvertical cliff and proceeds downslope by bouncing or rolling on talus or debris slopes (Varnes 1978). Rockfalls occur on steep slopes in fractured rock deposits during storms or periods of freeze-thaw and can be accelerated in areas of high-intensity burns. They can be a significant safety hazard for people and create maintenance challenges. Several techniques are available to prevent and protect against rockfalls (fig. 4.73).

Rockfall netting, rolls of fabric with lacing, and metal fencing or netting can cover the surface of slopes to protect infrastructure built on the foot of the slopes or to trap rock against the slope before it rolls downward. Rock bolts can be used to pin down specific rock blocks. Rock anchors usually involve a specific design and are used only on forest roads in problematic areas. Gabion or

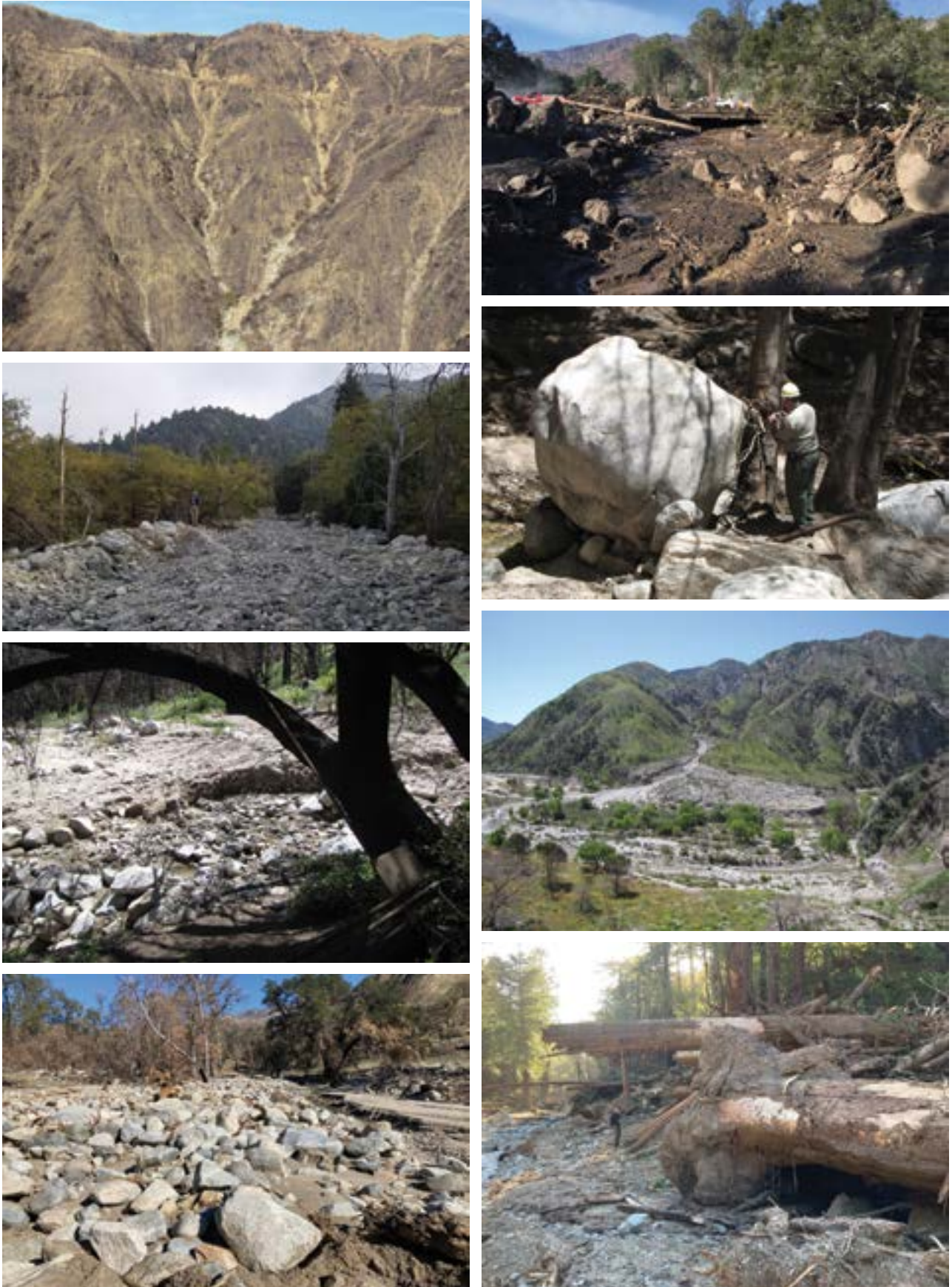


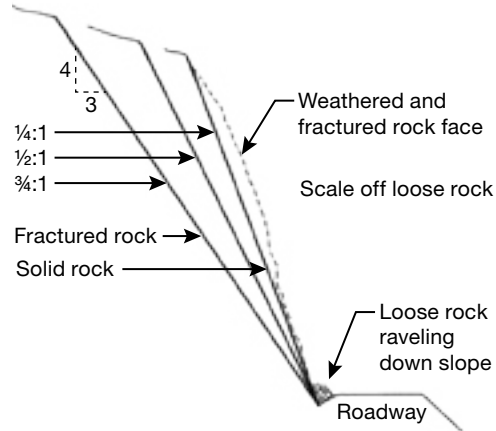
Figure 4.71—Source area of debris flows (top left) and damage to infrastructure from the debris flow after the Thomas Fire in Montecito (Los Padres National Forest) (top right). Other photos show a variety of debris-flow materials from other burned areas. Upper photos by Donald Lindsay, middle photos by Allen King, bottom photos by Yonni Schwartz.



Figure 4.72—A variety of debris-flow retention structures or adaptation measures, including gabion walls, ring net structures, bollard and other debris racks, debris retention basins, channel modification and enlargement, and K-rail or structures to stop or deflect flows. Top left and bottom right photos by Allen King; top right photo by Yonni Schwartz; all other photos by Donald Lindsay.



Typical cut slope angles in hard rock



Terraces (benches) built into a high rock cut

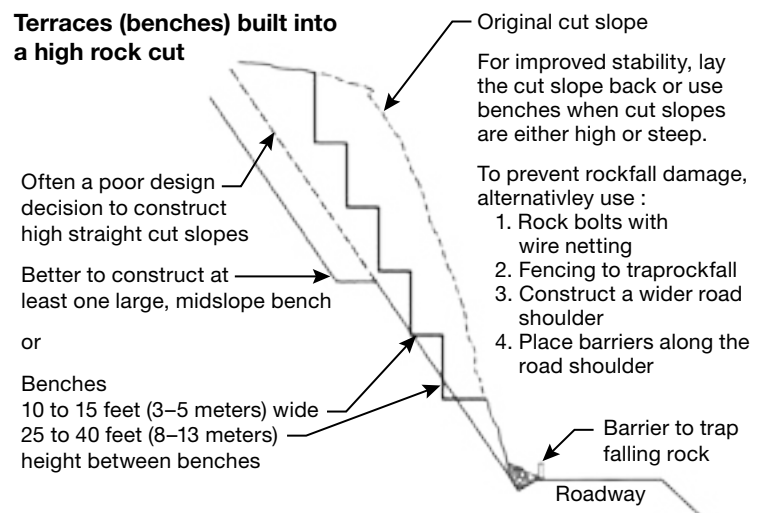


Figure 4.73—A common rockfall problem after a fire (photos) and rockfall prevention and protection measures (drawing). Adapted from Keller et al. (2011), Left photo by Allen King; right photo by Gordon Keller.

MSE barriers constructed as retaining walls can prevent stones from falling from a cutslope or cliff onto a road.

Catchment fences and rockfall protection embankments or berms can also be effective. Solutions may require a combination of scaling, rock bolting, buttressing, constructing terraces, and wire mesh or netting. Scaling removes loose rock, terraces catch rockfall, and road shoulder barriers prevent rock from reaching the roadway. Other mitigations include the installation of traffic signs along the road to warn of falling rock in mountainous areas where the road has a history of rockfall problems. Removal of loose rock, unstable soil, trees, and other debris from the slope are also effective in preventing rockfall during storms. Muhunthan et al. (2005) and Turner and Schuster (2012) describe rockfall analysis and mitigation.

Other Road Issues

Several road adaptation measures can be considered when evaluating the effects of climate stressors, such as atypically cold periods, early thawing, intense storms, drought, and wildfires. Challenges include timing and implementation of contracts, effects on asphalt roads, fire-related road issues and detours, removal of hazard trees after fires, declining water sources, and dust from roads during drought.

Fire and Cold Effects on Asphalt

Various climatic conditions are making road pavement management more difficult. Temperature extremes, soil saturation from flooding, and sea-level rise are all affecting asphalt pavements in some locations, leading to a shorter design life for roads. Climate-induced weather conditions have led to increased pavement

rutting and bleeding (in which asphalt binder fills the aggregate voids during hot weather and then expands onto the pavement surface), reduced flexibility, and increased maintenance needs (Haslett et al. 2021). Extreme cold and multiple freeze-thaw cycles, although rare in southern California, can damage asphalt and the subgrade materials. Intense heat from wildfires has also been observed to damage pavements in national forests, with premature cracking and oxidation of roads within the fire area. Reclamite³ and other asphalt rejuvenating agents may be able to extend the life of damaged asphalt.

Heat from a fire can bake the asphalt, making it stiffer and more brittle, resulting in fatigue cracking from hot and cold cycles and premature failure. In addition, some paved roads in the SOCAAP assessment area have reached the end of their design life and are in marginal to poor condition. Additional traffic from increased recreation, fire suppression, and rehabilitation activities can further damage paved roads. Thicker asphalt has been used to compensate for asphalts weakened from excessive heat. Asphalt mix designs and materials specifications are being modified to compensate for hotter temperatures, and regional climate projections are being incorporated into pavement designs and maintenance plans (Haslett et al. 2021). Soil moisture meters can be used to support management decisions to open or close

roads. Alternatively, during long drought periods, drier subgrade conditions can improve pavement performance. Evaluating new materials and pavement treatments can ensure that the carbon footprint of transportation systems is decreasing.

Fire Suppression Routes and Detours

During and after wildfires, some forest roads receive heavy traffic from fire suppression activities and rehabilitation efforts. Closed roads may be opened to trucks, engines, and crew buses for fire access. These roads are in most cases not stabilized to support heavy traffic, so considerable rutting or dust is produced. Alternate detour routes are often specified to accommodate normal traffic and fire suppression equipment. All these activities create additional work after fires to repair roads or close them again. Most roads used for fire suppression activities require maintenance after the fire.

Hazard Trees

Higher temperatures and higher drought frequency associated with climate change will increase stress for vegetation (Polade et al. 2017), in some cases leading to increased tree mortality. Dead and dying trees along a road with the potential to fall are considered hazard trees (fig. 4.74). Hazard trees present a safety risk to both forest visitors and agency employees. On local Forest Service and National Park Service roads, maintenance crews often remove hazard trees, and roads and facilities are often closed for some period, depending on the need for access.

³ The use of trade or firm names in this publication is for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.



Figure 4.74—Hazard-tree removal site along a forest highway for traffic safety (left); other roads may remain closed because of hazard trees killed by drought, insects, and fires. Photos by Gordon Keller.

Droughts and Dust

Prolonged droughts or a short rainy season followed by a long, hot summer—typical of southern California weather—commonly lead to dusty conditions on unsurfaced forest roads. Dust suppression materials are often needed on log-haul roads or heavily used recreation roads. Dust particles translocated away from the road surface reduce the growth of adjacent forest, increase erosion problems, and can reduce visibility for drivers. Reduced visibility can create a hazard for both forest management and recreation traffic.

Increased road operation and maintenance costs for dust suppression during drought can be anticipated. Many dust palliatives are available, depending on soil type and local conditions (Bolander and Yamada 1999, Jones 2017).

Water is commonly used to suppress dust, but water sources may be limited and distant during a drought. Blading can be performed when natural soil moisture is optimum, or water trucks can be used to maintain soil moisture. Calcium chloride is also used as a dust palliative in many locations. The cost and work involved with dust suppression can be considered a potential climate change effect.

Contracting Road Work

Projected climatic variability and stressors will affect the contracting process for roads and other infrastructure. Variable cycles of rain and drought, altered seasons, and warmer temperatures will affect the times during which roads and facilities are accessible. As a result, recreationists, contractors, and permittees will likely request that roads and campgrounds be opened earlier than has been done historically. Erratic weather makes it difficult to implement road maintenance contracts. Storm damage and fire rehabilitation require additional contracting beyond typical work. Agencies will need increased flexibility and experienced staff and contracting officers to respond to changing seasons and unanticipated events. On the other hand, improved access due to hotter, drier conditions may be beneficial for the preparation and implementation of contracts. Dry road subgrades may be stronger, and a longer construction season may evolve.

Trail Issues

Many of the adaptation options for roads discussed above also apply to making trails more resilient to climate change. Land managers can follow a similar assessment process for trail systems as for roads. The SOCAAP assessment area has an extensive trail system with 3,211 miles of trail, mostly nonmotorized, in a variety of ecosystems managed and maintained in collaboration with public-private partnerships and trail-user groups (table 4.3). The Pacific Crest Trail begins in Cleveland National Forest and traverses high alpine regions of San Bernardino and Angeles National Forests, including 176 miles of trail in Angeles National Forest. Los Padres National Forest has 205 hiking trails and 56 off-highway vehicle trails, for a total of 1,433 miles of trail. More than 500 miles of trail crisscross Santa Monica Mountains National Recreation Area. With the expected changing climatic and hydrologic regimes, trails will need to be increasingly resilient to higher temperatures, higher storm intensities, and likely fewer locations with available water.

Increasing the resilience of trail systems will require creative approaches, especially given that small budgets are available for trail work. Partnerships are helping national forests throughout the SOCAAP assessment area to maintain parts of its trail system. Adaptation treatments include moving some trail segments away from creeks or meadows; improving trail bridges; hardening the trail surface of some wet areas; adjusting trail maintenance timing and season of use; removing hazard trees along trails; limiting access and timing of use; modifying points of access; and developing more flexible agreements with partners to deal with earlier trail use, longer season of use, and damage from fires (see chapter 5). Remedies for fire damage can include replacing or repairing bridges and small walls, removing slope ravel from the trail tread, and reconstructing a section of the trail (fig. 4.75).

There are 44 trail bridges on the four southern California national forests; more than half of them are in Angeles National Forest (table 4.3). Trail bridges will require more robust designs to deal with increased streamflows in the future. In addition, trail bridges are more susceptible to fire damage, because many are constructed with wood. Trails and bridges are often damaged by falling trees during a fire, as well as by



Figure 4.75—Damage to trails and trail bridges after a fire. Structures may need replacing, and sections of trail may require heavy maintenance or reconstruction. Left photo by Allen King, right photo by Jonathan Berry.

burned hazard trees. A partial solution is to leave large shade trees along trails but remove most of the understory and ladder fuels. Groenier and Gubernick (2010) discussed issues related to the location and design of trail bridges.

Adapting Facilities Infrastructure to the Effects of Climate Change

Southern California national forests have a total of 2,256 fire, administrative, and other buildings and facilities (table 4.6). Santa Monica Mountains National Recreation Area has many additional facilities and campgrounds. The facilities serve many purposes, ranging from administrative offices in urban areas to backcountry cabins. Total current replacement value for these facilities is \$528 million dollars.

Since 2004, every national forest in the Forest Service’s Pacific Southwest Region has had a facility master plan. Some forests have done updates, but most facility master plans need updating. Following a standard template, a facility master plan has four management options: (1) retain, (2) decommission, (3) convert to alternate use, or (4) acquire. Each existing building has a management option listed. Owned and leased buildings are included, and proposed future acquisitions are discussed. The facility master plans are valid for 10 years. Incorporating components of climate change assessment and adaptation in future revisions of these plans would be beneficial.

The Forest Service has a capital improvement program, which is a national funding mechanism that funds top-ranked projects. This is typically the only funding source for new facilities. National forests or the regional office manage most maintenance and decommission projects. To date, emphasis has been on developing

Table 4.6—Forest Service-managed buildings in national forests in the Southern California Adaptation Partnership assessment area

National forest	Buildings ^a	Total deferred maintenance	Current replacement value
DOLLARS			
Angeles	734	25,850,983	191,044,180
Cleveland	476	50,309,011	113,137,829
Los Padres	564	36,624,983	102,572,447
San Bernardino	428	10,288,985	121,051,538
Total	2,202	123,073,962	527,805,994

^a Source: USDA FS (N.d.c).

energy-efficient facilities for which national funding is available for selected projects striving for net zero emissions (Meyer et al. 2013). Energy-savings performance contracts have been implemented to reduce energy usage. These use third-party financiers and contractors to develop large-scale (greater than \$1 million) energy-efficiency measures.

Wood products in building systems have lower environmental burdens than functionally equivalent products (steel, concrete), and require less energy if used in wall systems (Ritter et al. 2011). Replacing other materials with wood products reduces the rate of carbon emissions to the atmosphere (Furniss et al. 2018). However, because wood is flammable, additional fire protection measures may be preferable in some facilities. This can include clearing around buildings, treating the wood, removing loose flammable materials near buildings, fire-proofing structures with foam/gels when a fire threatens, or ultimately relocating some facilities to defensible locations. In addition, evacuation routes, alternative routes, and safety zones need to be identified.

Adaptation measures and building design modifications to accommodate a warmer climate include better insulation in the structures, modified roof design with respect to snow load and the weight of rain on snow, and modified footing depth with respect to the frost protection line (Olsen 2015). Although the climate is generally getting hotter, climatic variability and extreme conditions have produced severe cold events. The Forest Service uses current building standards for structures, but a warmer climate and more frequent forest fires may warrant altered designs.

Structures can be made more resilient to fires by creating defensible space through thinning, prescribing burns or mechanical fuel reduction once the area is thinned, and clearing vegetation adjacent to structures. Agencies can partner for mutual aid and work with local fire-safe groups to aggressively reduce fuels on federal lands and adjacent private lands. This includes environmental education and communications with the public about fire hazards. In addition, using nonflammable materials and metal roofing can make structures more fire resistant (fig. 4.76).

An ongoing concern is the existence of old facilities that are in poor condition but for which funds for renovation are limited, including fire guard stations, housing, administrative buildings, and support facilities. Fire prevention and fireproofing can be implemented,

but replacement of facilities is unlikely unless they are destroyed and need to be rebuilt. In the meantime, the facilities are a risk, but funds are used to maintain the structures and limit deterioration.⁴

⁴ **Globokar, D. 2023.** Personal communication. Chief facility manager, Santa Monica Mountains National Recreation Area, 26876 Mulholland Highway, Calabasas, CA 91302.



Figure 4.76—Tree thinning for defensible space, metal roofing, and nonflammable siding materials help make facilities more resilient to wildfires. Note that for fire safety, a couple of the trees nearest the structures can be removed. Photos by Gordon Keller.

Several actions can be implemented for forest facilities to reduce greenhouse gas emissions. A Santa Monica Mountains National Recreation Area study found that 76 percent of its greenhouse gas emissions was from transportation. Those emissions can be reduced by downsizing its fleet, buying hybrid and electric vehicles, accelerating replacement of old vehicles, analyzing fuel use for more efficient operations, reducing travel, and reducing vehicle idling by staff and visitors (box 4.8). Other actions include upgrading to energy-efficient lighting (LED), minimizing so-called vampire energy use (when appliances and electronics are turned off but still using electricity), installing solar systems, following Leadership in Energy and Environmental Design program recommendations for energy-efficient building construction, reducing lighting needs with motion sensors, weatherizing existing buildings, using recycled office products and reducing office waste, installing low-flow faucets and urinals, recycling visitor waste materials where possible, and promoting public education programs (USDI NPS 2011).

Other facilities and infrastructure found on federal lands include telecommunications installations, water impoundments, and powerlines. This infrastructure is often owned and managed by other agencies or utility companies but is located on federal land. Those nonfederal organizations are responsible for the operation, management, and protection of the infrastructure, but access is typically on roads across public land. The road maintenance and drainage measures discussed previously in this chapter can be implemented to reduce damage.

Developed Recreation Sites

Developed recreation sites are common assets that are often vulnerable to climate-related stresses. Damaged recreation sites reduce access for visitors, expose forest visitors to hydrologic and geologic hazards, and may cause considerable economic loss to local businesses (chapter 5). Campgrounds and trailheads near streams are particularly vulnerable to flooding and debris flows, with risks to infrastructure and human safety (fig. 4.77). Similar issues may affect boating sites along streams, and some lakeshore sites may become less accessible when water levels are low during droughts.

Adaptation measures to minimize climate vulnerabilities include moving developed recreation sites back from rivers or to upslope locations, modifying channels or hardening streambanks near campgrounds and facilities, and placing only expendable or flood-proof improvements in potential flood areas. Facilities must be managed to ensure swift evacuation in the event of forecasted flooding or other potentially damaging events. In certain areas, having additional access roads or broad access routes that double as evacuation pathways may be advantageous. Some campgrounds may be able to stay open longer during the year, while others may need to be closed or have reduced capacity.

Water Systems

Water supply systems are critical for facilities, administrative sites, campgrounds, ski areas, and occasionally trailheads. Evaluating future water needs and trends is key to meeting future demands. Pursuing both improved water conservation and increased sources can yield the most benefit. Fires and floods can damage pipelines and some historical water conveyances, such as flumes and ditches. Periods of drought will lower the groundwater in some areas, possibly reducing the yield of springs. Intense rainstorms often overwhelm water-diversion structures and temporarily contaminate the water supply. Wildfires can also damage water quality in lakes (including municipal water supplies) and streams.

Water supply sources and systems can be adapted to climate stressors by burying pipelines currently on the ground surface and by fireproofing pumphouses and related facilities. Wells or springs with a track record of limited water yield may require assessment, potential deepening, augmentation of water storage, enhancement of groundwater recharge, better management of runoff capture and storage, or the exploration of alternative water sources. Some historical flumes have been damaged by fires and may need to be reconstructed. Removing vegetation near the flume will reduce its vulnerability to fires. Plastic water pipes and facilities can be damaged or destroyed during a fire, and that damage can lead to water contamination. Buried pipes are typically safe, but exposed plastic pipes can benefit from being protected; or metal pipes could be used in exposed areas.

Box 4.8**Building Climate Resilience and Reducing Fossil Fuel Emissions at Santa Monica Mountains National Recreation Area**

Santa Monica Mountains National Recreation Area is managed by the National Park Service (NPS) in the mixed rural and suburban areas of the Santa Monica Mountains in the Transverse Ranges west of Los Angeles. Sixty percent of the land is public, and forty percent is private property. Spread over 157,700 acres, Santa Monica Mountains National Recreation Area is the largest urban national park in the world, and contains many structures, roads, and trails.

Santa Monica Mountains National Recreation Area is comprised of NPS land, California State Parks land, other local-agency parks, university study reserves, and private property with conservation easements. It includes Griffith Park, Will Rogers State Historic Park, Topanga State Park, and Malibu Creek State Park.

Wildfires are a significant threat to Santa Monica Mountains National Recreation Area. The Woolsey Fire (2018) was driven by strong winds for over 36 hours, burning 83 percent of the NPS land (25,000 acres). Given the vulnerability of structures in this location, efforts are underway to make facilities more resilient to fires. In addition, the NPS and Santa Monica Mountains National Recreation Area have developed several strategies to reduce greenhouse gas emissions.

Fire Protection and Adaptation

Many structures were burned or damaged during the Woolsey Fire, which helped motivate current efforts to “fire harden” structures in Santa Monica Mountains National Recreation Area.¹ A wide variety of “fireproofing” measures have been undertaken for structures, including moving to, or building new structures in more defensible locations. Fire-hardening measures include the following:

- Mowing vegetated areas around structures
- Removing overhanging vegetation
- Using fire-resistant doors

- Sealing soffits and keeping gutters clean
- Raking debris, leaves, and litter away from building perimeters
- Building with nonflammable materials where possible
- Using metal roofs (siding and roofing materials are replaced only if a structure needs to be rebuilt)
- Moving new buildings to low-fire risk locations

Greenhouse Gas Mitigation Measures

The document *Santa Monica Mountains National Recreation Area Action Plan* (USDI NPS 2011) describes strategies and actions that the NPS is taking to reduce greenhouse gas (GHG) emissions. Seventy-six percent of their GHG emissions are from the transportation sector.

Transportation management efforts include the following:

- Replace old NPS vehicles with hybrid, electric vehicles, or fuel-efficient vehicles.
- Reduce the number of fleet vehicles.
- Analyze fleet fuel-consumption patterns to improve efficiency.
- Promote reduced vehicle idling by visitors and staff.
- Reduce travel for meetings.

Other agency efforts for GHG reduction include the following:

- Encourage energy conservation in all park activities.
- Upgrade light fixtures and bulbs to energy-efficient products.
- Install energy-efficient light emitting diode (LED) or solar outdoor lighting.
- Purchase only energy-efficient electronic equipment.
- Weatherize park buildings (add insulation, improve window glazing, etc.)
- Purchase recycled materials and office supplies; reduce product packaging.
- Encourage recycling.
- Install low-flow water faucets and toilets.

Finally, Santa Monica Mountains National Recreation Area is engaged in climate change education and outreach to the park staff, visiting public, and local communities.

¹ Globokar, D. 2023. Personal communication. Chief facility manager, Santa Monica Mountains National Recreation Area, 26876 Mulholland Highway, Calabasas, CA 91302.



Figure 4.77—A trailhead, buildings, and campgrounds damaged by fires, flooding, and debris flows. Top left, middle, and bottom right photos courtesy of Alan Yamada; top right photo courtesy of Allen King; bottom left photo by Yonni Schwartz.

Adapting Dam Infrastructure to the Effects of Climate Change

National forests in the SOCAAP assessment area contain a total of 87 dams (table 4.7); the Forest Service manages 39. The remaining 48 dams operate under authorizations, such as preforest easements, ditch-bill easements, and permits. These are managed by groups or agencies such as the California Department of Water Resources; Los Angeles Department of Power and Water; Arrowhead Lake Association; Big Bear Municipal Water District; homeowner groups; and cities, local governments, and other water districts. The authorized dams are vital to

the communities they serve. They provide drinking water, generate power, and provide flood protection. Many of the authorized dams are high hazard (loss of life is likely in the event of failure) with thousands of people at risk downstream. The hydropower facilities in national forests are within Federal Energy Regulatory Commission (FERC) boundaries and subject to the commission and Forest Service regulations (FPA 1920: Sec. 4 (e) provisions).

Nonfederally owned dams in national forests are subject to the regulatory authority of the California Department of Water Resources, Division of Safety of Dams. In addition, there are more than 200 debris

Table 4.7—Dams managed by the Forest Service, Federal Energy Regulatory Commission, and other organizations in national forests in the Southern California Adaptation Partnership assessment area

National forest	Infra database	Forest Service	Federal Energy Regulatory Commission	Other organizations
NUMBER				
Angeles	13	4	6	9
Cleveland	24	14	0	10
Los Padres	15	8	2	7
San Bernardino	35	13	6	22
Totals	87	39	14	48

Source: USDA FS (N.d.d).

structures throughout the SOCAAP assessment area. They provide debris retention, grade control, and tailings impoundment. Most of the grade-control structures are located in drainages of the San Gabriel Mountains in Angeles National Forest. These structures are designed to retain soil and rock much like a retaining wall. They are porous, allowing water to drain through and dissipate pore pressure in the soil. They are not designed for water storage. Some drainages may have up to 12 debris- or grade-control structures along the channel. These structures are tracked but not included in the jurisdictional Forest Service dam inventory (or National Inventory of Dams), which is focused on water-retention structures.

Dams are included in the reportable inventory if they are considered jurisdictional. A jurisdictional dam includes dams that are (1) at least 6 feet high and store at least 50 acre-feet of water or (2) at least 25 feet high and store at least 15 acre-feet of water. Dams that fall outside of these size and storage requirements can still be in the reportable dam inventory if they are significant or high hazard. The hazard classifications—low, significant, and high—categorize consequences resulting from a dam failure. A high-hazard dam has a high probability of loss of life. A significant-hazard dam has a low probability of loss of life but high probability of environmental and economic loss. The hazard classification is somewhat subjective. For example, a dam might be classified as high hazard if a critical service (e.g., emergency access to a community) would be lost if the dam failed.

Spillway capacity requirements are a function of hazard level. High-hazard dams are required to pass the “probable maximum flood” (PMF)

standard. Significant-hazard dams must pass a half-PMF. Low-hazard dams must pass a 100-year flood. The size of the flood a dam must pass can be lowered through an incremental damage assessment that analyzes risk downstream. Most Forest Service-owned dams were not built to a rigorous standard and may not be designed to accommodate increased flood flows. A changing climate will likely increase the magnitude of floods at various recurrence intervals, including the PMF. Dettinger (2011) and others have discussed the effects of extreme climate events in California. Increased PMF could exceed 30 percent based on climate model simulations that show significant potential for higher atmospheric mean and maximum water-vapor concentrations, leading to higher maximum precipitation values across the United States (Kunkel et al. 2013). In any event, a dam built in the context of climate change risks will need specifications for design and management that accommodate expected future conditions.

Increasing temperature and periods of drought in the future are expected to reduce water supplies for agriculture, industrial uses, human consumption, and fisheries, particularly during late-summer months when water is most needed. In regions where lower precipitation is projected, dams are usually a buffer to prevent water shortages. As a result, there may be increased emphasis on maintaining current dams, adding storage to dams, and applications for additional dams on public lands, particularly upstream from areas where private uses of water exceed or nearly exceed streamflows during critical water-need seasons. Additional dams and hydroelectric generation can also contribute to meeting renewable energy goals.

If rainfall intensity and high-volume events increase in the future as model projections suggest (chapter 2), dams will be increasingly subject to flow patterns that were not characteristic during the time of their design and construction (chapter 3). It will be critical to assess storage capacity, spillway capacity, and operable gates. Historically, water levels are lowered in the reservoir during the winter months on many dams to provide downstream flood protection. Ongoing drought conditions could force changes in the operation of dams to include increased storage in the winter to help meet water- and power-generation demands. Such changes could increase risk downstream, especially during extreme storms because the capacity to store water and attenuate flows downstream will be lower. Large population centers are located downstream of many dams.

Some dams have lost significant storage capacity over the years because sediment has infilled their reservoirs. Larger storms and wildfires may accelerate this problem as sediment and debris are mobilized in watersheds. This can affect control structures in the dam or reservoir, and less water will be available in the reservoir. Periodic cleaning of the reservoir may be needed.

Periodic inspections of dams for safety hazards by federal agencies may be even more important in the future. Dam inspections after major storm events are critical. This issue is a high priority for federal agencies because dam maintenance and inspections may not be up to date because of limited funds and personnel.

Gates, valves, and overflow or water release apparatus are inspected and repaired to ensure that increased

inflows during major storms can be released. Freeboard (the distance between the waterline and the top of the dam) on dams can be evaluated to ensure that the dam will not be overtopped. If the freeboard is small, an auxiliary spillway can be added to increase capacity, or the spillway can be lowered to increase freeboard (fig. 4.78). Because reservoir water levels may fluctuate considerably during periods of drought or heavy rainfall, managers can be flexible and make adjustments for recreational use of facilities adjacent to lakes. Some boat ramps may need to be lengthened, or adjustable elevation platforms can be installed on docks to facilitate use of facilities (chapter 5).

Effective spillways and associated apparatus are functional and free of debris and vegetation. If increased inflows are anticipated, the spillway capacity can be determined. If the spillway is too small for the anticipated flows, then it can be increased in size to allow the passage of the routed hydrograph associated with the flood recurrence level. Alternatively, an auxiliary spillway or embankment hardening (overtopping protection) can be added.

Wildfires near dams can damage access roads, transmission lines, penstocks, and other infrastructure. Some dam embankments are covered with vegetation, creating a potential fire hazard. When a fire burns across the dam, the vegetation is burned, and if roots burn, deep voids may be created in the embankment (fig. 4.79). If the roots do not burn immediately, they will decay in several years, leaving possible voids in the dam embankment that can leak, lead to piping, and cause dam failure. Prevention measures include lowering the pool elevation of the



Figure 4.78—Earthen dams with minimal freeboard (distance between the waterline and the top of the dam) and risk of overtopping because of a blocked or inadequate spillway. In the left photo, the spillway is being lowered to create more freeboard. Left photo courtesy of Herman Wendell, right photo by Gordon Keller.

water to decrease pressure on the dam face or reworking and recompacting the dam face to fill voids. Keeping trees with deep roots off the embankment is a good maintenance practice.

Fires also cause additional hydrologic risks. Postfire conditions in the watershed can greatly increase sediment and flows into the reservoir, with flow peaks that are 10 times that of normal flows. In some cases, spillways may not be large enough to accommodate this increased flow. Sediment transport into a reservoir reduces water storage capacity and can clog outlet control structures. Woody debris entrained in large flows and carried downstream can be especially damaging because they can plug spillways, causing overtopping and failure of the dam. This condition is transitory, usually dissipating gradually over several years. However, frequent droughts may increase the time needed for watershed recovery, extending this transitory period significantly.

Federal Energy Regulatory Commission (FERC) Dams

A total of 14 FERC-authorized hydropower projects are in Angeles, Los Padres, and San Bernardino National Forests. In the Forest Service, Pacific Southwest Region, 26 small hydropower projects fall under a FERC-exempt category, administered under special-use authorizations. Currently, 10 licensed dams are undergoing various stages of the FERC relicensing process.

Incorporating climate change stressors and adaptation into current FERC relicensing of dams and related facilities will lead to improved outcomes for long-term dam management. Many of the dams under FERC license are large and operated by municipalities and other stakeholders. Many are high-hazard dams because of their size, storage capacity, and vulnerable populations downstream. FERC licenses extend for 20–50 years, a period in which many climate-induced events may occur.

Operational changes that increase water storage during the winter for water and power generation and for instream flows for fish habitat could become more of a focus, especially if prolonged droughts occur. Extended transitory postfire conditions in watersheds above dams have generally not been a priority but should be emphasized in emergency action plans in the future. Watershed conditions should be assessed annually to ensure assumptions made in the establishment of the design flood are still valid. Fires and floods will likely move more debris into reservoirs, plug or interfere with intake structures, or damage gates and water-control structures.

Some reservoirs will have a longer recreation season in a warmer climate (chapter 5). Large storm events, such as those that bring water vapor from the tropics (atmospheric rivers, pineapple expresses), are part of the global water cycle and influence water supply in the Western United States. Although most of these storms are weak systems, some storms can release large volumes of rain



Figure 4.79—An earthen embankment of a dam where wildfire has burned the vegetation and tree roots, leaving deep voids in the embankment. This increases the risk of piping and dam failure, which can be mitigated by removing large vegetation from the dam face and embankments. Photos courtesy of Jonathan Berry.

and snow along with strong winds, causing flooding events, especially if the storms stall after making land-fall (chapters 2, 3).

The recurrence interval of such storms is projected to decrease with climate change. Large flood events are expected to increase in frequency from once a century to twice or three times a century. For example, the great flood of 1862 left the California Central Valley under water for six months. Climate modeling suggests that this type of flood could occur at least twice a century in the future. These types of storms can significantly stress hydraulic and dam infrastructure. Downstream effects will be substantial if dams fail or simply pass floods through (little to no flood protection), potentially threatening downstream populations and damaging bridges and recreation facilities.

Hydroelectric power generation is a low-cost energy source, filling gaps for power generation when renewables drop off and providing power during peak demand periods. A changing climate could significantly alter hydroelectric power generation capacity, which depends on water stored in reservoirs. Less water means fewer turbines will be online at any given time or will be operated at less than optimal levels to meet peak demands. Increased storage or pumped storage systems may be partial solutions. However, economic viability of the hydroelectric facilities will be an issue for many utilities. Some already operate at a loss because power generation capacity has been reduced. Efforts to adopt alternative forms of energy in California could lead to less demand for hydroelectric dams, but future energy demands are also likely to increase overall. Therefore, hydropower is likely to persist unless the cost of alternative energy decreases significantly. This means climate change effects will be an important consideration for future operations of facilities in the SOCAAP assessment area.

Conclusion

Federal lands in the SOCAAP assessment area provide recreation opportunities, water, and a wide range of other resources. Road systems, hundreds of bridges, culverts, a major trail system, many dams, and thousands

of buildings are all part of the infrastructure needed for sustainable management on federal lands. These facilities and infrastructure represent a major investment that will be increasingly vulnerable to stressors associated with climate change. Key climate stressors include warmer temperatures, longer periods of drought, larger wildfires, larger storms, more intense precipitation, debris flows after storms, and altered timing of peak streamflows. Southern California is subject to frequent large wildfires that damage infrastructure and resources in the SOCAAP assessment area, illustrating the need for adaptation to climate change. The periodic sequence of fires, intense rains, and debris flows adds to management challenges on federal lands.

This chapter has described many types of infrastructure and vulnerabilities in the SOCAAP assessment area. Specific options for adapting roads to climate change are summarized in box 4.9. Infrastructure on federal lands in southern California is extensive and represents a huge capital investment, but even routine maintenance is often beyond the capacity of current funding and personnel. The additional challenges posed by climatic variability and change will make it more difficult to ensure long-term functionality of infrastructure. Therefore, assessing vulnerabilities, identifying resources at risk, and prioritizing adaptation actions are critical (box 4.1). Implementing climate change thinking and storm proofing in day-to-day resource management and agency operations can increase the likelihood of sustaining critical infrastructure for future generations.

Considerable infrastructure data are available in the Forest Service Infra database and other databases. Projections of temperatures, altered timing and amount of streamflow, and altered snowpack are also readily available (Dettinger et al. 2018: chapter 2). This information can be combined to identify areas of greatest vulnerability, such as where roads are located near streams with likely increased flows, or where undersized culverts will be subject to increased flows. Timely, effective responses to these vulnerabilities can help ensure the long-term sustainability of roads and other infrastructure on federal lands in southern California

Box 4.9**Options for Identifying and Reducing Vulnerability of Roads to Climate Change**

Identify areas with historical or potential vulnerability. Some high-risk sites are well known, others may be more subtle. Chronically undersized culverts will have a history of failure. The following generally have high vulnerability: geologically unstable materials or slopes, roads on steep slopes with sidecast fills, roads that cross steep channels subject to debris flows, wet slopes, areas subject to flooding, and areas subject to high soil erosion near streams. Some sites may have a documented history of storm-damage repairs.

Avoid local problematic and high-risk areas. Consider road closure or relocation to avoid problematic areas and poor road locations. Common problematic areas include steep slopes (over 60 percent); deep-seated rotational landslides; areas prone to shallow, rapid landslides and debris torrents; avalanche chutes; rock-fall areas; wet areas; saturated soils; and highly erodible soils.

Use appropriate minimum design standards. Minimize road design standards, particularly road width, where appropriate, while still considering traffic safety and road user needs. Because storm damage risk-reduction treatments involve existing roads, road standards are already in place. However, these treatments can be used to reduce the standard as appropriate and result in less earthwork, lower cuts and fills, and less concentration of runoff—all of which reduce risk of damage or failure during storms.

Employ self-maintaining concepts into the selection and implementation of treatments. Resources for road maintenance are often limited. Implementing treatments that reduce the amount of road miles that need frequent and costly maintenance will allow limited resources to be applied to more of the road system where maintenance is needed. Examples include outsloping (on appropriate soil types), additional cross drains, and redundant (backup) or larger drainage structures.

Incorporate relevant, cost-effective technology. Apply current appropriate technology to improve identification of priorities and for planning, design, and reconstruction. This includes the use of geographic information systems, and global positioning systems technology; geosynthetics for filters, separation, and reinforcement; mechanically stabilized earth retaining structures; current riprap-sizing criteria for bank stabilization; and bioengineered and biotechnical slope stabilization and erosion-control measures.

Perform scheduled maintenance. Perform scheduled maintenance at a planned frequency to be prepared for storms. Ensure that culverts have their maximum capacity, ditches drain well, and channels are free of excessive debris and brush that can plug structures.¹ Ensure that the roadway surface is shaped to disperse water rapidly and avoid areas of water concentration.

Use simple, positive, frequent roadway surface drainage measures and restrictions. Provide good roadway surface drainage so that water is dispersed off the road frequently and water concentration is minimized. Where soil properties are insufficient to support traffic when wet, restrict use during wet seasons to prevent rutting and gullyng. Outslope roads whenever appropriate and practical, and use rolling-dip cross drains for surface drainage rather than a system of ditches and culverts that require more maintenance and can plug during storm events. Frequent cross drains, insloping, outsloping, and rolling road grades all need to be in good working order. Failed cross-drain culverts are common after major storm events.

Properly size, install, and maintain culverts. Improperly installed, undersized, and plugged pipes are common reasons for culvert failure during storms.

¹ Limit clearing debris from stream channels to smaller mobile pieces that pose an immediate risk to a structure. Larger pieces that are integrated into the channel bed or banks or that are large enough to resist movement during most flows are important for stream function and aquatic habitat. Consult a fisheries biologist or hydrologist before any extensive debris removal.

Improper alignment or grade relative to channels and ditch lines, excessive woody debris in the channel, excessive channel constriction and headwater elevation, excessively wide inlet areas, and inadequate capacity all contribute to pipe plugging and subsequent failure. Concrete or masonry headwalls improve the resistance of culverts to failure during overtopping. Lack of proper maintenance can also cause culvert failure. Maintaining inlet configurations and removing debris that plug the pipe are essential for proper function during storms.

Use simple fords or vented low-water crossings. Use simple fords or vented low-water crossings (vented fords) as often as appropriate for small or low-flow stream crossings on low-volume roads, instead of culvert pipes that are more susceptible to plugging and failure. Protect the entire (100-year) wetted perimeter of the structure (and the downstream edge of the structure) against scour; provide for aquatic organism passage as needed.

Stabilize cut and fill slopes. Remove or treat unstable fill slopes as necessary to improve stability. Ensure cut and fill slopes are well covered (stabilized) with vegetation to minimize surface instability and erosion. Uncompacted sliver fills and settling or cracking fills are a high priority for stabilization or removal. Fill slopes also may be undercut and over-steepened by a stream or channel. Failing, over-steep slopes from road construction where material enters a stream can cause downstream problems to the watershed and contribute to plugging of structures.

Use deep-rooted vegetation to “anchor” soils. Promote slope stability by using deep-rooted vegetation for soil bioengineering and biotechnical treatments. Combine deep-rooted plants with a mixture of shallow-rooted grasses for ground cover and erosion control on slopes, preferably using native species.

Design high-risk bridges and culverts with armored overflows. High-risk bridges and culvert structures can be designed with armored overflow areas near the structure in case of overtopping, or they can have a controlled-failure point that is easy to repair and minimizes

environmental damage. Alternatively, oversizing the structure and allowing for extra freeboard on bridges will maximize capacity and minimize risk of plugging. Ensure the natural channel is not constricted. Consider culverts with a span that is at least bankfull-channel width and bridges that span the floodplain.

Eliminate diversion potential. Design and construct (or upgrade) all stream crossings, especially culvert crossings, to have no diversion potential. Design and construct (or upgrade) stream crossings in steep stream channels subject to debris flows to withstand such debris flows without being washed out or resulting in streamflow diversion. Structure damage from a plugged culvert may be minimal, but road damage from a stream diverted down the road can be extensive.

Use scour prevention measures for structures on questionable foundation materials. Install bridges, retaining structures, and structural foundations into bedrock or on firm, in-place material with good bearing capacity to minimize foundation failures. Apply foundation-strengthening and scour-prevention measures when foundation conditions are known to be marginal or a bridge is susceptible to scour.

Be aware of channel morphology and stream-channel changes near a bridge, culvert, ford, or road along a creek. Channel aggradation (deposition) and subsequent plugging of structures can occur when a stream transitions from a steeper reach to a flatter area or when a stream jumps out of its original channel. This is particularly problematic on alluvial fans where avulsion can damage roads and structures. In addition, tight channel bends promote concentration of flow to the outside edge, often leading to scour. Woody debris tends to accumulate at channel bends. Road work or improvements can also cut off stream access to the floodplain.

Plan for climate change. Climate change is projected to worsen over time. Expect higher temperatures, more wildfires, and more intense storms, all of which will affect forest infrastructure.

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Chapter 5: Effects of Climate Change on Outdoor Recreation in Southern California

Patricia L. Winter and José J. Sánchez¹

Introduction

This chapter considers social vulnerability to climate change effects on outdoor recreation. Social vulnerability refers to the resilience of groups and communities confronted by external stresses on human health, including natural or human-caused disasters, and disease outbreaks. Reducing social vulnerability can decrease human suffering and economic loss (Flanagan et al. 2011, Lehnert et al. 2020 ATSDR was replaced with Pembleton, so please revise parens to read: Flanagan et al. 2011, Lehnert et al. 2020, Pembleton 2022). The geographic focus, as applied throughout this report, covers the four southern California national forests (Angeles, Cleveland, Los Padres, and San Bernardino National Forests) and the federally managed portion of the Santa Monica Mountains National Recreation Area. The Southern California Adaptation Partnership (SOCAAP) assessment area extends from Monterey County in the north to San Diego County in the south (fig. 5.1).

By considering current and projected climate change effects, sociodemographic and economic characteristics, and outdoor recreation, we hope to provide land managers and stakeholders with information that can aid management, minimize loss, and support planning for socioecological resilience (Aplet et al. 2010). The assessment draws from existing data sources, published literature, and interviews with key contacts from the management units in the assessment area. Various adaptive approaches are considered in this chapter. Additional discussion of adaptation options, drawing from preliminary assessment findings on outdoor recreation and developed collaboratively in a series of virtual workshops, are found in chapter 7 of this report. Although many adaptation strategies and tactics are presented, the complexity and uncertainty involved will continue to require an adaptive management approach to effectively

address climate change effects (Arvai et al. 2006, Clark 2002, Joyce et al. 2009, USDI NPS 2021).

The future of outdoor recreation participation in the SOCAAP assessment area will likely be influenced by changes in population that are independent of climate change effects, including overall population size, increased urbanization, proportion of population from communities of color, increases or decreases in population age cohorts, and economic change. This is described in detail in the *2010 Resources Planning Act Assessment* update (USDA FS 2016). Some of these sociodemographic changes intersect with cultural change, a key factor in climate change effects, response, and adaptation (Adger et al. 2013). The counties proximate to the assessment area (fig. 5.2) are the focus of our summary of these influential sociodemographic and economic shifts. Although outdoor recreation visitation to the assessment area includes visitors outside the selected nine-county area, compilation of shifts specific to these counties affords a focused approach. In addition, visitation from outside the selected counties represents a smaller portion of overall visitation as reflected in National Visitor Use Monitoring reports for the four national forests in the SOCAAP assessment area as well as the Luskin Center for Innovation's report addressing visitor use in Santa Monica Mountains National Recreation Area (LCI 2020).

Demographic and Social Context

Population Change

Population sizes within and adjacent to the SOCAAP assessment area will likely continue to influence outdoor recreation participation. As a result, overall outdoor recreation use is projected to increase by mid-century. Population is forecast to increase about 10 percent across the nine-county region, growing from the current 23.3 million to more than 25.6 million in 2060 (table 5.1). San Bernardino and Riverside Counties are both projected to have the largest, sustained increases in population, with an almost 30-percent increase in each. Recent trends, however, are important to note, as the state has experienced a population decrease. Annual percentage

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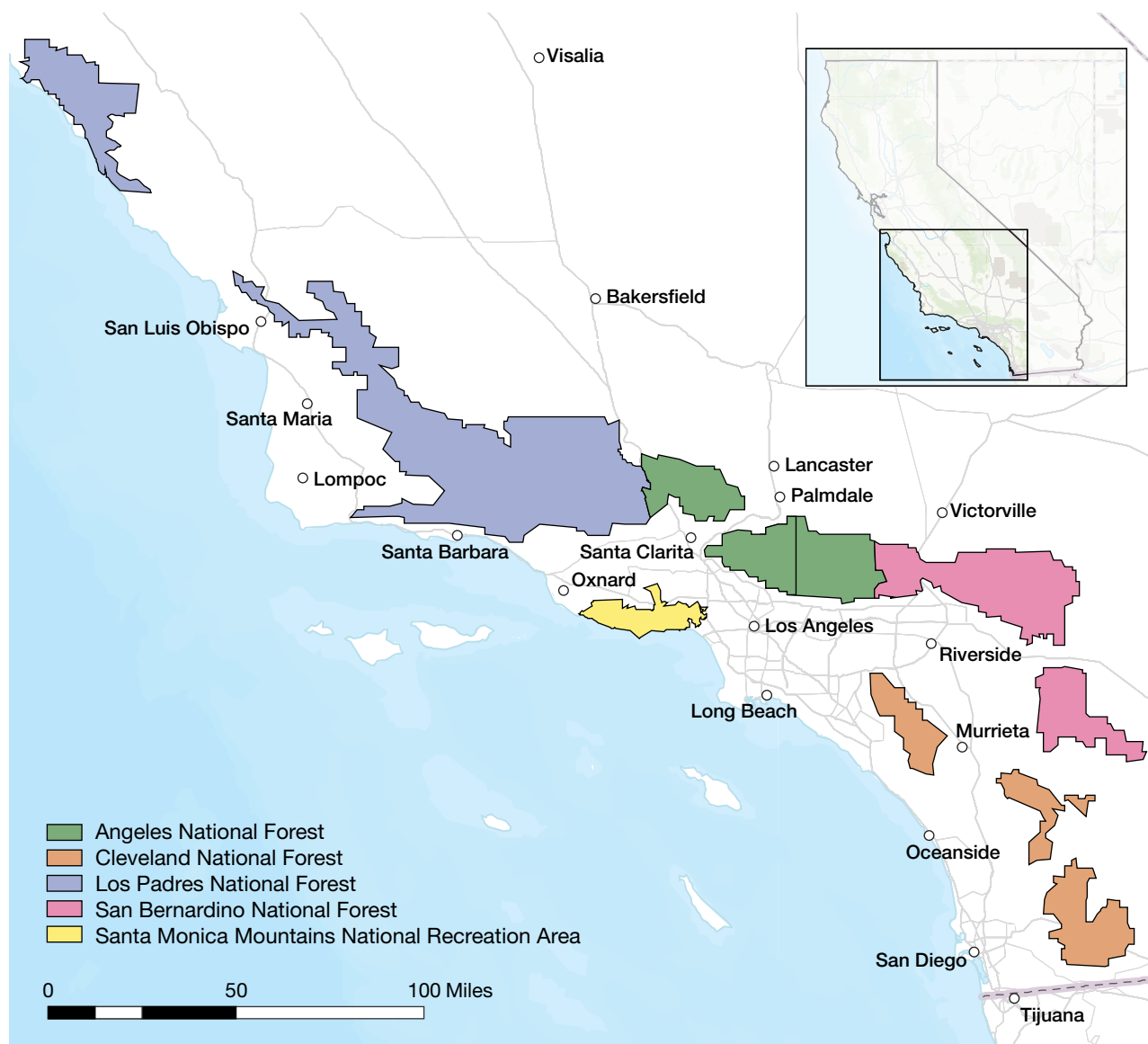


Figure 5.1—Southern California Adaptation Partnership assessment area.

of change in population from January 2021 to January 2022 showed a marginal decrease in population for most counties in the SOCAAP assessment area, although those decreases were less than during 2020 (CDF 2022). Declining baby boomer populations (individuals born in 1946 through 1964), lower birth rates, COVID-19 deaths, and less immigration, combined with outmigration to other states, all contribute to these population losses (CDF 2022). Even in these recent years, however, San Bernardino and Riverside Counties remained the fastest growing counties in the SOCAAP assessment area.

Population density is also important. Persons per square mile lends insight into population; however, it is important to consider that population is not necessarily

evenly distributed across the landscape in any one county. In some cases, populations may be heavily concentrated within some cities, contributing to elevated urbanization (table 5.2). Urbanized settings provide access to services (such as education and health care) and recreational amenities (such as built infrastructure) that are typically surrounded by open spaces (Hipp and Kim 2021, Seto et al. 2010). Individuals working and residing in close geographic proximity may benefit from supporting public transit, potentially reducing the environmental footprint of their daily commute (Hipp and Kim 2021). Transportation routes that link urbanized centers to greenspaces and larger natural areas, such as forests and parks, remain an essential element of planning and

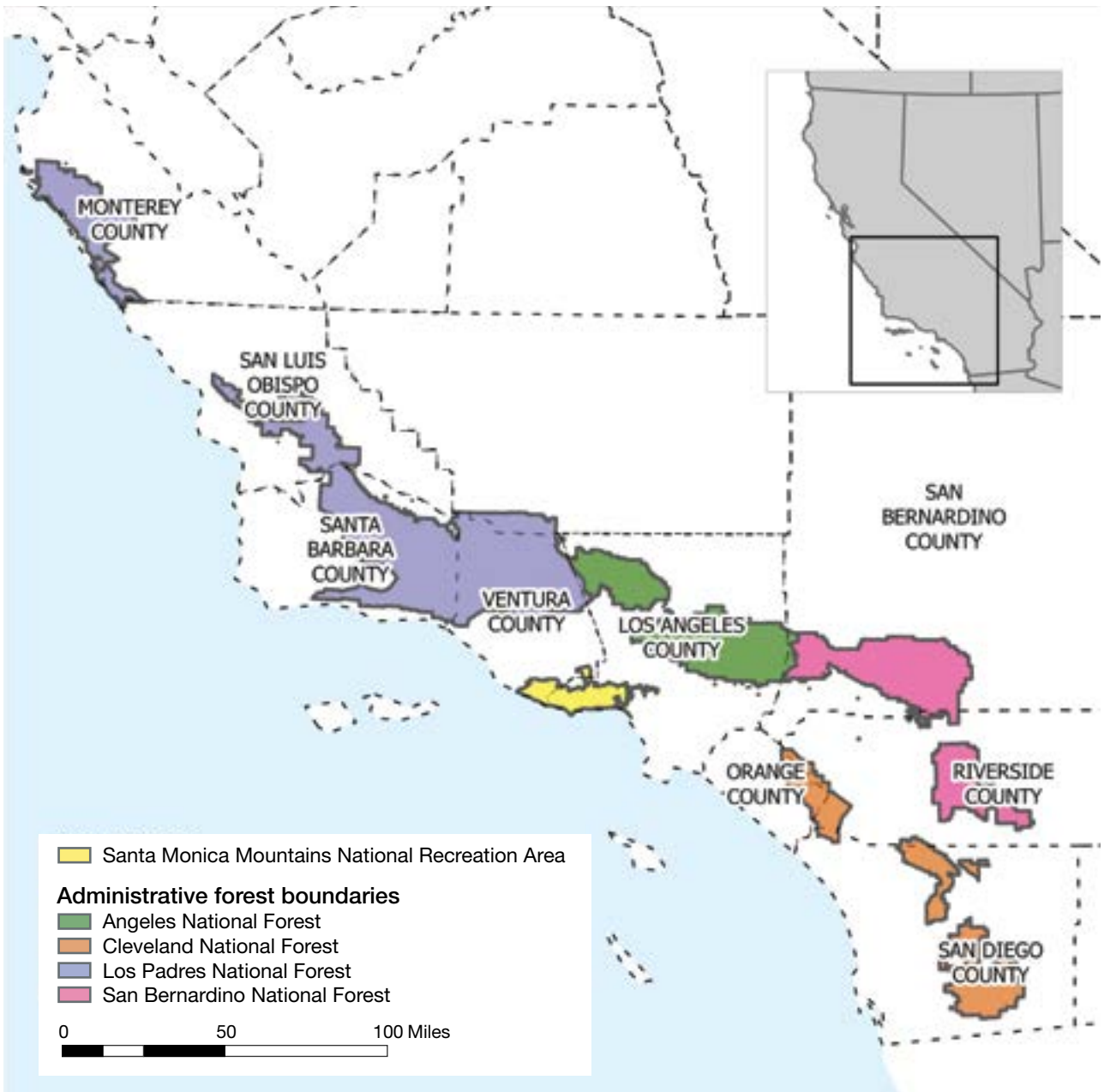


Figure 5.2—Counties overlapping the Southern California Adaptation Partnership assessment area. Map by Micha Solomon, USDA Forest Service, Pacific Southwest Region.

will be even more important under continuing urbanization (Sánchez et al. 2020).

An analysis by Kim et al. (2018), which covered 1990 through 2005, showed that a population increase in southern California may not shift land uses the same way in all areas. Their assessment showed that cities with limited options for expanding their jurisdictional boundaries (build-out) were more likely to preserve recreational areas and urban open space than cities with more options for annexation of such space. Given the identification of

land-use change as a threat to resilience of ecosystems in the assessment area, continuing development of open-space areas is important to monitor as these population shifts unfold (Hilberg et al. 2017a). Much of the development occurs in chaparral and other wildland systems, further affecting natural systems (Hall et al. 2018).

Continued urbanization and loss of open space nationally has greater effects on activities that require large spatial areas, such as hunting, visiting primitive areas, and off-road vehicle use (White et al. 2016). Continuing

Table 5.1—Population for the nine counties overlapping the Southern California Adaptation Partnership assessment area, 2020 and projected decadal through 2060

County	2020	2030	2040	2050	2060	Cumulative change
NUMBER						PERCENT
Monterey	441,290	464,124	477,265	481,305	476,734	8.0
San Luis Obispo	276,151	284,729	284,346	274,677	263,650	-4.5
Santa Barbara	451,329	469,717	479,622	479,532	473,067	4.8
Ventura	841,439	872,856	885,628	873,594	849,091	0.9
Los Angeles	10,171,593	10,322,678	10,286,350	10,061,774	9,697,634	-4.7
San Bernardino	2,184,112	2,368,002	2,536,592	2,681,796	2,818,707	29.1
Riverside	2,449,299	2,728,068	2,933,038	3,059,095	3,129,833	27.8
Orange	3,190,832	3,291,863	3,315,726	3,268,048	3,166,309	-0.7
San Diego	3,352,145	3,461,883	3,543,663	3,583,006	3,583,085	6.9
Total	23,358,190	24,263,920	24,742,230	24,762,827	25,671,561	9.9

Change from 2020 to 2060 calculated by the authors.

Source: (CDF 2021b).

Table 5.2—Population density for the nine counties overlapping the Southern California Adaptation Partnership assessment area, 2010, 2020, and projected for 2060

County	Land area	Population density			
	2010 ^a	2010 ^a	2020 ^b	2060 ^b	
	SQUARE MILE	PERSONS PER MILE			
Monterey	32,810.60	126.5	134.5	145.3	
San Luis Obispo	3,298.57	81.7	83.7	79.9	
Santa Barbara	2,735.09	155.0	165.0	173.0	
Ventura	1,843.13	446.7	465.5	460.7	
Los Angeles	4,057.88	2,419.6	2,506.6	2,389.8	
San Bernardino	20,056.94	101.5	108.9	140.5	
Riverside	7,206.48	303.8	339.9	434.3	
Orange	790.57	3,807.7	4,036.1	4,005.1	
San Diego	4,206.63	735.8	796.9	851.8	

^a Source: USDC CB (2019a, 2019b, 2019c, 2019d, 2019e, 2019f, 2019g, 2019h).

^b Data are calculated using total population projected for each county (CDF 2021b) and dividing by land area in square miles (USDC CB 2019a, 2019b, 2019c, 2019d, 2019e, 2019f, 2019g, 2019h).

urbanization may lead to shifts in values associated with natural resources and conservation (Gillespie et al. 2018). Kim et al. (2018) also noted the philosophical variations among municipalities regarding approaches to open space, suggesting effects will likely also differ among cities based on identified visions and priorities. For example, the Riverside-Corona Resource Conservation District described effects of planning and building patterns contributing to loss of open space in the region:

Many problems we face are largely due to the ways we have planned and built urban environments. Those problems include traffic congestion, loss of open space, and degraded air and water quality. We've used land inefficiently. We have paved over prime farmlands, built sprawled communities without providing effective mass transit, and destroyed important habitats, accelerating extinction rates.

In the past, many land use and management decisions were based on immediate economic returns, without full regard for environmental and quality of life costs and considerations. Today, it is essential that we comprehensively evaluate the potential consequences of land use conversion. Some factors to consider include the efficient use of land and natural resources, costs to ecosystem services, community livability, and economic benefits. With more thorough evaluation and planning, we can make meaningful land use decisions and invent sustainable solutions [RCRCD 2022].

The four national forests in the SOCAAP assessment area were designated as urban national forests some time ago based on the large adjacent urban populations (Chavez and Olson 2009). With forecasted population increases across the nine-county area, the urban national forest designation will remain an important part of the underlying character of the SOCAAP assessment area. Researchers have pinpointed some of the unique characteristics of the urban national forest outdoor recreation experience, including (1) heightened importance of access to natural areas for nature benefits (see below); (2) different normative trends for social carrying capacity (e.g., differences in perceived crowding); (3) seeking of solitude in nature experienced with others;² and (4) some preferences for more built amenities, including those that are more similar to an urban park than a national forest (Graefe et al. 1984, Roberts et al. 2009, Winter 2013).

The level of human use and management of opportunities sought in urban national forests and urban-proximate natural resource areas challenge the sustainability of outdoor recreation (Winter et al. 2020b). As populations and development increase near natural areas, additional issues arise related to delivery of ecosystem services (chapter 6) and the ability to manage ecological processes (e.g., wildfires) safely (Goldstein 2007, Tafazzoli and Sadoughi 2021, Westerling et al. 2011).

² Winter 2013 examined motivations for wilderness visits. Survey respondents in the study described seeking solitude in nature, but those experiences were often with others in the same hiking/camping party. Additionally, urban-proximate wilderness visitors have indicated enjoyment of encountering other individuals while hiking. Thus, solitude in nature can involve a shared experience.

Ethnoracial Change

Along with the current demand for outdoor recreation opportunities in the SOCAAP assessment area and anticipated population increases, consideration of additional sociodemographic trends will likely be beneficial. Ethnoracial composition of SOCAAP assessment area counties is changing. Across the nine-county area, an increase in the Hispanic population (of any race) is projected between 2020 and 2060, with six of the nine counties projected to have the largest proportion of their population from persons of Hispanic ethnicity (table 5.3).

Variation in recreation participation, preferences, and considerations for communication and engagement are of particular interest with respect to ethnoracial composition (Roberts et al. 2009, Sánchez et al. 2020, Winter et al. 2020a). Some of these identified differences have been associated with cultural variations (Li et al. 2010, Roberts et al. 2009). In this discussion, we do not consider members of any ethnoracial group to be similar to all others within the same group, although larger trends identified in research are noteworthy. Individuals from communities of color continue to be underrepresented as national forest visitors nationally and within the U.S. Department of Agriculture, Forest Service's Pacific Southwest Region (Flores et al. 2018). Residents of metropolitan areas from communities of color surrounding the four national forests in the SOCAAP assessment area are less likely to have visited national forests in their lifetime (Winter et al. 2020a).

Although having discretionary time for outdoor recreation is a common barrier among all ethnoracial groups, resource-related constraints are more often reported among communities of color (Winter et al. 2020a). Resource related constraints include access to transportation and discretionary funds. Although shifts in these disparities in outdoor recreation participation may be underway, they are an important aspect of recreation service delivery (Flores and Sánchez 2020, Thomas et al. 2022).

In addition to inequities in participation, other differences include recreation uses and site preferences, such as the preference for developed sites with more amenities, including day-use sites and developed camping areas (Flores and Sánchez 2020, Roberts et al. 2009). Differences in communication patterns and preferences have also been documented (Li et al. 2010). Although early studies highlighted the importance of

Table 5.3—Ethnoracial diversity for the nine counties in the Southern California Adaptation Partnership assessment area, 2020 and projected for 2060

County	Ethnoracial category	Proportion of county population	
		2020	2060
		PERCENT	
Monterey County			
	White (Non-Hispanic)	30.2	24.1
	Black (Non-Hispanic)	2.5	2.3
	American Indian or Alaska Native (Non-Hispanic)	0.3	0.3
	Asian (Non-Hispanic)	5.4	4
	Native Hawaiian or Pacific Islander (Non-Hispanic)	0.4	0.4
	Multiracial (Non-Hispanic)	2.3	2.9
	Hispanic (any race)	58.9	66.2
San Luis Obispo County			
	White (Non-Hispanic)	69.1	62.7
	Black (Non-Hispanic)	1.9	1.9
	American Indian or Alaska Native (Non-Hispanic)	0.5	0.5
	Asian (Non-Hispanic)	3.2	4.1
	Native Hawaiian or Pacific Islander (Non-Hispanic)	0.1	0.1
	Multiracial Non-Hispanic)	2.4	3.1
	Hispanic (any race)	22.8	27.5
Santa Barbara County			
	White (Non-Hispanic)	44.5	37.8
	Black (Non-Hispanic)	1.8	2
	American Indian or Alaska Native (Non-Hispanic)	0.4	0.4
	Asian (Non-Hispanic)	4.8	4.5
	Native Hawaiian or Pacific Islander (Non-Hispanic)	0.2	0.2
	Multiracial (Non-Hispanic)	2.2	3.3
	Hispanic (any race)	46.1	51.7
Ventura County			
	White (Non-Hispanic)	45.9	38.4
	Black (Non-Hispanic)	1.6	1.6
	American Indian or Alaska Native (Non-Hispanic)	0.3	0.3
	Asian (Non-Hispanic)	6.7	6
	Native Hawaiian or Pacific Islander (Non-Hispanic)	0.2	0.1
	Multiracial (Non-Hispanic)	2.3	3.3
	Hispanic (any race)	43.1	50.1
Los Angeles County			
	White Non-Hispanic)	26.3	23
	Black (Non-Hispanic)	8.1	7.8
	American Indian or Alaska Native (Non-Hispanic)	0.2	0.2

Table 5.3—Ethnoracial diversity for the nine counties in the Southern California Adaptation Partnership assessment area, 2020 and projected for 2060 (continued)

County	Ethnoracial category	Proportion of county population	
		2020	2060
		PERCENT	
	Asian (Non-Hispanic)	13.5	11.3
	Native Hawaiian or Pacific Islander (Non-Hispanic)	0.2	0.2
	Multiracial (Non-Hispanic)	2.1	3.2
	Hispanic (any race)	49.7	54.2
San Bernardino County			
	White (Non-Hispanic)	31.1	26.5
	Black (Non-Hispanic)	8.4	9
	American Indian or Alaska Native (Non-Hispanic)	0.4	0.4
	Asian (Non-Hispanic)	6.2	5.3
	Native Hawaiian or Pacific Islander (Non-Hispanic)	0.3	0.2
	Multiracial (Non-Hispanic)	2.3	3.1
	Hispanic (any race)	51.3	55.3
Riverside County			
	White (Non-Hispanic)	37.5	33.7
	Black (Non-Hispanic)	5.6	6.4
	American Indian or Alaska Native (Non-Hispanic)	0.5	0.5
	Asian (Non-Hispanic)	6.1	6
	Native Hawaiian or Pacific Islander (Non-Hispanic)	0.3	0.3
	Multiracial (Non-Hispanic)	2.3	2.9
	Hispanic (any race)	47.4	50.2
Orange County			
	White (Non-Hispanic)	41.6	35.9
	Black (Non-Hispanic)	1.5	1.9
	American Indian or Alaska Native (Non-Hispanic)	0.2	0.3
	Asian (Non-Hispanic)	18.2	17.1
	Native Hawaiian or Pacific Islander (Non-Hispanic)	0.3	0.3
	Multiracial (Non-Hispanic)	2.6	4.2
	Hispanic (any race)	35.6	40.3
San Diego County			
	White (Non-Hispanic)	46.1	40.4
	Black (Non-Hispanic)	4.8	5.2
	American Indian or Alaska Native (Non-Hispanic)	0.5	0.5
	Asian (Non-Hispanic)	10.7	9.6
	Native Hawaiian or Pacific Islander (Non-Hispanic)	0.4	0.4
	Multiracial (Non-Hispanic)	3.3	4.9
	Hispanic (any race)	34.2	39.1

Source: CDF (2021a).

communicating through key contacts, such as family and friends, and community networks, recent studies reveal increased use of the Internet for recreation information (Winter et al. 2020a). Tracking commonalities and differences as population trends continue to unfold is an essential part of broader sustainability, ensuring equitable access and opportunity to enjoy the benefits of outdoor recreation (Flores and Sánchez 2020, Johnson Gaither et al. 2015, Li et al. 2010, Winter et al. 2020b).

Shifts in Age Cohorts

Shifts in age cohorts intersect with future outdoor recreation projections and forecasted patterns. California's age ≥ 65 population is growing—at 14.8 percent of the total population in 2016 and projected to grow to 26.4 percent by 2060. Data from 2019 specific to the SOCAAP counties showed populations of 65 and older ranged from 11.9 to 20.9 percent of the total county population (table 5.4). National studies suggest that the elderly are more likely to experience constraints to outdoor recreation than younger populations (Ghimire et al. 2014). However, Burns and Robinson (2017) suggest that the baby boomer cohort has the potential to bring different patterns to outdoor recreation as they age, given an earlier exposure to outdoor recreation activities, better health overall, increased longevity, and higher average education and income. Findings from this cohort suggest an interest in opportunities closer to home that afford a range of activities supported by developed facilities, possibly provided

more often by state and local recreation providers (Burns and Robinson 2017).

An inverse relationship between age and desire for additional amenities was reported in a study conducted in Santa Monica Mountains National Recreation Area (LCI 2020). In addition, White et al. (2016: 35) projected significant decreases in some recreation activities associated with an aging population (hunting and fishing, motorized activities, backcountry activities, and nonmotorized winter activities) and a steady popularity in others (visiting developed sites, viewing and photographing nature). The need for continued monitoring of patterns and shifts in outdoor recreation as the baby boomer generation ages is evident given these mixed forecasts of future trends (Burns and Robinson 2017).

Economic Trends

Economic trends affect outdoor recreation participation, and outdoor recreation contributes to economic conditions within counties. Outdoor recreation counties, places identified by the U.S. Department of Agriculture, Economic Research Service as having a large recreation economy, tend to attract new residents with higher average incomes (Headwaters Economics 2019, 2021). This economic growth can shift economies in rural areas, driving the cost of living higher and shifting community quality (Headwaters Economics 2021). Similar effects were noted in communities in the Sierra Nevada and

Table 5.4—Income and poverty status by age cohort and county overlapping the Southern California Adaptation Partnership assessment area, 2019

County	Median household income ^a	Living in poverty ^a	Age ≥ 65 ^a	Age ≥ 65 living in poverty ^b
	DOLLARS		PERCENT	
Monterey	71,015	12.6	14.0	8.1
San Luis Obispo	73,518	11.6	20.9	6.8
Santa Barbara	74,624	12.0	15.7	7.7
Ventura	88,131	8.2	16.2	7.0
Los Angeles	68,044	13.4	14.1	13.2
San Bernardino	63,362	13.3	11.9	10.9
Riverside	67,005	11.3	14.8	10.5
Orange	90,234	9.5	15.3	9.2
San Diego	78,980	10.3	14.5	8.9

^a Source: USDC CB (2019a, 2019b, 2019c, 2019d, 2019e, 2019f, 2019g, 2019h).

^b Source: USDC CB (2019i).

Cascades region of California with respect to amenity migration and challenges of working in recreation and tourism (Winter et al. 2014b).

These effects are less pronounced in metropolitan areas (Headwaters Economics 2019), which dominate most of the nine-county region in the SOCAAP assessment area. Of the nine counties in the SOCAAP assessment area, Monterey, San Luis Obispo, and Riverside Counties were identified as recreation counties (Headwaters Economics 2019). These three counties would likely experience more economic effects from shifts in outdoor recreation than the other counties in the assessment area.

Outdoor recreation is further influenced by economic trends because household disposable income influences recreation participation, which involves the cost of equipment, transportation, rentals, permits, and licenses. Fee and permit cost increases may benefit maintenance and other resources allocated to an area but may have a negative effect on accessibility for recreation opportunities (White et al. 2016). As reported earlier in this chapter, resources (money and travel/transportation) were more commonly cited as a constraint to outdoor recreation among communities of color compared to White respondents in research incorporating metropolitan areas surrounding the four national forests in the SOCAAP assessment area and Santa Monica Mountains National Recreation Area (Winter et al. 2020a).

Occupational segregation has intensified in the Los Angeles metropolitan region, which contributes to economic inequality; the most significant trend is that the highest status occupations are increasingly spatially segregated (Hipp and Kim 2021). The COVID-19 pandemic added to economic stressors in the state, especially for populations already at risk that are lower wage earners and typically from communities of color (Bohn et al. 2020). Although stimulus programs helped stem economic losses, recovery may be less robust among these communities. For example, unemployment rates by county are much higher for lower-income earners who also suffer from underemployment (Bohn et al. 2020).

Because of projected increases in ethnoracial diversity for several counties discussed previously in this report, economic inequality may increase over time. African American and Hispanic families are overrepresented among low-income households in California (Bohn et

al. 2020). Along with the increase in the senior population noted previously, a possible increase in individuals living in poverty may occur because of the larger share of seniors in poverty (CDA 2024). This will be especially true for individuals age ≥ 65 from communities of color (CDA 2017). Influences of the baby boomer generation will need to be monitored to see if the trend of more seniors in poverty holds for this cohort.

Some counties may have a trend of improved economic status, and current median income differs among SOCAAP assessment area counties (table 5.4). For example, in San Bernardino County, seniors age ≥ 65 living in poverty moved from 11.8 percent in 2010 to 11.5 percent in 2019 (San Bernardino County 2022). Studies of these trends over the past few years are complicated by the COVID-19 pandemic, which shifted economic and employment trends in ways that may persist for some time.

Several of the trends for the nine-county region are associated with vulnerability to climate change. Analyses by the California Department of Public Health identified vulnerable populations that would be likely to have greater susceptibility to climate change effects (Maizlish et al. 2017). These vulnerable populations include outdoor workers, populations that are very young or older, those with preexisting health conditions, and additional characteristics often associated with underserved and disadvantaged communities (Maizlish et al. 2017). For example, California residents living in subsidized housing were found to live in tracts most vulnerable to extreme heat exposure, have the most sensitive/vulnerable populations, and have the most barriers to adaptive responses (Gabbe and Pierce 2020). Davies et al. (2018) reported that communities of color tend to live in census tracts with a higher fire potential and lower adaptive capacity.

Social vulnerability intersects with wildfire vulnerability, indicating the need for a socio-ecological perspective to studies of climate change risk and resilience (Davies et al. 2018). A separate study in the Los Angeles County region revealed that tree canopy cover and green vegetation, both higher in more affluent areas, provide more fuel to burn in a wildfire (Frietag et al. 2022). However, those locations also have more resources to care for and maintain the health of green infrastructure, thereby attenuating that risk (Frietag et al. 2022). Forest-proximate communities that are less affluent are therefore at considerable risk from climate change effects.

COVID-19 Pandemic

The recent COVID-19 pandemic has directly affected outdoor recreation in the United States, including in southern California. Tourism has been directly affected because of global travel restrictions (Gössling et al. 2021). However, despite these restrictions, visitation in forests from surrounding communities was reported internationally (e.g., Derks et al. 2020) and in the United States (e.g., Rice et al. 2020). Some evidence suggests an increase in visitation to greenspaces during the pandemic, with magnitude of the increase affected by longitude and latitude of natural area, age ranges of residents (less increase among counties with more elderly residents), and length of stay-at-home restrictions (longer duration was associated with decreased visitation rates) (Rice and Pan 2021).

Grima et al. (2020) also reported an increase in visitation rate to urban-proximate natural areas and in the perceived importance of these areas during the pandemic. Likewise, a multinational study reported a shift to more local activities among birders during the pandemic (Randler et al. 2020). However, Rice et al. (2020) reported significant decreases nationally in the frequency of outdoor recreation participation, distance traveled to recreate, distance traveled beyond roads to recreate, and size of group recreating. These shifts were more pronounced among urban residents than what was evident for urban clusters or rural residents (Rice et al. 2020).

Local visitation patterns for prepandemic recreation during the time this report was written were not fully available for the SOCAAP assessment area. However, from separate discussions with forest managers on various projects, we learned that there was a considerable increase in visitation in the SOCAAP assessment area. The increase appears characteristic of forest recreation use nationwide, especially in dispersed use and wilderness areas (USDA FS NVUM 2021a). Slater et al. (2020) noted the negative effects of limited recreation access caused by area closures, quotas, and closures of built features in urban parks and natural areas. Paired with nearby effects such as limitations on public transportation, the effects on already vulnerable communities resulted in even greater costs to public health and well-being. Although the effects of the COVID-19 pandemic will have likely dissipated by press time, trends highlight sensitivities affecting future outdoor recreation sustainability and resilience under climate change.

Sustainable Outdoor Recreation

A trend overlapping the period of the pandemic is of further interest regarding sustainable delivery of outdoor recreation opportunities. In March 2020, identified as a period of economic recession, job separations were higher than they had been for more than a decade (USDL BLS 2022). Job departures have been labeled the “Great Resignation.” As of March 2022, nonfarm job openings continued to increase and had been at a historical peak (USDL BLS 2022). The ability to recruit and fill positions to manage and deliver outdoor recreation opportunities and maintain ecosystem health has therefore been challenged and may have an even greater effect if outdoor recreation demand increases as expected. The current inflation trend contributes to the complex economic status of individuals and households and their ability to engage in outdoor recreation opportunities, especially those involving travel, fees, or special equipment.

Improvements and developments in technology and specialized equipment are another example of a societal trend that affects outdoor recreation participation and sustainability under climate change (Winter et al. 2020b). Technologies have expanded the range of outdoor recreation use; for example, e-bikes support travel farther into minimally developed areas. Cellular phones host myriad platforms that provide additional information to those planning and participating in outdoor recreation (e.g., the Forest Service’s *Interactive Visitor Map* [USDA FS, n.d.a.]). Hands-free hydration packs allow recreationists to easily access water. Fabrics with built-in sunblock protect the skin from sun damage, and lighter weight materials are available for hiking poles, sleeping bags, and other gear. Virtual platforms transport visitors either in advance of a visit, or in place of one. For example, online hikes have been used in youth conservation education programs to introduce youth to hiking trails and forest wildlife (Bruni et al. 2015), and virtual reality offers nature exposure and virtual (as compared to in-situ) visits to recreation settings (Winter et al. 2020b). These represent changes in access, transportation, comfort, safety, communication, and information (Ewert and Shultis 1999). Advances may provide paths to engage youth who might not otherwise be interested in the outdoors, although attaining and maintaining relevance and sustainable management across technologies is challenging (Winter et al. 2020b).

Recreation Participation in the Southern California Adaptation Partnership Assessment Area

Recreation opportunities offered in the SOCAAP assessment area are as diverse as the ecosystems contained within them and are available through a network of federal and state lands (table 5.5, box 5.1). The latest reports for the SOCAAP assessment area (Angeles, Cleveland, Los Padres, and San Bernardino National Forests and Santa Monica Mountains National Recreation Area) available at the writing of this chapter estimated about 7.8 million annual recreation visits. The level of annual visitation and acreage of lands reflect the many opportunities for natural resource-based outdoor recreation in the region.

The Forest Service, National Visitor Use Monitoring (NVUM) program conducts a systematic assessment of recreation visitation in 5-year rotations for each national forest. These rotation dates vary by forest.³ NVUM surveys that were reported between 2016 and 2019 covered the four national forests in the SOCAAP assessment area (USDA FS 2021b, 2021c, 2021d, 2021e). A total of 27 activities (and one other category) were examined. Recreation use at Santa Monica Mountains National Recreation Area was addressed in a 2018 survey (LCI 2020).⁴

The NVUM data indicate that most visitations (85.9 percent) involved warm-weather and other activities (table 5.6, fig. 5.3) (note that respondents could report more than one primary activity; percentage of total represents weighted estimates for visits involving single or multiple main activities). Warm-weather activity categories extend across most seasons in the assessment area because the climate is temperate.

The recreation visits by primary activity reported in table 5.6 and category in fig. 5.3 show warm-weather activities accounted for 62.8 percent of recreation visits at the four national forests in the SOCAAP assessment area, with hiking/walking and bicycling being the most popular of these activities. Hiking/walking accounted for more than 3.7 million visits per year and bicycling accounted for another 512,000 visits. Additional warm-weather activities contributing to this activity category include viewing natural features, other nonmotorized use, developed camping, picnicking, backpacking, horseback riding, and primitive camping. “Other activities” was the second most frequently reported category of primary activities, with relaxing accounting for 7.8 percent of overall annual visitation at more than 669,000 visits. “Some other activity” and driving for pleasure represented 6.7 and 3.7 percent of total visitation, respectively.

Snow-based winter activities, including downhill skiing (8.2 percent) accounted for more than 703,000 visits. Cross-country skiing and snowmobiling represented 0.23 and 0.05 percent of total visitation, respectively. Wildlife-related activities, including fishing (2.0 percent), viewing wildlife (1.6 percent), and hunting (1.5 percent) accounted for 5.1 percent of overall visitation, representing just under 442,000 visits. Water-based activities (including motorized and nonmotorized), other than fishing, and gathering forest products accounted for less than 1 percent of visitation.

Summer and spring were the most popular seasons to visit Santa Monica Mountains National Recreation Area among 2018 survey respondents (LCI 2020). Although data collection and analysis differed between Santa Monica Mountains National Recreation Area (Luskin Center for Innovation data) and national forests (NVUM data), comparisons can be made with some caution.⁵ For Santa Monica Mountains National Recreation Area, warm-weather activities were reported by most survey respondents (up to three activities could be selected). Most respondents (85.4 percent) reported that they planned to hike during their visit. Other activities

³ The National Visitor Use Monitoring survey is administered using a set of methods, analytical approaches, and reporting that may be helpful to understand further. These approaches are described in English et al. (2020), White (2017), and USDA FS (2021a).

⁴ The National Park Service managed portion reflects a collaborative endeavor to accomplish the assessment. Data and manager insights were not available for the non-federally managed areas outside of the LCI report. Although some information is referenced from the LCI (2020) report, findings include areas managed by two conservation authorities and California State Parks. The assessment is focused on the federally managed portion of Santa Monica Mountains National Recreation Area. While the sociodemographic and cultural shifts are applicable to the areas managed by other agencies, our area-specific analysis of niche opportunities concentrates on the federally managed portions only.

⁵ The Luskin Center for Innovation report (LCI 2020) is drawn from to offer insights into the only known and available recreation use data. Because the data cover the full recreation area, not just the federally managed area, we are unable to determine the portion relatable to this or other chapters of this publication focused solely on Santa Monica Mountains National Recreation Area.

Table 5.5—Acreage and annual visitation for select state and federally managed recreation units in the Southern California Adaptation Partnership assessment area

Unit	Managing agency	Area	Annual visits	
			Estimate	Confidence interval
			NUMBER	PERCENT
		ACRES		
Los Padres National Forest	USFS	1,750,000	1,007,000 ^a	±11.8
Pinnacles National Park	NPS	26,653	177,224 ^b	
Andrew Molera State Park	CSP	4,766	75,022 ^c	
Julia Pfeiffer Burns State Park	CSP	2,142	215,075 ^c	
Pfeiffer Big Sur State Park	CSP	1,347	216,140 ^c	
Carrizo Plain National Monument	BLM	250,000		
Bitter Creek National Wildlife Refuge	USFWS	14,097		
Hopper Mountain National Wildlife Refuge	USFWS	2,471		
Mojave National Preserve	NPS	1,589	841,516 ^b	
California Coastal National Monument (Piedras Blancas and Orange County Rocks and Islands)	BLM	2,272		
Channel Islands National Park	NPS	249,561	409,630 ^b	
Leo Carrillo State Park	CSP	2,513	492,085 ^c	
Malibu Creek State Park	CSP	8,151	422,767 ^c	
Malibu Lagoon State Beach	CSP	69	190,662 ^c	
Point Magu State Park	CSP	13,925	518,272 ^c	
Robert H. Meyer Memorial State Beach	CSP	37	545,129 ^c	
Angeles National Forest	USFS	700,176	2,880,000 ^d	±21.6
San Gabriel Mountains National Monument ^e		346,177		
Santa Monica Mountains National Recreation Area	NPS	157,700	707,566 ^b	
Topanga State Park	CSP	11,501	1,260,560 ^c	
Rio de Los Angeles State Park	CSP	58	284,500 ^c	
Seal Beach National Wildlife Refuge	USFWS	965		
Lake Perris State Recreation Area	CSP	1,430	553,542 ^c	
San Bernardino National Forest	USFS	677,982	2,532,000 ^a	±20.1
Santa Rosa and San Jacinto Mountains National Monument	USFS/BLM	280,071		
Silverwood Lake State Recreation Area	CSP	2,019	347,126 ^c	
Mount San Jacinto State Park	CSP	13,718	3,404,103 ^c	
Sand to Snow National Monument	USFS/BLM	154,000		
Joshua Tree National Park	NPS	800,000	2,988,547 ^b	
Mojave Trails National Monument	BLM	1,600,000		
Sonny Bono Salton Sea National Wildlife Refuge	USFWS	2,200		

Table 5.5—Acreage and annual visitation for select state and federally managed recreation units in the Southern California Adaptation Partnership assessment area (continued)

Unit	Managing agency	Area	Annual visits	
			Estimate	Confidence interval
			ACRES	PERCENT
Salton Sea State Recreation Area	CSP	3,304	40,730 ^c	
Cleveland National Forest	USFS	460,000	717,000 ^a	±15.3
Palomar Mountain State Park	CSP	1,909	84,396 ^c	
Anza Borrego Desert State Park	CSP	592,022	770,382 ^c	
Dos Palmas Preserve	BLM	1,400		
Imperial Sand Dunes Recreation Area	BLM	26,000		
Cabrillo National Monument	NPS	144	761,485 ^b	
San Diego National Wildlife Refuge	USFWS	12,445		

BLM = Bureau of Land Management, CSP = California State Parks, NPS = National Park Service, USFS = USDA Forest Service, USFWS = U.S. Fish and Wildlife Service. Management units are shown in order from north to south.

^a Source: 2019 Cleveland, Los Padres, and San Bernardino National Forests survey data (USDA FS, n.d.b.).

^b Source: In 2020, the data showed a marked trend away from typical visitation numbers, so 2019 was used as the reference year (USDI NPS, n.d.).

^c Source: CSP (2020).

^d Source: 2016 Angeles National Forest survey data (USDA FS, n.d.b.).

^e Overlaps boundaries of the Angeles National Forest.

Box 5.1

Diversity of Ecotypes and Recreation Opportunities Define the Complexity of Recreation Management Under Climate Change

Diversity and complexity define the Southern California Adaptation Partnership (SOCAAP) assessment area both socioculturally and ecologically. In addition, multiple ecotypes exist within a given management area. Surrounded by a large human population that is expected to increase over the next four decades, individuals come from many cultures, speak many languages, have varied connections to community, and have diverse relationships with nature.

Preferences for outdoor recreation opportunities and actual recreation behaviors are also diverse and complex and are likely to increase in complexity. Shifts in outdoor

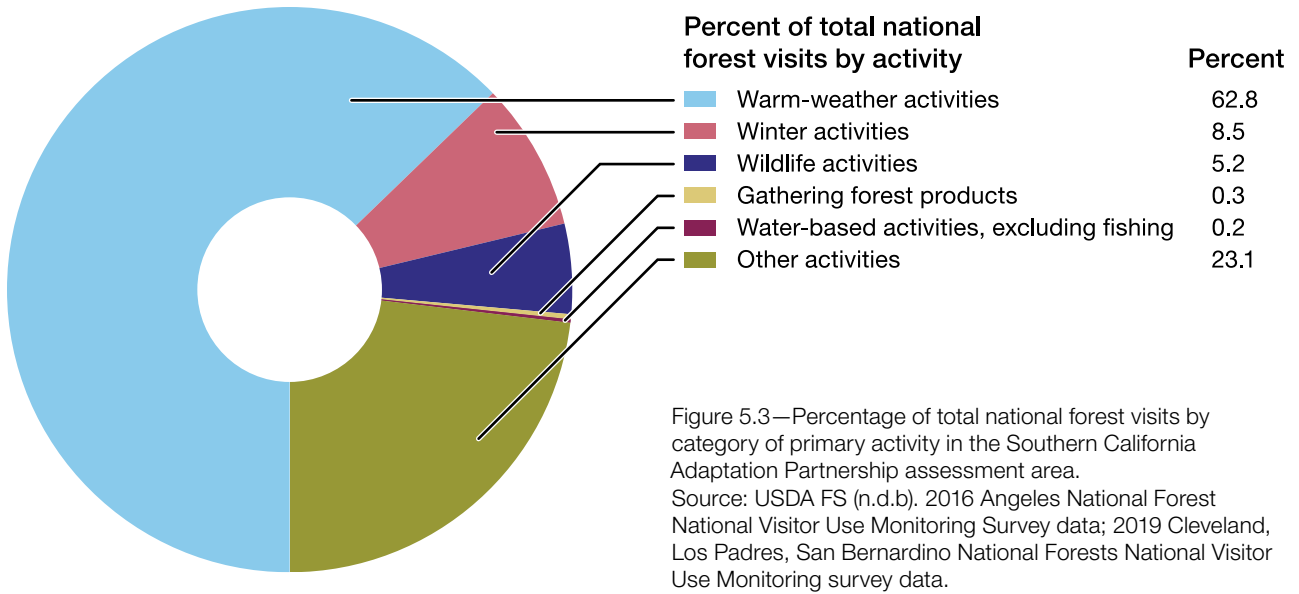
recreation associated with changes in technologies supporting outdoor recreation activities further enrich the recreation management landscape. Applications of technologies that extend and augment contact between people and nature further shift options for nature exposure and interactions, including virtual reality experiences and “mindful minute” software applications that feature nature.

Current conditions and projected effects of climate change pose a challenge in comprehensively describing the SOCAAP assessment area and its specific locations. They also present difficulties for devising plans and strategies that will help adapt to climate change. Management under current and projected conditions requires monitoring and feedback loops to assess unexpected shifts in ecosystems, human populations and cultures, technologies, and how all these factors interact.

Table 5.6—Main activities at national forests in the Southern California Adaptation Partnership assessment area

Activity	Frequency	Percent of total
Warm-weather activities:		
Hiking/walking	3,719,586	43.31
Bicycling	511,878	5.96
Viewing natural features	409,028	4.76
Developed camping	261,847	3.05
Picnicking	251,056	2.92
Other nonmotorized	118,364	1.38
Backpacking	59,284	0.69
Primitive camping	39,060	0.45
Horseback riding	20,750	0.24
Total	5,390,853	62.77
Winter activities:		
Downhill skiing	703,388	8.19
Cross-country skiing	20,070	0.23
Snowmobiling	4,107	0.05
Total	727,564	8.47
Wildlife activities:		
Fishing	175,234	2.04
Viewing wildlife	133,960	1.56
Hunting	132,672	1.54
Total	441,866	5.14
Gathering forest products:		
Gathering forest products	24,787	0.29
Water-based activities, excluding fishing:		
Nonmotorized water activities	11,784	0.14
Motorized water activities	4,290	0.05
Total	16,074	0.19
Other activities:		
Relaxing	669,820	7.80
Some other activity	571,285	6.65
Driving for pleasure	316,078	3.68
Off-highway vehicle use	235,116	2.74
Motorized trail activity	101,740	1.18
Nature study	26,721	0.31
Nature center activities	25,109	0.29
Visiting historic sites	17,992	0.21
Resort use	16,116	0.19
Other motorized activity	6,738	0.08
Total	1,986,716	23.13
Total for all activities	8,587,860	100

Source: USDA Forest Service (n.d.b). 2016 Angeles National Forest National Visitor Use Monitoring survey data; 2019 Cleveland, Los Padres, San Bernardino National Forests National Visitor Use Monitoring survey data.



reported by one-fifth or more of visitors to Santa Monica Mountains National Recreation Area included jogging and photography (table 5.7).

The NVUM also captures visitor point-of-origin and sociodemographic characteristics. Most (65.6 percent) national forest visits in the SOCAAP assessment area occurred from within a 50-mile radius of the visitor's residence (table 5.8). Less than one-fourth (23.5 percent) of visits involved an overnight stay away from home; however, most of those were still within a 50-mile radius of home. More than one-fourth (28.7 percent) of forest visits were by visitors of Hispanic ethnicity. Visits were primarily by White recreationists (82.2 percent), with Asian visitors (13.2 percent), Black/African American visitors (4.5 percent), American Indian/Alaska Native visitors (4.2 percent), and Hawaiian/Pacific Islander visitors (2.3 percent) accounting for fewer visits to the four national forests in the SOCAAP assessment area.

Similar to visitor demographic profiles reported for the four national forests in the SOCAAP assessment area, most visitors to Santa Monica Mountains National Recreation Area were local, from Los Angeles County, although about one-fifth of visitors were from Ventura County (LCI 2020). Distance traveled to and from the park was 35 miles round trip on average (LCI 2020). Visitors are predominantly White non-Hispanic (63 percent), although the percentage of Hispanic visitors nearly doubled from what was reported in a 2002 survey (21.1 percent in 2018) (LCI 2020). Additional non-White, non-Hispanic visitors included Asian visitors (7.2

Table 5.7—Main visitation activities at Santa Monica Mountains National Recreation Area, 2018

Activity ^a	Percent of respondents ^b
Warm-weather activities:	
Hiking/walking	85.4
Sightseeing	50.4
Jogging	20.2
Mountain biking	13.2
Sunbathing	8.3
Rock climbing	8.1
Picnicking	7.3
Camping	4.4
Horseback riding	2.7
Wildlife activities:	
Bird watching	13.4
Water-based activities, excluding fishing:	
Wading/swimming	6.4
Other activities:	
Photography	24.3
Walking dog(s)	18.2
Some other activity	6.8
Painting/crafts	2.7

Category structures are aligned with the Forest Service, National Visitor Use Monitoring survey and do not mirror the reporting by the Lusk Center for Innovation. These data cover all areas in Santa Monica Mountains National Recreation Area, not just those managed by the National Park Service.

^a Up to three activities could be selected by respondents in the 2018 survey.

^b Based on 4,381 respondents.

Source: LCI (2020: 84, table 6.1).

Table 5.8—Distance traveled by recreationists to visit national forests in the Southern California Adaptation Partnership assessment area

Distance from survey respondent's home to interview location	National forest visits ^a
MILES	PERCENT
0–25	41.3
26–50	24.3
51–75	10.6
76–100	9.3
101–200	7.2
201–500	2.4
>500	4.7

Source: 2016 data was used for the Angeles National Forest; all other national forest data is from 2019. (USDA FS, n.d.b).

percent), Black/African American visitors (2.3 percent), American Indian/Alaska Native visitors (1.0 percent), Hawaiian/Pacific Islander visitors (0.5 percent), “other” visitors (2.1 percent), and multiracial visitors (2.7 percent). These demographics may be somewhat different for the portion managed by the National Park Service. Visitors to primary trailheads in Santa Monica Mountains National Recreation Area were mostly White non-Hispanic (LCI 2020).

Benefits of Outdoor Recreation Participation in the Southern California Adaptation Partnership Assessment Area

Outdoor recreation provides many individual, community, and societal benefits (Winter et al. 2014b). These include opportunities to connect with nature, wildlife, forests, and fellow recreationists, which have been shown to produce several benefits (Winter 2013, Winter et al. 2020b). In some cases, contact with nature affirms cultural identities and practices associated with connections to the land (Winter et al. 2020b). In other cases, outdoor recreation in nature affirms connections to social groups and selected activities (Winter 2013, Wolsko et al. 2019). Connections with social groups and activities, including recreationist groups, represent benefits involving a sense of belonging within social communities, contributing to personal and social identity (Schneider and Winter 1998).

Connections to nature involve a sense of belonging in nature or being a part of nature, contributing to environmental identity (van der Werff et al. 2013). Contact with nature, especially such experiences that lead to a sense of connection or empathy with nature, is associated with practicing more environmentally sustainable behaviors (Clayton et al. 2017, Frantz and Mayer 2014, McCreary et al. 2018, Winter et al. 2019, Zelenski et al. 2015). In some cases, this contact with nature is associated with support for conservation (Zaradic et al. 2009). Experience in nature fosters development of attitudes and motivations that make environmentally responsible behaviors more likely (Capaldi et al. 2015, Clayton et al. 2017, Kil et al. 2014, Zelinski et al. 2015). These associations are beneficial to managing agencies that rely on public support through indirect acts (e.g., voting for nature-related investments) and direct acts (e.g., volunteering to assist with restoration projects) (Gillespie et al. 2018).

Spending time in nature contributes to overall well-being at individual, community, and societal scales (Capaldi et al. 2015, Winter et al. 2020b). Public health benefits from exposure to nature and outdoor recreation (Barton et al. 2009, Evans 2019, Winter et al. 2014b) are important considerations when assessing the value of natural areas (Winter et al. 2019). One study conducted within the SOCAAP assessment area showed that spending time in the forest elicited significantly greater positive emotions, including awe, gratitude, and contentment, when compared to walking in an urban environment (Goldy et al. 2022⁶). Improved psychological well-being from nature-based recreation has likewise been cited by others as an important benefit (Pretty et al. 2007, Wolsko et al. 2019). Ewert and Chang (2018) similarly reported physiological and psychological benefits of being in nature through stress reduction when compared to more urbanized settings. Hansmann et al. (2007) also cited stress reduction as a benefit of exercising in green spaces.

In another series of studies, visitors to urban-proximate wilderness in the SOCAAP assessment area reported benefits of nature visits include spending time with others, solitude, and spiritual experiences (Winter

⁶ Goldy, S.; Davis, N.; Piff, P. [et al.]. 2022. Walks in national forests: exploring distinct positive emotions and salivary responses. 27 p. Unpublished report. On file with: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, 4955 Canyon Crest Drive, Riverside, CA 92507.

2013). Physical movement during many recreation activities (e.g., hiking and walking) provides an opportunity to counteract sedentary lifestyles (Kondo et al. 2015). Increases in physical activity have been assessed for their potential effect on reduced costs for medical care for adults and children (Lee et al. 2017, Pratt et al. 2000), and studies on national forest lands reveal significant contributions to physical health (Kline et al. 2011). Although physical activity benefits overall were associated with visitors of higher socioeconomic status, benefits also favored lower-income community members that reside near forest lands (within 60 miles of a forest by road).

Nature-proximate areas are especially important for socioeconomically disadvantaged populations (Jennings et al. 2016). For example, parks and green spaces may help remedy some income-associated inequalities in health outcomes (Mitchell and Popham 2008, South et al. 2018). Because the effects of climate change on marginalized communities, particularly those of color, are disproportionate, the significance of outdoor recreation benefits is heightened (Evans 2019, Maizlish et al. 2017).

Outdoor recreation makes significant direct economic contributions. The Outdoor Recreation Jobs and Economic Impact Act of 2016 (Public Law 114-249) required the Secretary of Commerce to assess the outdoor recreation economy and its effects on the overall economy of the United States (USDC BEA 2018). As a result, the U.S. Department of Commerce, Bureau of Economic Analysis reported from this assessment that outdoor recreation accounted for 2.2 percent of the nation's gross domestic product in 2016 (USDC BEA 2018). Additional economic data are likewise informative. Annual expenditures for recreational fishing nationwide (including licenses, equipment, transportation, and other services) was \$45 billion in 2011 and \$46.1 billion in 2016 (Gillespie et al. 2018). Economic benefits from recreational fishing alone on National Forest System waters are valued at \$1.35 billion (Gillespie et al. 2018). In California, the outdoor recreation economy represents 1.5 percent of the gross domestic product, providing 489,000 jobs with an average annual wage of \$25,778 (Headwaters Economics 2021).

Economic benefits from outdoor recreation and tourism are important to the communities adjacent to, and surrounded by, national forests in the SOCAAP assessment area. These economic contributions influence community well-being (Charnley 2014, Winter et al.

2014a). Total annual visitor expenditures within 50 miles of surveyed forests/units (considered to be local community areas) were higher among those traveling from outside a 50-mile radius than for visitation that originated locally (table 5.9). Lodging accounted for 26.2 percent of expenditures for nonlocal visitation, followed by restaurants at 19.9 percent. Gas and oil was the primary spending category for local visitation (31.4 percent).

Economic impact is a direct assessment of how spending benefits a geographic area (e.g., table 5.9), whereas economic value is an assessment from a broader perspective. The **economic value** of recreation is the benefit that individuals receive from participation in various recreation activities. The economic value of recreation can be estimated with the benefit-transfer method (Rosenberger et al. 2017). Updating the *Recreation Use Values Database* (Loomis 2005, Rosenberger and Loomis 2001) and annual visitation estimates from the NVUM survey, Rosenberger et al. (2017) estimated the economic value for each forest recreation activity. We used the procedure outlined by Rosenberger et al. (2017) to estimate the annual economic benefits to individuals recreating in the four national forests in the SOCAAP assessment area.

Equation (1) estimates the number of visits per recreation activity using annual recreation visits (NVUM dataset) and the percentage of primary activity for each national forest.

$$\text{Visits per activity} = \text{annual national forest recreation visits} \times \text{percentage of main activity} \quad (1)$$

We translated visits into primary activity days using the conversion coefficient derived by Rosenberger et al. (2017) and visits per activity. The conversion coefficients are the average number of days a recreation activity lasts for a national forest visit. For example, hiking and walking has a 1.1 conversion coefficient, meaning a national forest visit for hiking and walking lasts on average 1.1 days.

$$\text{Primary activity days} = \text{conversion coefficient} \times \text{visits per activity} \quad (2)$$

Next, primary activity days are multiplied by the average economic value for each recreation activity. We use the economic values from Rosenberger et al. (2017),

Table 5.9—Total annual expenditures by expense type from nonlocal and local visitors within 50 miles of surveyed national forests in the Southern California Adaptation Partnership assessment area

Spending category	Nonlocal spending ^a		Local spending ^b	
	Total annual expenditures	Spending for each category	Total annual expenditures	Spending for each category
	THOUSANDS OF 2019 DOLLARS	PERCENT	THOUSANDS OF 2019 DOLLARS	PERCENT
Lodging	40,588	26.2	4,048	4.2
Camping fees	5,284	3.4	3,105	3.2
Restaurant	30,812	19.9	16,888	17.6
Groceries	18,810	12.1	20,791	21.7
Gas and oil	24,940	16.1	30,100	31.4
Local transportation	1,312	0.8	496	0.5
Entry fees	11,069	7.1	7,345	7.7
Recreation and entertainment	13,122	8.5	4,153	4.3
Sporting goods	4,430	2.9	7,173	7.5
Souvenirs and other expenses	4,748	3.1	1,623	1.7
Total	155,116	100.0	95,722	100.0

Spending totals were calculated using procedures in White (2017) and parameters and spending averages used by the Forest Service, Ecosystem Management Coordination office.

^a Nonlocal refers to trips that required traveling more than 50 miles to the survey site.

^b Local refers to trips within 50 miles of surveyed national forests.

Source: White, E. Personal communication. Research quantitative social scientist, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, 1220 SW 3rd Avenue, Suite 310, Portland, OR 97204.

which are the most up-to-date values available, to estimate the aggregate recreation benefit value:

$$\text{Aggregate recreation benefit value} = \text{average economic value} \times \text{primary activity days} \quad (3)$$

For example, using the 2016 NVUM dataset for Angeles National Forest, we multiplied the percentage of primary activity by the annual number of national forest visits (more than 2.9 million in 2016) to obtain the number of visits per activity (equation 1). Next, we multiplied the conversion coefficient by the number of visits per activity to obtain the number of primary activity days (equation 2). Finally, we multiplied the number of primary activity days by the average economic value to estimate the aggregate recreation benefit value for each activity (equation 3), arriving at the annual aggregate economic value of \$246.1 million for Angeles National Forest (adjusted using 2019 dollars). The same procedure was undertaken for the other three national forests in the SOCAAP assessment area using the 2019 data. The annual aggregate economic value (adjusted using 2019 dollars) was \$84.2 million for Cleveland National

Forest, \$121.2 million for Los Padres National Forest, and \$275.8 million for San Bernardino National Forest.

We summed the annual aggregate economic values of the four national forests in the SOCAAP assessment area to estimate the aggregate annual economic benefit (table 5.10). The aggregate annual economic benefit for the assessment area was more than \$727.3 million. Hiking had the highest annual value of almost \$338.8 million, followed by relaxing at \$62.4 million, and downhill skiing at \$62.2 million. Expenditures and benefits to local communities offer a way to understand social vulnerability and how climate change might affect that vulnerability (Fischer et al. 2013).

We describe outdoor recreation activities and climate-related effects in the following section to inform natural resource planning and management.⁷ Adopting

⁷ Our focus on recreation does not include the full array of ecosystem services represented in the SOCAAP assessment area, such as the importance of nonuse values (Cordell et al. 2003, Williams and Watson 2007). Ecosystem services in the SOCAAP assessment area are assessed in chapter 6 of this report.

Table 5.10—Estimate of annual aggregate economic benefit of main activities in national forests of the Southern California Adaptation Partnership assessment area

Activity participation ^a	Annual economic benefit ^b
2019 DOLLARS	
Warm-weather activities:	
Hiking/walking	338,787,157
Viewing natural features	47,986,514
Bicycling	27,956,623
Developed camping	22,671,063
Other nonmotorized	13,655,219
Backpacking	8,824,844
Picnicking	4,697,332
Horseback riding	2,542,228
Primitive camping	1,547,069
Total	468,668,048
Winter activities:	
Downhill skiing	62,233,130
Cross-country skiing	1,172,784
Snowmobiling	230,027
Total	63,635,941
Wildlife activities:	
Fishing	15,731,370
Hunting	14,987,837
Viewing wildlife	8,393,032
Total	39,112,239
Gathering forest products:	
Gathering forest products	1,694,015
Water-based activities, excluding fishing:	
Nonmotorized water activities	1,794,830
Motorized water activities	307,293
Total	2,102,122
Other activities:	
Relaxing	62,424,449
Some other activity	39,043,660
Driving for pleasure	21,601,937
Resort use	13,168,836
Off-highway vehicle use	6,173,332
Motorized trail activity	3,204,104
No activity reported	1,867,710
Visiting historic sites	1,716,064
Other motorized activity	1,342,750
Nature center activities	1,127,275
Nature study	377,376
Total	152,047,494
Total for all activities	727,259,860

^a Considers only the main recreation activity.^b Combined annual benefit for the Angeles, Cleveland, Los Padres, and San Bernardino National Forests in 2019 dollars.

Source: 2016 data was used for the Angeles National Forest; all other national forest data is from 2019. (USDA FS, n.d.b).

this approach broadens the range of choices available to managers toward sustainable resource management (Vose et al. 2012).

Relationships Between Climate Change and Outdoor Recreation

Effects of climate change on outdoor recreation vary by region of the United States and by type of recreation activity (USDA FS 2016). The influences of climate change affect the demand for outdoor recreation opportunities, the availability of supply, and the quality of experiences within the SOCAAP assessment area. Effects may be direct or indirect and vary in duration and magnitude. Climate change effects are already evident in the SOCAAP assessment area (chapter 2), and further change is anticipated. Recent observed change and anticipated future change affect decisions made by recreationists and alter the benefits they derive in many ways (Day et al. 2021, Miller et al. 2022).

Direct Effects

Altered Ambient Temperature

Direct effects of climate change include altered ambient temperature, both minimum and maximum. Average temperatures have already increased in southern California, and the number of high-heat days is projected to increase in the future (chapter 2). The rate of temperature increase differs by elevation (Jardine and Long 2014) as well as proximity to the coast, thus effects will vary by recreation destination. As ambient temperatures increase, populations are more likely to seek respite from the heat in nearby natural areas, especially in warm-weather seasons, increasing overall participation (Morris and Walls 2009).

Altered temperatures are more likely to affect urban centers, given several features that exacerbate heat generation and concentration in urban settings. These factors contribute to increased outdoor recreation demand from the largely urbanized population in the SOCAAP assessment area seeking respite from the heat (Tafazzoli and Sadoughi 2021). Overall, thermal comfort will likely influence the types of locations visited and the types of activities pursued on warm days (Chen and Ng 2012, Potchter et al. 2018). Locations in proximity to water, shaded areas, and higher elevations are more likely to experience increases in visitation.

Manley and Egoh (2022) modeled future popularity and visitation of outdoor recreation spaces under climate change. Their findings suggest that currently popular and high-demand nonurban recreation settings will intensify in popularity for summer recreation use, and less popular areas will decrease further in popularity. It is important to note that their exploration was based on social media data (Flickr), a promising source for assessing climate effects on outdoor recreation at larger spatial scales than previously possible (Wilkins et al. 2021c). Furthermore, results were based on large landscape areas (northern California, Sierra Nevada, coastal zones), not specific sites or smaller areas (Manley and Egoh 2022). The analysis suggests that recreation in southern California—typically warm and dry—would be likely to decrease with higher temperature during the warm-weather season, contrary to other findings reviewed for this chapter.

Wilkins et al. (2021a) examined shifts in recreation patterns across the United States under increased temperatures and identified a large amount of variation in patterns of change. They anticipate a lengthening of peak visitation season under climate change, with lower demand in summer and an increase in other seasons when the weather is cooler by comparison. In a separate study, Wilkins et al. (2021b) examined U.S. national park visitation and spatial variations during the summer in response to altered temperature and precipitation. They hypothesize that the elevation of the area visited and the distance from features, such as water bodies, roads, buildings, and parking areas, will influence shifts in visitation. For warmer ecoregions, they posit that for unusually hot days, visits will be concentrated nearer the features mentioned above and at higher elevations. They expect concentrated visitation near those same features on high-precipitation days, but at lower elevations. Finally, they expect these patterns will differ by U.S. ecoregion.

Wilkins et al. (2021b) noted some variations in these ecoregions, with microclimatic variations within parks. Their analysis revealed some inconsistencies, given the likely increase in number of visitors on warmer days and the spatial concentration of visitors at higher elevations and in shaded canyons near water. In sum, the allocation of resources and development of opportunities in these preferred locations will be important for climate change adaptation. Where Manley and Egoh (2022) considered large-landscape variations, Wilkins et al. (2021b)

highlighted variations **within** natural areas, affording insights on where increased outdoor recreation visitation may occur during warm-weather seasons. This finer scale approach, considering subregional differences, is important to more precise assessments of vulnerability as well as the development of adaptation strategies (Buotte et al. 2016).

Although a large section of the SOCAAP assessment area already has temperate weather most of the year, outdoor recreation days may be increased further, especially at high elevations as increased average temperatures extend the warm-weather season (Rosselló-Nadal 2014). Evidence from one study suggests that this has already occurred, where an examination of recreational visits at 55 national parks demonstrated an association between warmer spring temperatures and earlier seasonal park attendance (Buckley and Foushee 2012). Extended warm-weather seasons may elevate the effects of human use, extending the recreation season as well as increasing the number of locations subject to recreation use for longer periods of the year and possibly by more individuals (Ellison et al. 2018).

On the other hand, unusually hot days may lead to a decline in visitation (Richardson and Loomis 2004, Rosselló-Nadal 2014), especially if a recreation zone has also experienced extended drought. Spatial variations are likely (Wilkins et al. 2021b). Unseasonably warm or cool weather may diminish satisfaction with a location or outdoor recreation experiences (Day et al. 2021, Hipp and Ogunseitan 2011). Increased temperatures contribute to faster evaporation of water and lead to decreased water flow and availability in lakes and rivers. Elevated temperatures can lead to heat-related illnesses and risks to recreationists, especially those not prepared for extended high-heat exposure, physical exertion, and lessened access to shade and water (Evans 2019). Climate change effects, especially elevated temperatures, can adversely affect the positive contributions of outdoor recreation (Evans 2019, Hipp and Ogunseitan 2011).

Altered Precipitation

Although overall precipitation may not shift substantially across the SOCAAP assessment area, extended drought (chapter 2) will have immediate and extended effects on recreation use. Reduced water flow caused by extended drought, or reduced water levels in lakes and reservoirs, may negatively affect recreation opportunities and access (Hand and Lawson 2018). Extended drought tends to

affect summer recreation differently, decreasing water-dependent activities and sometimes increasing dryland activities (Prestemon et al. 2016), although the degree to which popularity of areas shifts under climate change, while informed by the work of Manley and Egoh (2022), would be better understood by additional study specific to the SOCAAP assessment area.

Conversely, an abundance of water from atmospheric-river events may periodically increase water flow, causing extended high-water levels. These conditions lead to long-term effects in which extreme events alter or damage water-based recreation and adjacent habitat, requiring a shift in management approaches (Huang et al. 2018). Recreation behavior also shifts after extreme events, especially when recreationists attempt to modify an area to restore preferred uses (e.g., Milburn and Winter 2015⁸) (box 5.2, fig. 5.4). Extreme-precipitation events can increase risks during the event, as well as contribute to elevated pollutant loads in rivers, compounding ecosystem effects and recreation use-related human health concerns (Clow et al. 2011, 2013).

Higher average temperatures, drought, and altered snowfall patterns affect cold-weather season activities, including downhill skiing, cross-country skiing, and other snow-dependent activities (Chapagain et al. 2018). Although projected changes in cross-country skiing, snowmobiling, and downhill skiing are smaller in the assessment area than those projected for other regions of the United States (USDA FS 2016),⁹ the benefits to recreationists and economies from snow-based activities warrant consideration. Projected changes in demand for downhill skiing as a result of climate-related changes in precipitation, temperature, and snow depth reveal likely changes in recreation demand and economic benefits (Chapagain et al. 2018). The winter recreation season may be shorter, thereby reducing participation in snow-dependent activities (Wobus et al. 2017).

Although snowmaking capabilities extend seasons and provide support for winter recreation use, existing cases across the SOCAAP assessment area suggest challenges in implementation for smaller and family-owned businesses, those at lower elevations, and those with anticipated or current constraints in water access.

Other Ecological Shifts

Other ecological shifts exacerbated by climate change may result in effects on ecosystems, wildlife, fish, and the health of recreationists. Harmful algal blooms are associated with many factors, including warmer water accentuated by climate change (fig. 5.5). Although risks from inhalation appear to vary, direct exposure from water contact can be toxic to both people and animals (Backer et al. 2010, Derlet et al. 2009). Some locations in the SOCAAP assessment area experience closures or limits on use resulting from seasonal algal blooms; for example, algal blooms affected Silverwood Lake and Pyramid Lake in the summer of 2021. Increases in some toxins can affect fishing seasons and the safety of the catch.

Indirect Effects

Indirect effects of climate change on outdoor recreation may be associated with changes in ecological features and ecosystem inputs, including vegetation, wildlife, and water. For example, demands for access and use may increase if high rainfall leads to a shift in flowering species. Higher than average snowfall or an extended snow season may also lead to increased use. These increased demands for access and use must be managed effectively to preclude diminished visitor experiences because of perceived crowding or inability to access desired opportunities. Degraded quality of an area or experiences may result in altered visitor behaviors, including decisions to not visit an area (Ferguson et al. 2018, Morris and Walls 2009).

Additional indirect effects may influence the recreational setting, opportunities, and benefits derived. In the SOCAAP assessment area, wildfire may require an area closure that precludes access, or may discourage visitation because of smoke or diminished viewsheds, and thereby, can reduce economic benefits from recreation (Wigtil et al. 2016) (fig. 5.6). However, there may be some benefits from certain types of fires. For example, landscape conditions after low-intensity fires may increase demand for wilderness hiking (Sánchez et al. 2016) (box 5.3, fig. 5.7). Some plant species rely on wildfire for seed

⁸ Milburn, L.-A.S.; Winter, P.L. 2015. Final report: Cattle Canyon participant observations. California State Polytechnic University, Pomona. 30 p. Unpublished report. [On file with: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, 4955 Canyon Crest Drive, Riverside, CA 92507.]

⁹ Projections from the Resource Planning Act (USDA FS 2016) consider changes with and without the impacts of climate change. Reports consider projected effects nationwide as well as by region. Variations by regions reveal complexities in recreation management.

Box 5.2**Angeles National Forest Study Reveals Poststorm Visitor Behavior**

Researchers monitored Cattle Canyon in Angeles National Forest to better understand outdoor recreation use and assess the effects of an environmental education outreach program (Milburn and Winter 2015). The program sought to reduce the negative environmental effects from (1) direct contact with the water, including alterations to water flow and introduction of contaminants from high use and (2) the indirect effects from littering and other activities adjacent to the San Gabriel River. To date, little attention has been given to monitoring the effects of recreation near water in protected natural areas (Dunham et al. 2018).

The research team collected data on days when the outreach program was active in the canyon and on days when it was not. During the study, a heavy rainstorm provided an opportunity to capture the effects of erratic storms associated with climate change. Recreationists

were observed using preexisting deeper pools that either were created naturally or by other recreationists who added makeshift dams to sections along the river; this dam building was infrequently seen on both outreach and non-outreach programming days. However, an uptick of new dam building occurred immediately after a large rain event, where artificially built structures and natural pools had been washed away or eroded.

These findings show how rivers can be social-ecological systems that might benefit if managers better understand the human dimensions involved in effective riverscape management (Dunham et al. 2018). Although the landscape and forest beauty are valued, so are the recreational experiences sought during a visit involving direct water contact (Milburn and Winter 2015, Winter and Chavez 2008). Applying insights from recreation ecologists and visitor management guides may help improve sustainable management and recreation opportunities (IVUMC 2019a, 2019b; Marion et al. 2016).



Figure 5.4—Recreationist-built dam across the San Gabriel River, California, to create a deeper swimming pool. Photo courtesy of Pomona San Gabriel Canyon research team, California State Polytechnic University.



Figure 5.5—Algal blooms like this can occur for many reasons, including climate change. Photo by Patricia L. Winter.



Figure 5.6—This barren landscape in the footprint of the 2020 Apple Fire exemplifies postfire decrease in scenic values. Photo by Joshua Direen; USDA Forest Service, San Bernardino National Forest.

Box 5.3

Wildfire Effects on Outdoor Recreation in San Bernardino National Forest

Wildfires have an enormous effect on outdoor recreation. In most cases, wildfires have a negative effect on recreation demand because fires alter forest vegetation and landscapes. As a result, recreation sites can be closed for an extended period because of damaged trails, campsites, and other infrastructure. For example, the 2009 Station Fire left large portions of the Gabrielino Trail in Angeles National Forest closed for nearly a decade (see box 5.4).

Sánchez et al. (2016) used an online survey of back-country recreationists to understand how different types of wildfires affect recreation behavior in the San Jacinto Wilderness Area of San Bernardino National Forest (see

fig. 5.7). Recreationists were presented with photographs of hypothetical fires occurring in the various trails within the study area to understand how recreationist's trip behavior would have changed given new trail conditions. A fire-caused closure in the San Jacinto Wilderness would decrease annual economic benefit by \$3.7 million. However, outdoor recreation demand differs by the type of wildfire. For the same study, Sánchez et al. (2016) also found that a recent low-intensity fire (see fig. 5.7) would increase visitation to the wilderness. This increase in demand would increase annual economic benefit by \$1.1 million for the wilderness. Other studies (Englin et al. 2001, Hilger and Englin 2009) have found similar visitation trends in other locations following recent wildfires.

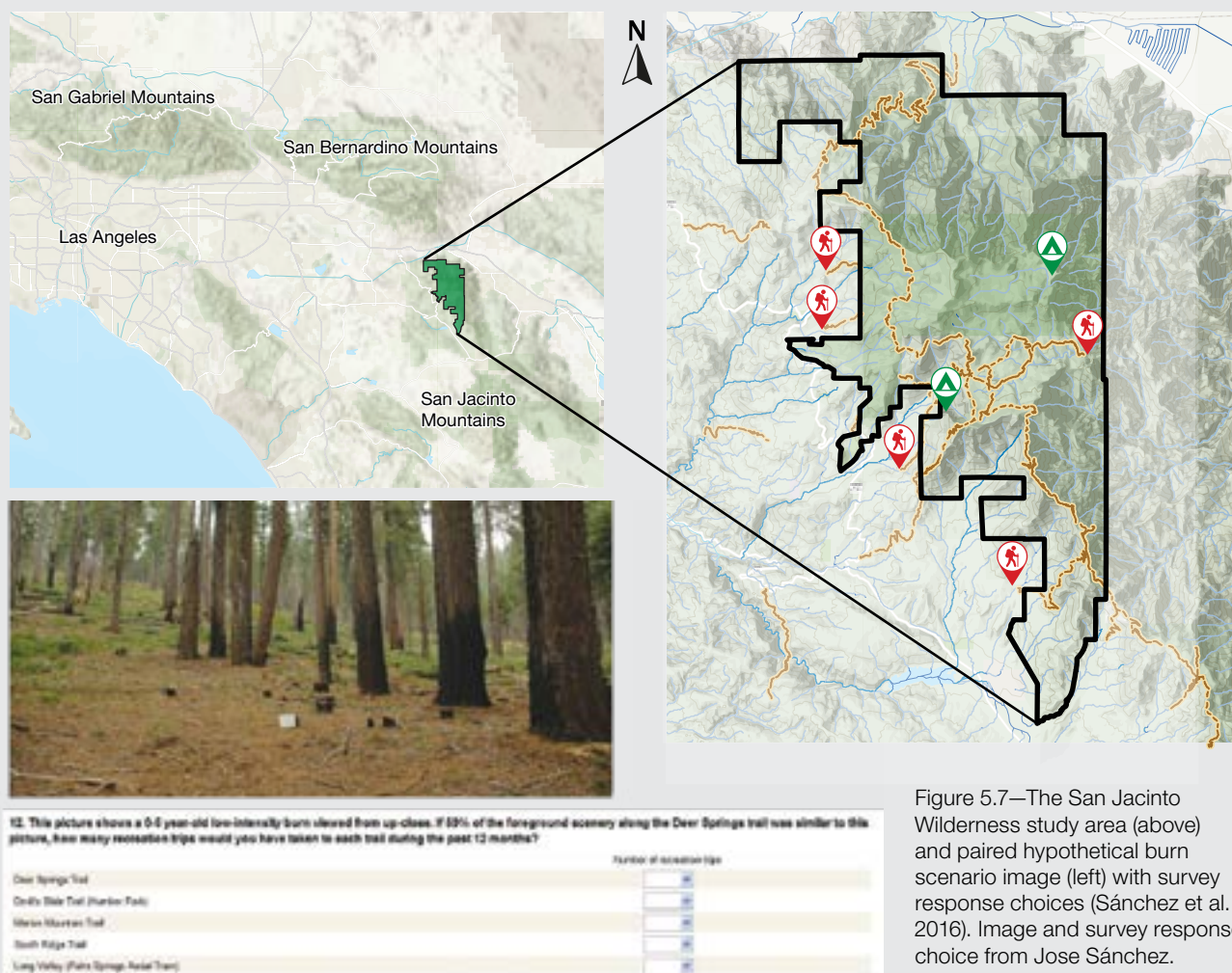


Figure 5.7—The San Jacinto Wilderness study area (above) and paired hypothetical burn scenario image (left) with survey response choices (Sánchez et al. 2016). Image and survey response choice from Jose Sánchez.

sprouting, growing, and blooming, demonstrating that postfire recovery can increase interest in an area.

Wildfires near urban areas involve health-related concerns, including the effects of degraded air quality on local communities, recreationists, and tourists (Burley et al. 2016, Bytnerowicz et al. 2013, Cisneros et al. 2010, Hall et al. 2018, Jones et al. 2020, Preisler et al. 2010, Tafazzoli and Sadoughi 2021) (chapter 6). Although wildfire smoke may not always deter recreation use on public lands, increased wildfire frequency and extent under climate change is of particular concern for vulnerable populations, which have the greatest health-related risks from wildfires but also the greatest need of the myriad benefits from outdoor recreation (Jones et al. 2020, USCDC NCEH 2020). Risks from exposure to wildfire smoke and association with out-of-hospital cardiac events are greatest during dense wildfire smoke events and continue several days after exposure to smoke (Jones et al. 2020). One study suggests that wildfire smoke-related losses are associated with health effects from trips taken, rather than losses from canceled trips (Gellman et al. 2021). Individuals at risk may underestimate their risk (Jones et al. 2020). Some effects may continue to increase in severity under climate change because of the ecological effects described in chapter 2 of this report. In recent years, Pete Lahm (Forest Service, Fire and Aviation Management) has observed the following:

Air quality impacts from wildfires have become significant health events and are now, in fact, the greatest source of air pollution exposure faced

by the American public. In addition, as wildfires increase in duration, communities often face multiple weeks of exposure. In 2018, there were over 3,700 times that fine particulate levels exceeded the 24-hour standard in the Western United States” (Lahm 2019).

Wildfire effects may be compounded if agency funding and capacity are insufficient to quickly restore a burned area, extending the effect of fire and postfire damage for many years (box 5.4). Where extensive damage occurs to recreation infrastructure, the ability to recover or restore an area for visitor use may represent extended losses through reduced benefits and limited substitution opportunities. The loss of revenue from local expenditures made during recreation visits may affect surrounding communities (Winter et al. 2014a).

Additional shifts associated with climate change that affect recreationist and outdoor worker safety in the assessment area include possible increases in growth and toxicity of Pacific poison oak (*Toxicodendron diversilobum* [Torr. & A. Gray] Greene) and increased diseases from ticks (Mohan et al. 2006, Porter et al. 2021). The distribution of some tick species in the Western United States is shifting, with climate change considered a contributing factor (Porter et al. 2021). Increased skin cancer has been observed over the past 50 years and is expected to continue to increase because of shifts in temperature, leading to increased outdoor exposure with less coverage from garments and increased ultraviolet radiation exposure (Parker 2021).

Box 5.4

Gabrielino Trail Restored After Almost a Decade

The 2009 Station Fire in Angeles National Forest and subsequent damage from postfire rain, erosion, and fallen trees left large portions of the 26-mile Gabrielino Trail closed to public use for almost a decade (Cardine 2018). In 2016, a plan was developed to restore the trail (Cardine 2018).

The Gabrielino was the nation’s first National Recreational Trail designated under the National Trails

System Act of 1968 (Cardine 2018). In September 2018, U.S. Department of Agriculture, Forest Service employees joined volunteer groups, community members, and sponsors in celebrating completion of this extensive restoration effort.

The trail reopened on the 50th anniversary of its designation. This was the culmination of a successful partnership involving grants to hire contractors for technical aspects of trail restoration, Forest Service funding and personnel, and more than 1,900 contributed volunteer hours.

—Reprinted from Winter et al. (2021: 193).

Interactions with Sociodemographic Factors

Indirect effects of climate change on recreation will interact with social change (USDA FS 2016). Interest in overall participation and types of activities that people engage in are influenced by increasing urbanization, economic conditions, changing age-related demographics, and shifts in culture associated with ethnicity, race, and community differences. Furthermore, increasing population may result in increased demand and popularity of some locations, especially those near urban communities. This increased demand and popularity may necessitate limits or controls on access, compounding the effects of climate-related stressors on access. A sense of crowding, or lessened access to desired spaces or opportunities may diminish the overall recreation experience (USDA FS 2016). Monitoring the implementation of visitor limits or restrictions can help ensure that these measures do not have adverse effects, particularly on underserved groups.

The intersection of recreation settings and opportunities sought by vulnerable communities of color, and the areas projected to be altered by climate change, will determine the degree to which these populations may be affected. For example, if locations popular among Hispanic visitors require more extensive closures (short term to mitigate risk, or longer term for recovery from damage), an environmental justice perspective would suggest identifying substitute areas for use and enhanced efforts to expedite restoration (ideally with an assessment of how to improve the area for diverse visitors) to address climate equity (EPIC 2019). As noted previously, Hispanic recreationists prefer recreation settings with developed amenities (Roberts et al. 2009). Loss of these enhanced built amenities, which require resources and time to restore, are of concern when the loss disproportionately affects underserved groups.

Communities dependent on the outdoor recreation and tourism economy may see some increases in use from extended recreation seasons but may also see increased effects to the community's way of life and ecosystem services (Lal et al. 2011). As noted previously, most recreation visits occur within a 50-mile radius of home. Access and the range of opportunities available within a close travel distance may increase or decrease. The ability of economically disadvantaged community members, or other vulnerable populations, to travel farther to alternate destinations may be constrained when climate change adversely

affects local areas. Understanding inequities in sensitivity to climate change effects will help facilitate planning and management for sustainable outdoor recreation.

Projecting the Effects of Climate Change on Outdoor Recreation

The NVUM reports provide insight into how visitors might have responded to climate change effects, wildfires, and other factors that influence recreation in national forests. Visitors were asked to select one of several substitute choices, if for some reason they were unable to visit the national forest where they were contacted. On most forests, most visitors indicated that they would have gone elsewhere for the same activity (fig. 5.8). However, the distance they would have traveled to get to an alternate location still indicates intent to recreate within a 50-mile radius from their home (fig. 5.9). This overall response pattern is independent of questions surrounding place attachment, place dependence, and recreation specialization, which all intersect with likely substitution behaviors (Kainzinger et al. 2018, Orr and Schneider 2018). It is also quite likely that populations reporting travel or transportation resources or both, as a barrier would find additional travel an unworkable burden (Winter et al. 2020a).

A *2010 Resource Planning Act Assessment* update (USDA FS 2016) assessed current and projected recreation use in the Pacific Coast assessment region (composed of the Forest Service Pacific Northwest and Pacific Southwest Regions, including the SOCAAP assessment area) with and without climate change effects by groups of activities (table 5.11). "Region" in this analysis is based on the point of origin of recreation visitors and thus is not specific to recreation use in the SOCAAP assessment area. The Pacific Coast assessment region was identified as having the greatest stability in recreation activity participation and consumption overall, with smaller climate-associated effects than other assessment regions of the Resource Planning Act, or with wider ranges of variation that are unclear (Askew and Bowker 2018).

Increases of 50 percent or more were projected for some categories of activities in the region, **excluding climate change** (table 5.11). These categories included developed-site use, observing nature, backcountry activities, motorized water activities, and nonmotorized water activities. Developed sites, as used here, included

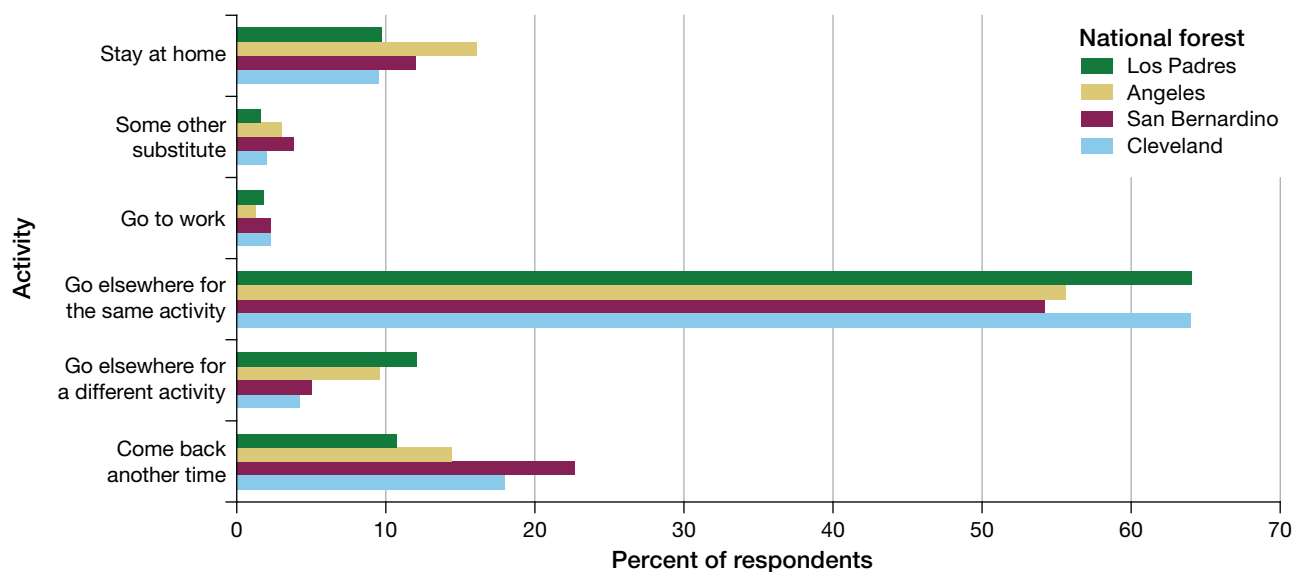


Figure 5.8—Substitute choices that surveyed visitors to national forests in the Southern California Adaptation Partnership assessment area said they would have made if they had not been able to visit the national forest where they were surveyed. Source: 2016 data was used for the Angeles National Forest; all other national forest data is from 2019. (USDA FS, n.d.b).

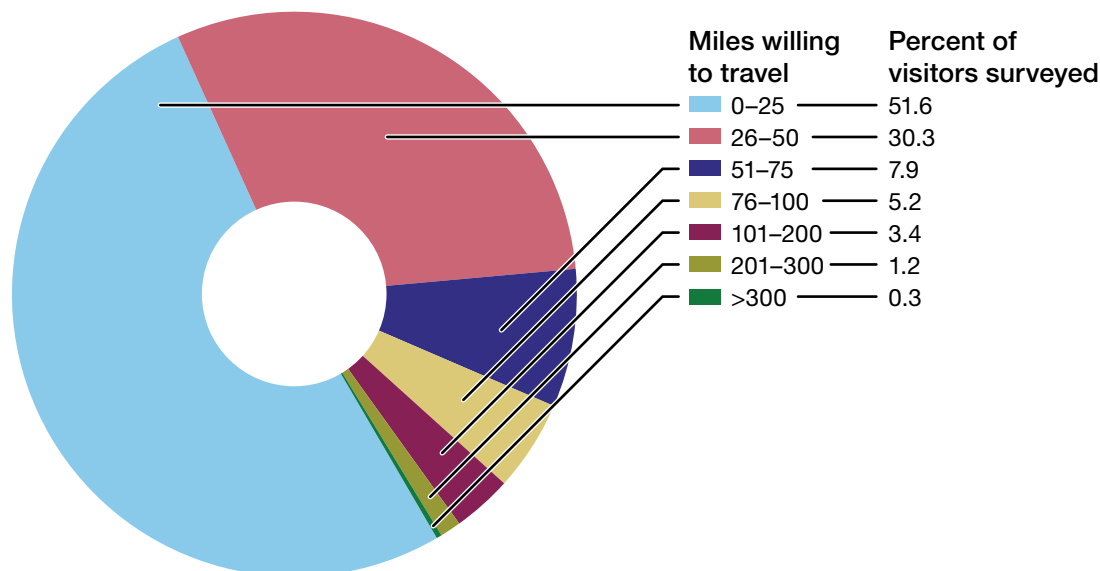


Figure 5.9—Distance that surveyed visitors to national forests in the Southern California Adaptation Partnership assessment area said they would travel to an alternate location. Source: 2016 data was used for the Angeles National Forest; all other national forest data is from 2019. (USDA FS, n.d.b).

developed camping and picnic sites; interpretive sites included nature centers and historic sites (Askew and Bowker 2018). Observing nature included birding and nature viewing. Backcountry activities included horse-back riding on trails, day hiking, challenge activities, and primitive area uses. The non-motorized water activities included swimming and floating.

Specific activities that are expected to have a ≥ 5 percent net increase with climate change were hunting

and undeveloped skiing. Only one activity showed a ≥ 5 net decrease with climate change, motorized snow activities. Thus, the activity categories and specific recreation activities are not as a whole projected for largescale shifts because of climate change effects.

Areas with a projected change associated with climate are likely to benefit from being included in sustainable recreation plans. The Recreational Opportunity Spectrum (Clark and Stankey 1979) is a

Table 5.11—Modeled projections of the effects of climate change on recreation in the Resource Planning Act Pacific Coast assessment region, 2060

Recreation activity	Number of participants in 2008	Projected change without climate change ^a	Projected change with climate change	Net effects of climate change ^b
	MILLIONS	PERCENT		
Developed site use:				
Visiting developed sites	31	68	67	-1
Visiting interpretative sites	26	72	71	-1
Observing nature:				
Birding	13	69	71	2
Nature viewing	31	66	65	-1
Backcountry activities:				
Challenge activities ^c	5	54	57	3
Horseback riding on trails	3	78	75	-3
Day hiking	17	67	63	-4
Primitive area use	18	53	55	2
Motorized activities:				
Motorized off-roading	9	47	49	2
Motorized water activities	10	80	78	-2
Motorized snow activities	1	52	44	-8
Consumptive activities:				
Hunting	3	9	19	10
Fishing	10	52	54	2
Nonmotorized winter activities:				
Developed skiing	5	91	96	5
Undeveloped skiing	1	22	32	10
Nonmotorized water activities:				
Swimming	25	75	74	-1
Floating	6	55	53	-2

The Resource Planning Act Pacific Coast assessment region includes the Southern California Adaptation Partnership assessment area. Model output is based on an average of results under the A2, A1B, and B2 greenhouse gas emission scenarios.

^a Percentage changes for total number of participants are compared to 2008.

^b Net effects of climate change equal “with climate change” minus “without climate change.”

^c Challenge activities include caving, mountain biking, mountain climbing, and rock climbing.

Source: USDA FS (2016).

helpful tool for assessing delivery of sustainable recreation activities, and its use is a requirement of the Forest Service’s 2012 Planning Rule (USDA FS 2012). The Recreational Opportunity Spectrum provides for a variety of outdoor experiences under six management-class categories: primitive, semiprimitive nonmotorized, semiprimitive motorized, roaded natural, rural, and modern developed. Social, physical, and managerial characteristics are incorporated (Hand et al. 2018).

The Forest Service framework for sustainable recreation (USDA FS 2010) emphasizes the importance of restoring and adapting recreation settings; implementing “green” operations (Ma et al. 2020, Winter and Burn 2010); investing in special places; forging strategic partnerships; promoting citizen stewardship; enhancing communities; knowing visitors, community stakeholders, and other recreation providers; providing the right information; building a solid financial foundation; and

developing the workforce. Knowing who is visiting forests, as well as their values and preferences, relies on monitoring systems and data, including the NVUM survey. Selin et al. (2020) describes details of visitor-focused recreation assessments, monitoring, and application of research toward improved sustainability.

Climate Change Vulnerability in the Southern California Adaptation Partnership Assessment Area by Management Unit

In this section, we further explore recreation activities in the SOCAAP assessment area, recreation opportunities and special places, and current or expected climate change effects for specific opportunities and places. For each management unit we identify niche recreation areas which are characterized by a unique set of features that help to demonstrate the range and variety of recreation opportunities. In some cases these niche areas are known nationwide or internationally for their unique recreation market appeal. In other cases they were selected for their specific features, visitation levels, and likely shifts in recreation opportunities associated with climate change effects. In sum they reflect a specialized segment of the market for a unique recreation experience. To augment our understanding of current challenges and management strategies within each management unit, particularly those associated with climate change effects, we queried natural resource managers. Queries included virtual group discussions. Personnel unable to attend the group discussions were invited to submit written responses, provided in group or individual form. Responses to these queries are summarized as ‘key contacts’ throughout the chapter.

Findings are presented from the northernmost management units and areas within them to the south. Some recreational experiences intersect with individual identities and place meanings, thus having cultural aspects that influence climate response and adaptation (Adger et al. 2013). The approach affords the opportunity to consider current and future subregional effects from climate change (Buotte et al. 2016).

Los Padres National Forest

Los Padres National Forest comprises 1.75 million acres, 10 designated wilderness areas, 1,453 miles of trails, 14 developed picnic areas, and 62 developed campgrounds (USDA FS 2020c) (fig. 5.10). Natural features include 293 lakes and ponds, 2,892 miles of rivers and streams, and 115 miles of wild and scenic rivers. The forest spans sections of Monterey, San Luis Obispo, Santa Barbara, and Ventura Counties, with the latter three counties accounting for the top U.S.-based visitor origins reported in the NVUM survey (USDA FS 2021d).¹⁰ More than one-fifth (24.4 percent) of visitors traveled more than 100 miles to visit Los Padres National Forest (USDA FS 2021d). Annual recreation visitation has been estimated at more than \$75 million in value to recreationists (USDA FS 2020c). Visitation is primarily during the summer and is concentrated in chaparral vegetation (Garnache et al. 2018).

Niche Recreation Area: Pfeiffer Beach

Pfeiffer Beach day-use area is located along the Pacific Coast at the northernmost portions of the forest adjacent to California State Highway 1, just west of the Pfeiffer Big Sur State Park (fig. 5.10: area 1). The site is open year-round, and day use is administered by Parks Management Company, as are many of the developed sites in this forest. Pfeiffer Beach is a high-demand location and tends to reach parking capacity by mid-morning in May through October. Recreation uses include surfing, beachcombing, saltwater fishing, wildlife and bird viewing, and tide pooling. Visitors can access the beach and creek for sightseeing and day-use activities, such as surf fishing. Popular fish species caught include barred surfperch (*Amphistichus argenteus*), Walleye surfperch (*Hyperprosopon argenteum*), yellowfin croaker (*Umbrina roncadore*), spotfin croaker (*Roncadore stearnsii*), and California halibut (*Paralichthys californicus*) (CDFW, n.d.). Fishing accounts for only 1.4 percent of overall participation in the forest (USDA FS 2021d). Visitors may also gather shellfish. Photographers and sightseers visit this location to enjoy the keyhole rock arch and the purple sand beach. Viewing natural features is one of the most popular outdoor recreation activities at 60.7 percent of overall participation (USDA FS 2021d). Pfeiffer Beach is one of the most popular attractions in the Big Sur area, providing a niche opportunity.

¹⁰ In each NVUM report, the top 15 areas of origin—determined by U.S. ZIP codes and including state and county—are reported, along with the proportion of respondents coming from foreign countries, lumped into a single category.

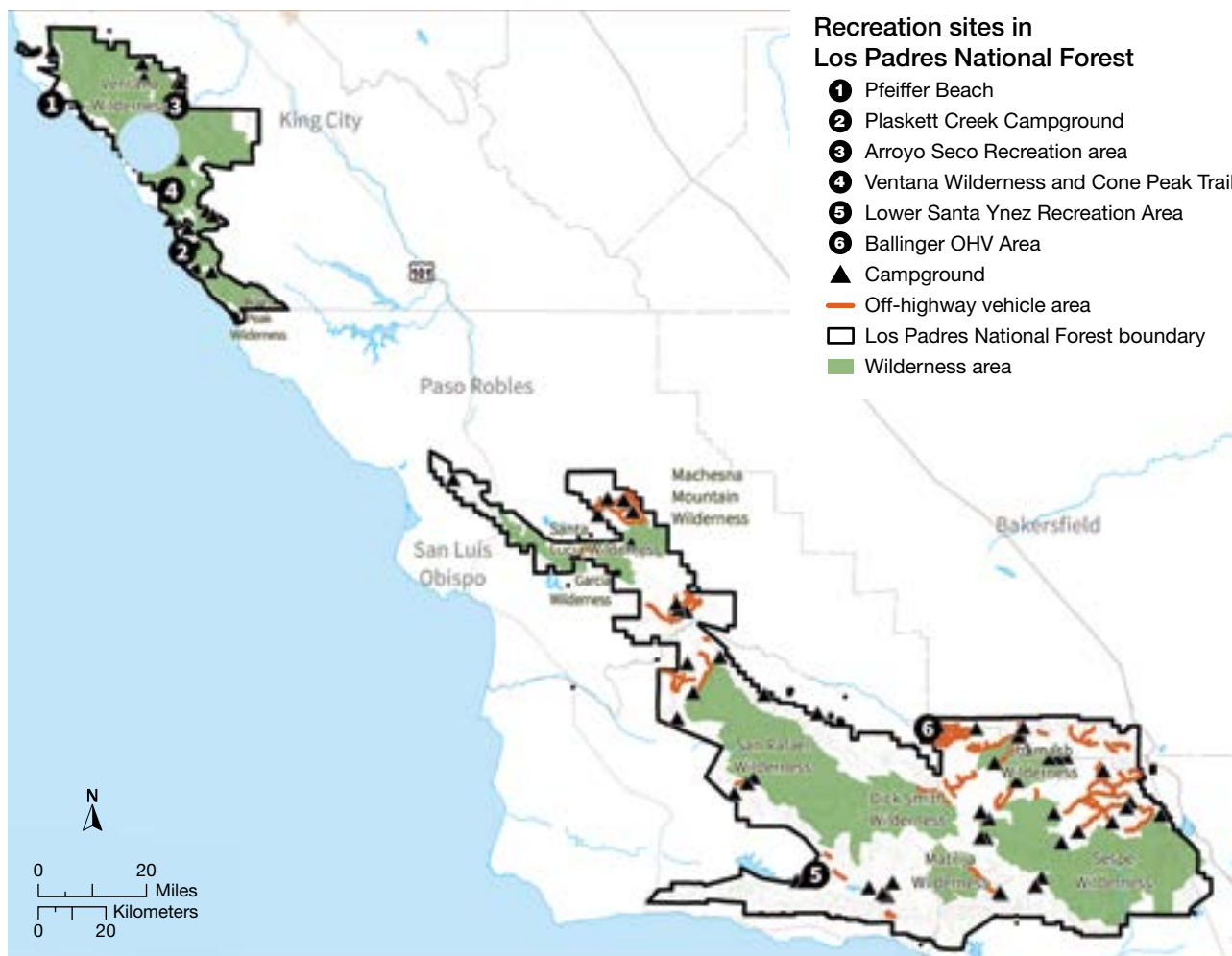


Figure 5.10—Niche recreation areas of the Los Padres National Forest. Map by Micha Solomon, USDA Forest Service, Pacific Southwest Region.

The coastal area is generally cooler than inland locations and is often windy. Fog is common at Pfeiffer Beach and in the greater Monterey area. Fog cover is expected to increase with climate change, although potential changes in coastal fog and clouds are uncertain (Langridge 2018) (fig. 5.11). Tide pooling is available at low tide but may be affected by shifts in tides or sea-level rise. Gathering shellfish may be dangerous (specifically because of paralytic shellfish poison or domoic acid) during certain seasons because some naturally occurring algae contain toxins. California Department of Public Health routinely monitors mussels, clams, and scallops for toxins and issues warnings or quarantines if needed.

An increase in algae associated with toxins and increasing sea surface temperatures was recently identified in Canada (McIntyre et al. 2021), although more research is needed on this topic. Shifts in tides or erratic storms might affect surfing. Fishing is from the beach into the surf, so altered waves or tides could potentially

affect fishing. According to California Department of Fish and Wildlife, a fisher is more likely to be successful in an incoming high tide and during mild to moderate surf (CDFW 2025), demonstrating that variable conditions can influence recreation opportunities.

Although Sycamore Canyon Road (the access from Highway 1) is open year round, it is subject to flooding after high rainfall. This location is susceptible to atmospheric river events that affect not only direct access to the site for recreation activities but may also be affected by closures along Highway 1. While atmospheric river events are likely to increase, so are extratropical storms, the main drivers of coastal flooding (Langridge 2018). Sycamore Canyon Road is also sensitive to increases in the intensity of wildfires (chapter 2). Effects are not only experienced from wildfires in the immediate location but also from adjacent locations that may result in closures to Highway 1 or may involve closures because of elevated risks of wildfires (chapter 4).



Figure 5.11—Fog is often present along the Big Sur coastline. Photo by Patricia L. Winter.

Niche Recreation Area: Plaskett Creek Campground and Sand Dollar Beach Day-Use Area

Beach access and coastal day use opportunities (with some similarities to Pfeiffer Beach) are found at Willow Creek and Mill Creek (small sites) and Sand Dollar Beach day-use area. The latter site is adjacent to Plaskett Creek Campground (fig. 5.10: area 2), offering calmer access for saltwater fishing. Swimming and wading opportunities vary because of the rough surf and rip currents that are sometimes present. Hang gliders and paragliders take flight from the bluffs above Sand Dollar. It is one of the best surfing spots in the Big Sur area and has the longest stretch of sandy beach. It is also near Jade Cove, where people can search for and gather jade.

The walking paths along the bluff provide an opportunity to whale watch and enjoy varied wildlife and plants (fig. 5.12). Overwintering monarch butterflies (*Danaus plexippus*) at Plaskett Creek Campground and surrounding areas are a big attraction, representing a niche opportunity in Los Padres National Forest. Viewing wildlife is popular in Los Padres National Forest, with 43.5 percent of visitors participating in this activity (USDA FS 2021d). Climate change affects abundance and range of species, including wildlife and insects, in part because of species dependence on flowers, fruits, and seeds (Molinari et al. 2016). As a result, climate change may affect available wildlife viewing opportunities.

The Plaskett and Kirk Creek day-use sites and campgrounds have climate-related challenges similar to those at Pfeiffer Beach, including reliance on access from California State Highway 1 and safety hazards associated with water access because of large surf and rip currents and abrupt dropoffs. Waves and storm damage, coastal erosion, ocean acidification, and sea-level rise are already affecting the California coast, increasing risk for recreation opportunities, ecosystem services, and human communities (Maizlish et al. 2017, Reiblich et al. 2019).

The climate adaptation priorities report prepared by the California Department of Transportation for district 5 (north of Monterey to Santa Barbara) identifies high-priority bridges and sections of roadway along Highway 1 (Caltrans 2021) (box 5.5, fig. 5.13). The central coast region, including the Monterey coast, is susceptible to long-term coastal shoreline change, involving erosion, loss of shoreline, cliff retreat, and coastal slope failures (Langridge 2018). Under the influence of climate change, these coastal areas will continually change, affecting outdoor recreation.

Niche Recreation Area: Arroyo Seco Day-Use Area and Campground

Freshwater fishing is another recreation opportunity in Los Padres National Forest. Trout fishing is available along Salmon Creek, providing 10–12 miles of fishable stream. Arroyo Seco is a popular developed day-use area with picnic tables, grills, potable water, and flush toilets (fig. 5.10: area 3). Picnicking was the reported activity of 9.3



Figure 5.12—Sand Dollar Beach, Los Padres National Forest. Photo by Kayla Snell/Stocksy.

percent of visitors (USDA FS 2021d). Aside from picnicking and barbecuing, visitors reported enjoying swimming and wading on warm days in the Arroyo Seco River, which is surrounded by oaks and Fremont cottonwoods (*Populus fremontii* S. Watson). Nearby campgrounds provide access to trout fishing along the river. This developed campground is busiest in the summer. Camping in developed sites was reported by 11 percent of visitors to Los Padres National Forest (USDA FS 2021d). Rivers and streams such as the Arroyo Seco are susceptible to climate change effects, especially at lower elevations where reduced streamflow from shifts in precipitation, increased water temperatures, and wildfires affect biodiversity and ecosystem services, including recreation (Hilberg et al. 2017b).

Key contacts from Los Padres National Forest described perennial streams in the forest as unique in the SOCAAP assessment area. They described a pattern of concern because extended drought creates isolated pools of water, separating these stream segments so that they lose their perennial nature, isolating fish and affecting habitat. Perennial streams are becoming intermittent and even ephemeral on the forest. Shifts in fish species over time are possible, affecting recreation opportunities in Los Padres National Forest and beyond (Miller et

al. 2022). Algal blooms pose a threat to the streams and rivers as they lead to greater oxygen loss in waterways, further affecting natural systems (fig 5.5). Harmful exposure to algal blooms and associated release of toxins with resulting health effects to people and animals is expected to increase with climate change for the central coast region (Langridge 2018). The degree of effect is complex, resting on many factors, including development, shifts in precipitation, shifts in wildfire, elevation, distance from the coast, and restoration measures (Hilberg et al. 2017b).

Niche Recreation Area: Ventana Wilderness and Cone Peak Trail

The Cone Peak Trail represents a niche opportunity as the trail begins at sea level and ascends to the second highest peak along the Santa Lucia Range (fig. 5.10: area 4). Water availability affects day use and extended overnight use in some areas of Los Padres National Forest. Campers and backpackers who once relied on water availability from rivers and streams now need to bring their own water. Backpacking is the main activity reported by 4.1 percent of visitors recreating in Los Padres National Forest (USDA FS NVUM 2021d). Effects on backpacking trips can be inferred from experiences described at alltrails.com (AllTrails, LLC 2010–2025):

Box 5.5**Wildfire and Atmospheric River Lead to Closures**

Reported August 18, 2020, the Dolan Fire burned chaparral, brush, and timber understory south of Big Sur (Kostelnik et al. 2021); firefighters fully contained the fire on December 31. The fire burned private, state, and federal lands, but most of the area burned (124,924 acres) was in Los Padres National Forest. Officials closed Highway 1 between Pfeiffer State Park and Lucia to the south.

In January 2021, an atmospheric river caused heavy rainfall and subsequent soil saturation (Kostelnik et al. 2021). Caltrans closed 40 miles of highway because it was concerned about hazards in the burn area. However, a section that they did not close collapsed after saturated soil gave way, according to the Los Angeles Times (Logan 2021). On January 28, 2021, about 23 miles of the highway was lost at Rat Creek, just south of Big Sur. In the interim, visitors to Big Sur had access from the northern route though Carmel. Highway repairs were

sufficient to allow reopening on April 23, 2021. This fire (ultimately attributed to arson) demonstrates the combined effects of fire and extreme precipitation on recreation access and safety across extended spatial and temporal scales. It is a fitting example, as most fires in southern California are ignited by humans (Syphard and Keeley 2015).

At the time of writing this report, several national forest roads, trails, and campgrounds remained closed to public use because of the Dolan Fire. Closures along the state route are not unusual but are a consideration to recreationists hoping to access sites along the coast. Caltrans also had to close a section of Highway 1 from May 2017 through July 2018 because of a large landslide; it was one of the longest closures in recent history and involved \$54 million in repairs.

In the future, closures along the central coast may increase as a result of climate change, affecting Los Padres National Forest recreation opportunities (Langridge 2018).



Figure 5.13—Big Creek Bridge, which was flagged by the California Department of Transportation as a high-priority bridge for climate change and in need of a detailed climate vulnerability assessment (Caltrans 2021). Photo by Lisa Wallace.

- A recreationist starting at Highway 1, hiking into the Ventana Wilderness and hoping to summit at Cone Peak, did not have sufficient water (February 8, 2022).
- A seasonal spring 3 miles from Cone Peak did not have sufficient water, leading to altered trip plans and a recommendation to prepare to bring water from Vicente Flat.

Multiple online accounts echo similar experiences concerning water availability.

Niche Recreation Area: Lower Santa Ynez Recreation Area

Spring and summer weekends are typically high-use days in the Lower Santa Ynez Recreation Area (fig. 5.10: area 5). Drought, including lack of water in creeks and rivers, has affected day use in this location. Key contacts interviewed from the Los Padres National Forest suggest a considerable reduction in use during the hot summer months because of a lack of flowing water. Low flow has affected the Red Rock pools, a popular swimming area on the Santa Ynez River. Reduced water levels observed at Lake Cachuma, an important recreation destination and a main source of surface water in Santa Barbara, are evidence of drought effects (Langridge 2018) (fig. 5.14).

In addition to campgrounds at Plaskett Creek, Kirk Creek, and Arroyo Seco, the Monterey Ranger District lists four open campgrounds at the writing of this report, with closures to three due to fire. Most recreation opportunities in Los Padres National Forest are susceptible to wildfire affects. Threats of wildfire, when elevated because of dry conditions, high heat, and wind, lead to larger area closures affecting recreation throughout the SOCAAP assessment area (chapter 2) (fig. 5.15). Areas adjacent to a fire may also be closed to increase safety for visitors, community members, and first responders. Burns in an immediate area result in closures as do postburn periods to allow for recovery of built and natural systems. A key contact from the San Bernardino National Forest clarified that temporary closures before and after a fire may last up to 1 year, after which a reassessment must occur. Postfire effects interact with winter storms to increase damage and risks for multiple seasons and sometimes years.

Higher temperatures, altered wildfire regimes, increased extreme precipitation events, increased invasive grasses,



Figure 5.14—Water level at Lake Cachuma showing evidence of recent drought. Photo by Patricia L. Winter.



Figure 5.15—September 15, 2021 Facebook post by Angeles National Forest exemplifying how high wildfire danger has spurred forest-wide closures in the Southern California Adaptation Partnership assessment area. USDA Forest Service image.

increased drought, and increased human population were all assessed in the Ojai Community Defense Zone Project (EcoAdapt 2017a), serving as a reminder that effects combine to elevate climate change vulnerabilities. As part of this effort, the Forest Service restored and expanded fuel breaks to (1) reduce the threat of wildfire to communities in the wildland-urban interface, (2) create safer conditions for the public and firefighters, (3) protect watershed habitat value and water quality, (4) reduce potential effects of high-intensity wildfire, and (5) increase the efficiency and

cost effectiveness of fire suppression activities. The project also addressed “trigger points for recreation closures and restrictions,” to reduce the number of ignitions during high-risk periods (EcoAdapt 2017a). Postfire recovery periods for natural systems may be extended further under climate change effects (Langridge 2018).

As part of the EcoAdapt assessment, managing recreation in the heavily used conifer and subalpine zone of Mount Pinos was also examined (EcoAdapt 2017a). The Mount Pinos Ranger District offers camping, day hiking, backpacking, mountain biking, fishing, hunting, off-highway vehicle (OHV) riding and camping, scenic drives, nature viewing and winter sports (cross-country skiing and sledding) (USDA FS LPNF 2025). Strategies to address high levels of use, reduce ecosystem affects, and reduce wildfire risk include signage, fencing, and public education (EcoAdapt 2017b). These strategies are centered on changing human behavior using traditional behavioral change interventions (Balmford et al. 2021). Using the Interagency Visitor Use Management Council monitoring and visitor capacity guidebooks (IVUMC 2019a, 2019b), as well as the handbook developed for natural resource managers (Burn and Winter 2008), may help develop these strategies. Marion and Wimpey (2017) described ecologically focused techniques that may further assist sustainable management of trails.

Niche Recreation Area: Ballinger Canyon OHV Area

Of those surveyed, 2.9 percent of visitors reported OHV use as an outdoor recreation activity in Los Padres National Forest (USDA FS NVUM 2021d). OHV users visited the Ballinger Canyon OHV area (fig. 5.10: area 6) and Deer Park primarily for day use and camping. These sites combined make up the most heavily used OHV area in Los Padres National Forest, encompassing 68 miles of marked and rated trails that range from novice to advanced in the high desert (Parks Management Company 2025).

Trails supporting heavy use from horses or motorized vehicles require greater attention to ecological sustainability guidelines (Marion and Wimpey 2017). Interventions to reduce wildfire risk and other ecological effects during drought-stressed conditions may affect OHV use, although some interventions could be viewed as improving the recreation opportunities and maintaining access. Applications of sustainable approaches

can maintain levels of use, keep resource effects within acceptable limits, and maintain access and experience quality (Marion and Wimpey 2017). EcoAdapt (2017b) cited management of OHV use as a current management action, but it was not addressed further.

Angeles National Forest

Angeles National Forest has 121,482 acres of wilderness areas, 541 miles of trails, 39 developed picnic areas, and 49 developed campgrounds (USDA FS 2020a) (fig. 5.16). Eighty-seven miles of the Pacific Crest Trail cross the forest. Natural features include 126 lakes and ponds, 508 miles of rivers and streams, and 6 miles of wild and scenic rivers. The national forest spans sections of Los Angeles County, which account for the top U.S. based visitor origins reported in the NVUM survey (USDA FS NVUM 2021b). Few (3.4 percent) visitors traveled over 100 miles to visit Angeles National Forest (USDA FS NVUM 2021b).

Annual recreation visitation has been estimated at more than \$232 million in value to recreationists (USDA FS 2020a). The forest represents about 70 percent of the open space for the largely urban area within a 90-minute drive. The forest spans the northern desert zone to high peaks, home to limber pine (*Pinus flexilis* James). Much of the forest is covered in chaparral, and visits are concentrated in this system type and are heaviest from June through August (Garnache et al. 2018). Most visits occur on weekends, and some sites (e.g., the San Gabriel River concentrated-use area) have their highest visitation on Sundays (Barry et al. 2012¹¹).

According to a key contact interviewed for this assessment, Angeles National Forest is unique because of its cool-water streams and, in many locations, perennial water access. Heavy use is concentrated close to riparian zones, roads, and trails, affecting streambanks and complicating the protection of riparian habitat and ability to maintain recreation experience quality. Climate change effects from extended drought and erratic precipitation patterns may further complicate management in already affected riparian zones.

¹¹ Barry, K.; Johnson, S.; Schwartz, M. [et al.]. 2012. Sustainable visitorship at the Angeles National Forest: strategies for solid waste management. 117 p. Unpublished report. On file with: U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, 4955 Canyon Crest Drive, Riverside, CA 92507.

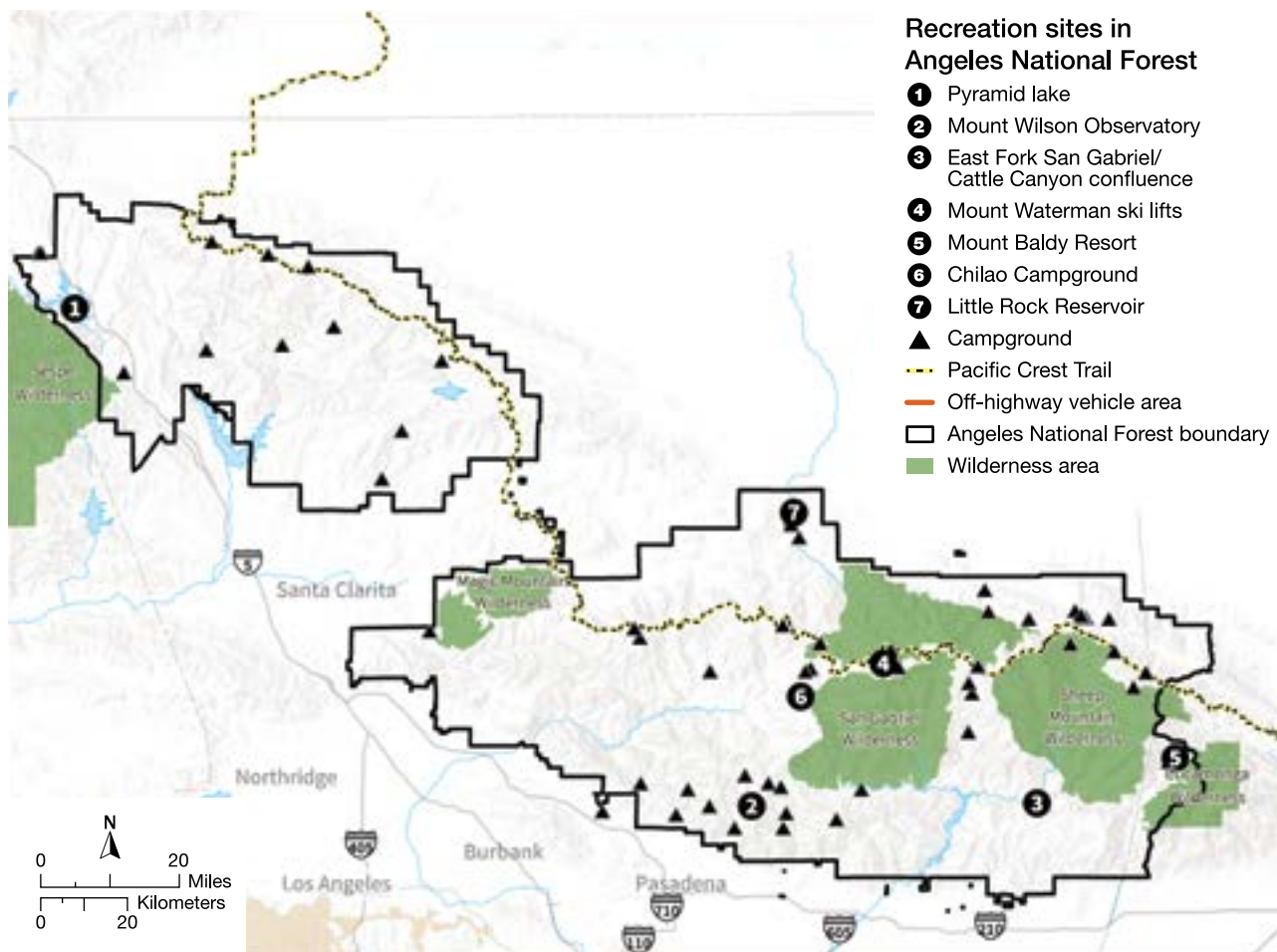


Figure 5.16—Niche recreation map of the Angeles National Forest. Map by Micha Solomon, USDA Forest Service, Pacific Southwest Region.

Many recreationists visiting Angeles National Forest seek to escape elevated temperatures and diminished air quality. The Los Angeles Basin is still considered the smoggiest in the nation, and elevated temperatures along with other climate related shifts are likely to further contribute to elevated ozone, including peaks well above thresholds that affect human health (Hall et al. 2018). Recreationists from communities of color bear an elevated burden of ozone exposure in the Los Angeles Basin (Padgett et al. 2021, Winter et al. 2019).

Niche Recreation Area: Pyramid Lake

Pyramid Lake is on the western side of Angeles National Forest (fig. 5.16: area 1). Activities here include boating, fishing, swimming, and picnicking. Fish species caught at the lake include smallmouth and largemouth bass (*Micropterus dolomieu* and *Micropterus salmoides*, respectively), channel catfish (*Ictalurus punctatus*), rainbow trout (*Oncorhynchus mykiss*) planted by the California Department of Fish

and Wildlife, and carp (*Cyprinus carpio*). (SCFR 2025). Camping is within a mile at the Los Alamos Campground. Fishing is reported by 3.3 percent of visitors as an outdoor recreation activity in Angeles National Forest (USDA FS NVUM 2021b). Harmful algal blooms periodically reduce recreation opportunities at the lake (box 5.6).

Niche Recreation Area: San Gabriel Mountains National Monument and Mount Wilson Observatory

Primarily within the boundaries of Angeles National Forest, San Gabriel Mountains National Monument was designated in 2014 and comprises 346,177 acres. The monument incorporates the heaviest used areas for outdoor recreation of this forest. The monument designation is expected to encourage additional recreation visitation, while protecting myriad important assets and services (chapter 6).

The Mount Wilson Observatory (fig. 5.16: area 2) has hosted a variety of astronomical researchers and

Box 5.6**Pyramid Lake Recreation Use Limited by Algal Bloom**

Following a month-long closure to public access and outdoor recreation, Pyramid Lake (in Angeles and Los Padres National Forests) opened on September 23, 2021. However, the California Department of Water Resources issued an advisory warning people to avoid direct physical contact with the lake and consuming large fish from it because of an active blue-green algal bloom (cyanobacteria) (CDWR 2021). Health risks from exposure to the toxic algae include eye irritation, skin rash, mouth ulcers,

gastrointestinal upset, and cold- and flu-like symptoms (Backer et al. 2010, Derlet et al. 2009). Pets are especially susceptible because they may drink the water while in contact with it or clean their fur afterward (Carney 2022). Algal conditions can change rapidly, affected by waves and wind, and algae can accumulate along the water surface and shore (Backer et al. 2010). The 2021 advisory was not the first of such events; a similar advisory was issued in July 2018 (CDWR 2018). Because high temperatures promote the abundance of toxic algae, climate change is expected to cause a greater risk associated with algal blooms (Derlet et al. 2009).

their discoveries, including the work of Edwin Hubble. Visitors can enjoy a short hike around the observatory and view the Los Angeles Basin. The site allows visitors to combine contact with nature and astronomy.

Viewing natural features is among the more frequent recreation activities in Angeles National Forest; 37.2 percent of visitors reported it as a recreational activity (USDA FS NVUM 2021b). A challenging hike lies between the Chantry Flat Picnic Area and the observatory (a 13.5-mile loop). Stargazing and astronomical viewing are degraded by air pollution, which may worsen under climate change (Haywood 2021, Kocifaj and Barentine 2021, Padgett et al. 2021). Although a strong focus has been on light pollution, reducing air pollution may darken the night sky, leading to improved recreational stargazing (Kocifaj and Barentine 2021). Significant concern arose in 2020 when the Bobcat Fire threatened the observatory, approaching within 500 feet of the facility (McGreevy, 2020). Some effects were still seen on the forest where the fire led to a large designated-area closure that was still in effect at the writing of this chapter, including the closure of the trail between Chantry Flat and the observatory.

Hunting is a seasonal activity in Angeles National Forest and is subject to state regulations and permits as well as Forest Service regulations. It represents about 0.4 percent of outdoor recreation participation on the forest

(USDA FS NVUM 2021b). Deer and bear hunting with rifle or bow are allowable with appropriate licenses and tags within the Angeles National Forest, which overlaps California Department of Fish and Wildlife zone D-11 (CDFW 2021). A key contact for Angeles National Forest noted a recent increase in the black bear (*Ursus americanus*) population, which has been associated with increased human-bear encounters. A study is underway to better assess the bear population. Media accounts mention the possible role of drought in bears leaving the forest and moving into surrounding communities, noting the apparent increase in bear-human encounters at the wildland-urban interface (Rojas and Scauzillo 2021). The California Department of Fish and Wildlife describes highly variable weather for this location, mostly dry and hot but with erratic storms (CDFW 2021). According to the California Department of Fish and Wildlife, the deer population in this zone is relatively stable but has been declining since the 1960s (fig. 5.17). Deer habitat was recently described as follows:

Generally speaking, deer populations in this area respond favorably to vegetation disturbances that enhance brush species (wildfire and timber harvesting). Riparian areas (areas along watercourses), recently burned areas, or clear

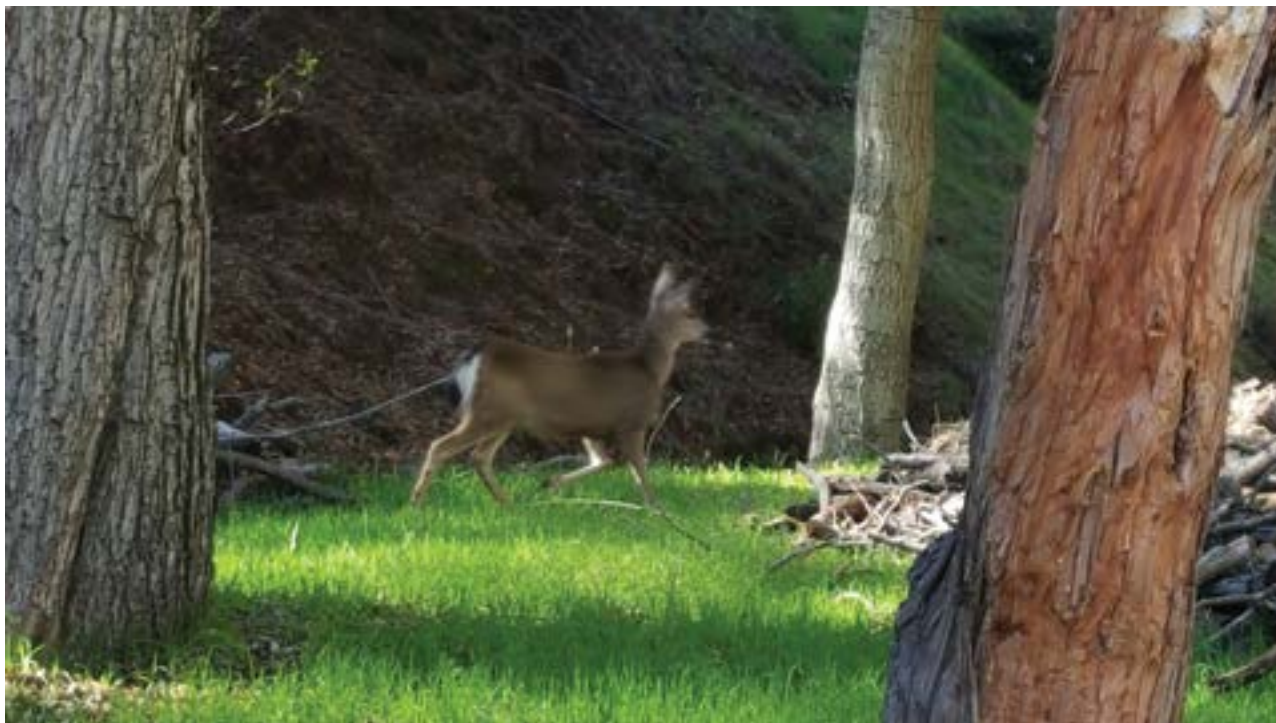


Figure 5.17—A mule deer (*Odocoileus hemionus*) walking in Angeles National Forest where the deer population is relatively stable. Photo by Patricia L. Winter.

cuts that have re-sprouted with brush are good areas to hunt. Areas where oaks are producing acorns may also attract deer. Typically, lower densities of deer are observed in the more densely forested areas or in older, more decadent brushlands. (CDFW 2021: 5).

Climate-related disturbances can affect hunter access (e.g., wildfire-related closures) and increase safety-related concerns (lack of available water, heavy precipitation leading to flooding), although disturbances can afford advantages aligned with habitat preferences for various wildlife species. These interactions reveal the complexity of climate change effects.

Niche Recreation Area: East Fork San Gabriel River and Cattle Canyon Confluence

The East Fork San Gabriel River and Cattle Canyon confluence (fig. 5.16: area 3) are the focus of some of the heaviest recreational day use in Angeles National Forest. Noteworthy for a high concentration of use from traditionally underserved populations, especially Hispanic visitors, the area also has many ecological concerns, including habitat for threatened and endangered species. The East Fork San Gabriel is a concentrated-use area that is about 5 miles in length along East Fork Road (Barry et

al. 2012). Visitors gather in developed lots and pullouts to recreate along the water's edge, sometimes in makeshift recreation areas (Barry et al. 2012) (figs. 5.18 and 5.19). This configuration of recreation use makes managing the effects more complicated than use in developed sites where toilet and trash facilities, as well as some clearing and hardening of paths, can reduce the effects on the environment.

Social science research conducted in the 1980s and beyond has focused on this riparian area and adjacent sections of the forest to understand sociodemographic characteristics of visitors, the outdoor recreation opportunities they seek, communication patterns and preferences onsite and offsite, and visitor values (Absher et al. 1997, Chavez 2008, Chavez and Olson 2008, Johnson Gaither et al. 2015, Roberts et al. 2009, Winter and Chavez 2008). Some studies informed pilot programs intended to benefit recreation visitors, resource managers, the surrounding community, and the ecosystems (Absher et al. 1997, Barry et al. 2012, Roberts et al. 2009). Increases in extreme heat are expected to disproportionately burden low-income residents and communities of color across the Los Angeles region, increasing the importance of understanding climate effects and adaptations that



Figure 5.18—Visitor vehicles parked along the highway next to San Gabriel Canyon on a high-demand recreational use day. Photo courtesy of California State University, San Bernardino recreation research field team.



Figure 5.19—Recreationists have modified this riverbed by adding tables and shade for day use. Photo courtesy of California State Polytechnic University, Pomona San Gabriel Canyon research team.

promote socioecological resilience (Hall et al. 2018). An overarching objective is to maintain or improve opportunities provided for a diverse visitor population.

The East Fork San Gabriel area is currently the focus of a managed recreation project developed over several years by Angeles National Forest, the Watershed Conservation Authority, the San Gabriel and Lower Los Angeles Rivers and Mountains Conservancy, and the Los Angeles County Flood Control District. The project encompasses 198 acres on the forest and balances outdoor recreation demand with long-term resource protection. Development in the area will influence uses as well as future effects from climate change.

Elevated ambient temperatures may further increase recreation demand along the already popular San Gabriel River, increasing issues surrounding access, recreation experience quality, and resulting visitor behaviors. For example, some visitors modify water flow to create pools (box 5.2), especially after erratic storm events that alter preexisting pools. Alterations may restore pre-existing pools that occurred naturally but were changed during a storm, or pools that visitors had previously constructed. Pools are built from natural items such as rocks or branches, or may be built from human-manufactured items discarded in the area (for example, trash cans or car bumpers). Because visitors to this area value water access, shade, and open views, recreation in this area is highly susceptible to climate-related effects (Garnache et al. 2018) (fig. 5.20). Drought reduces water flow and

increases competition over direct water contact, increasing the possibility of user conflicts and crowding. Water quality becomes a concern under drought conditions; exposure to waterborne diseases and contaminants may increase (USCDC NCEH 2020). Water quality is also a concern for habitat and species protection. Shortages of water-based opportunities may increase competition and contribute to degradation of sites (Garnache et al. 2018).

Climate-associated events, such as flooding or wildfire, increase safety concerns involving transportation corridors, evacuation routes, and the ability to safely exit along steep canyon roads under stressful conditions (chapter 4). Some areas of the forest have limited cellular access, complicating timely updates to visitors in canyons or remote locations. A key contact interviewed for this assessment reported that visitor safety and adequate evacuation routes were concerns given high-use levels and because some visitor populations may be less familiar with the forest and associated risks. Based on risk assessments showing these patterns of high risk, the possibility of extended closures was viewed as increasingly likely as climate change continues to effect the region.

The San Gabriel Canyon Off-Highway Vehicle Area along the West Fork San Gabriel River sees moderate to heavy use over its 160 acres of rocky, sandy river bottom by users of 2-, 3-, and 4-wheeled OHVs. Across the forest, OHV use accounts for 3.9 percent of recreation visits (USDA FS NVUM 2021b). Like other federal areas



Figure 5.20—Visitors value water access in shaded locations, such as this one along San Gabriel Canyon. Photo courtesy of California State University, San Bernardino San Gabriel Canyon research team.

with high levels of recreation demand, visitors must make a reservation through Recreation.gov (USA 2025), the federal government's centralized travel planning and reservation platform, year round. Same-day reservations are reportedly available on some days.

Niche Recreation Areas: Mountain High, Mount Waterman, and Mount Baldy

Although snow-based recreation has higher levels of visitation during winter seasons in San Bernardino National Forest, Angeles National Forest has developed ski and snow-play areas: Mountain High, Mount Waterman (fig. 5.16: area 4), and Mount Baldy (fig. 5.16: area 5). Downhill skiing is involved in 9.5 percent of forest recreation participation (USDA FS NVUM 2021b). According to a key contact we interviewed, these are unique ski resorts because small businesses own and operate them. In recent years, Mount Waterman has been unable to sustain business because of lower snowfall and snowpack, and Mount Baldy has struggled. Adaptations such as increased snow making are not reasonable for these locations because of limited access to water, and

there is no ability to drill new wells. In recent years, summer-based recreation opportunities have been the focus of development and programming, with hopes that eventually these areas will gain in sufficient summer-time popularity to offset most of the winter recreation losses associated with overall elevated temperatures, reduced access to water, and reduced snow. Examples of summer-based adaptations include disc golf and zip lines at Mountain High, as well as scenic lift rides and tent cabin rentals at Mount Baldy.

Another key contact interviewed for this assessment expressed concern about fire behavior observed during the 2020 Bobcat Fire that involved crown fires in old-growth conifers and rapid downhill spread pushed by wind and fuels. Loss of natural infrastructure (conifers) and built infrastructure in these ski areas seems possible. A separate contact observed that loss of conifers is a concern on the Angeles National Forest because lower moisture (less precipitation) and higher temperatures make restoration very challenging. Although replanting has been conducted in some locations, a 1-percent

survival rate of seedlings reported by this contact suggests challenges moving forward. Conversion of areas of the forest from conifer forest to chaparral on drier slopes may be permanent because of recent and future climate effects (Hall et al. 2018).

Niche Recreation Area: Chilao Campground

Not all climate change effects will necessarily be negative. For example, a key contact noted that Chilao Campground (fig. 5.16: area 6) remained open a few years ago during the winter season because of lessened snowpack. Managers were able to keep the campground and picnic area open, extending the recreation-use season and enhancing recreation revenues. This contact said that opening and closing locations are more resource intensive than leaving them open, and staffing flexibility on this forest accommodated the extended opportunity. Chilao Campground is at an elevation of 5,300 feet and has 84 developed campsites across two loops. Scenic views of Big Tujunga Canyon and Vetter Lookout, as well as hiking along the Silver Moccasin Trail, are part of the unique offerings of this location. The location is heavily used, with water, vault toilets, picnic tables, tent camping, and trailer camping. The campground is about 2 miles from the Upper Chilao Day-Use Area. Nearby, along Angeles Crest Highway, is the Chilao Visitor Center (open on weekends) with access to four self-guided interpretive trails (including the Silver Moccasin Trail).

Niche Recreation Area: Little Rock Reservoir

When asked about communities that have been or will be affected by climate change on the Angeles National Forest, one of our key contacts mentioned the desert community in Antelope Valley. Residents of this community were recreation visitors to the Little Rock Reservoir (fig. 5.16: area 7) that, at the time of writing this report, remained under extended closure. Reopening this Forest Service-managed resource area is challenged in part by low precipitation, extended drought, and lack of resources to support the restoration needed to protect it from previous heavy uses that affected the ecosystems. The Palmdale Water District manages the reservoir area (including Little Rock Dam by way of a special-use permit), which provides opportunities for OHV use, boating, fishing, swimming, and picnicking.

Niche Area: San Dimas Experimental Forest

San Dimas Experimental Forest, collaboratively managed by the Forest Service, Pacific Southwest Research Station and Angeles National Forest, lies within the boundaries of Angeles National Forest and San Gabriel Mountains National Monument. In 1933, the experimental forest was established as a large natural laboratory for hydrologic research. Given the importance of water in southern California, research focused on increasing water yield for downstream human consumption, originally for agriculture and ultimately for domestic water supply.

Research on the experimental forest over time has examined watershed hydrology, chaparral ecology, water yield, precipitation monitoring, postfire erosion control treatments, soil non-wettability, hillslope erosion and watershed sediment fluxes, soil nutrient cycling, and bird habitat use (Dunn et al. 1988). The experimental forest made a major contribution to the study of southern California systems and nitrogen deposition, revealing the role of dry deposition and fostering of weedy exotics (Fenn et al. 2003). This was important given the predominant role of wet deposition in other areas nationally. The experimental forest serves as a critical area for fire defense according to a key contact we interviewed. It is bordered by the backcountry on one side and the perimeter of the wildland-urban interface on the other.

Climate change effects on water yield, fire dynamics, air quality, and wildlife are potential topics for continuing study in the forest. Climate change effects associated with wildfires but also from extensive flooding could potentially damage the research infrastructure and limit future research contributions. Impaired air quality increases susceptibility to drought effects according to another key contact, which subsequently increases wildfire risk (Grulke et al. 2009). The experimental forest offers unique opportunities in a chaparral ecosystem to explore comparisons to similar ecological conditions without recreation use in the rest of the Angeles National Forest. Not many similar sections of chaparral systems remain with comparable minimal effects from recreation use.

Santa Monica Mountains National Recreation Area

Santa Monica Mountains National Recreation Area is managed by the National Park Service and other agencies, including California State Parks and two conservation authorities (LCI 2020) (fig. 5.21). Our focus for the SOCAAP assessment area is on the area managed by the National Park Service (25,000 of Santa Monica Mountains National Recreation Area's 150,000 acres).

Key contacts interviewed for this portion of Santa Monica Mountains National Recreation Area were concerned about combined climate change effects, including extended drought, erratic precipitation patterns, increased average temperatures and extended warm weather seasons, and reduced air quality. The creation of Santa Monica Mountains National Recreation Area was in large part to provide a natural area to surrounding communities but primarily to serve as an airshed to improve air quality. The greatest concern to experts interviewed for this area was an increase in wildfire frequency and severity. Like the work reported in Keeley and Syphard (2020), they noted that most fire ignitions in the Western United States are human caused, yet their fire patterns and severity intersect with climate change effects. Low live fuel moisture and Santa Ana

winds are additional contributors to wildfire risk in the Santa Monica Mountains National Recreation Area (Federico et al. 2012, Molinari et al. 2016).

Niche Recreation Area: Paramount Ranch

Climate change has affected the Santa Monica Mountains National Recreation Area and recreation opportunities. Closures have occurred across multiple National Park Service units, lasting for a few weeks to several months because of large precipitation events, high-heat days, and high fire danger (including high winds). Wildfire has damaged some recreation facilities. In 2018, a wildfire led to the loss and subsequent closure of Paramount Ranch's Western Town, which was previously used for filming and special events, such as weddings (fig. 5.21: area 1, box 5.7). Multiple hikes extend out of this location, and portions of the area are now open for day use and mountain biking.

Niche Recreation Area: Arroyo Sequit

Multiple factors have altered vegetation that in some cases has made trails and developed sites less pleasant to visit. The Woolsey Fire (2018) burned the tops of some trees, such as California sycamores (*Platanus racemosa* Nutt.), altering canopy structure and reducing shade. These conditions create more sun exposure and higher temperatures for recreationists (fig. 5.22).

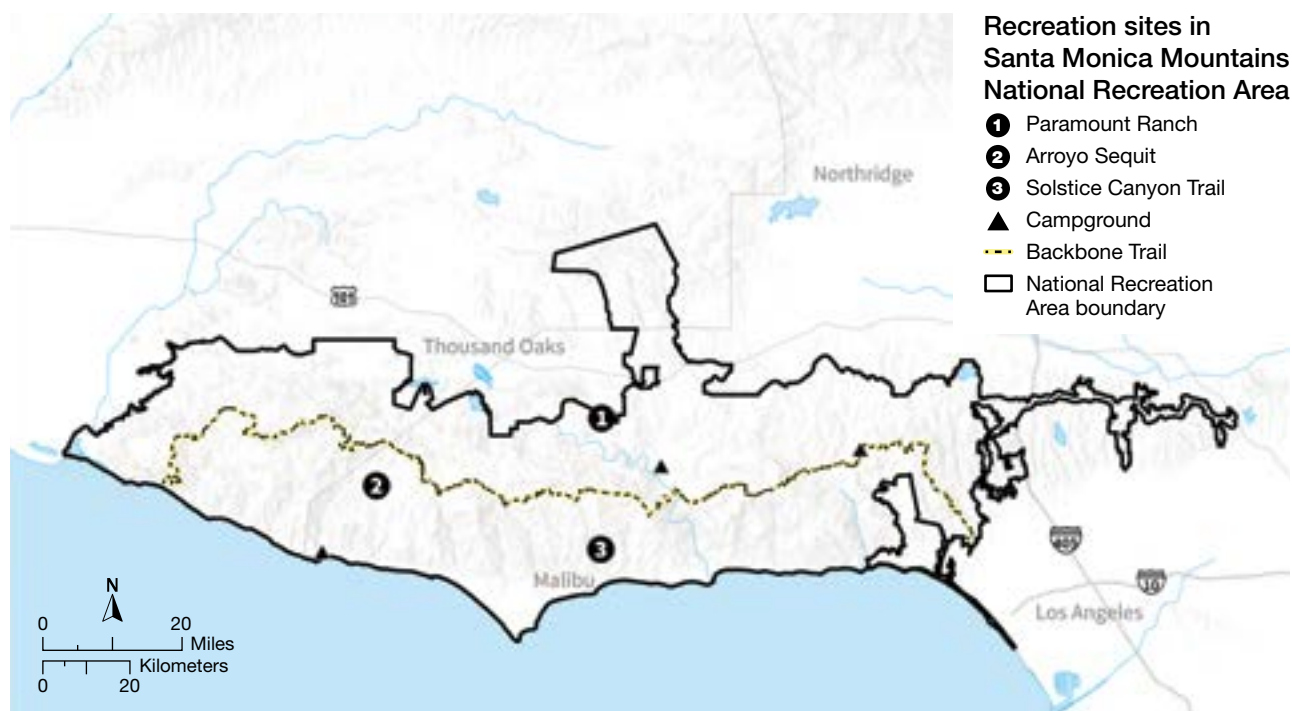


Figure 5.21—Niche recreation map of the National Park Service unit within Santa Monica Mountains National Recreation Area. Map by Micha Solomon, USDA Forest Service, Pacific Southwest Region.

Box 5.7**Western Town at Paramount Ranch
Damaged in 2018 Woolsey Fire**

The 2018 Woolsey Fire damaged much of Western Town within the Paramount Ranch (Santa Monica Mountains National Recreation Area). A historic site that highlights filmmaking and is used for films and television production, the National Park Service purchased Paramount Ranch in 1980 (USDI NPS 2023). Filming at the ranch began with the 1927 release of *Two Flaming Youths* with W.C. Fields and ended with the 2019 release of *The*

Outsider (USDI NPS 2023). Beginning in the 1950s, many television shows were filmed here, including an episode of *Gunsmoke* and more recently, episodes from season 9 of *The Great Food Truck Race* (USDI NPS 2023). An episode of Huell Howser's series, *California's Golden Parks*, features the Paramount Ranch.

Plans for restoration are in progress, making this a unique location in the National Park System set aside for film production. Trails extend out from the location with hikes named after various film projects.

The National Park Service closed the Arroyo Sequit area after the Woolsey Fire (USDI NPS, n.d.) (fig. 5.21: area 2). Day uses in this area include hiking, mountain biking, horseback riding, dog walking, picnicking, and bird watching. Hikers move along a loop trail to enjoy an intermittent stream and meadows. It is a premier site for viewing wildflowers. Although this small area is easily accessible from the highway, postfire recovery and infrastructure loss (the ranger residence) continue to affect this niche opportunity.

Niche Recreation Area: Solstice Canyon

Solstice Canyon (fig. 5.21: area 3) is open to day use, including hiking, picnicking, mountain biking, dog walking, and wildlife viewing. This niche recreation area offers hikes at varied levels of difficulty through primarily coastal sage scrub and riparian plant communities (fig. 5.23). Visitors might see the Keller House, a stone cabin that was severely damaged in 2007, and the ruins of the Roberts Ranch. Hikers can travel through the shaded canyon to the perennial Solstice Canyon waterfall. A portion of the trail leads to ocean views. Because the location is popular, parking is in high demand and often full before mid-day on weekends. Increasing interest in shaded nature areas, especially those leading to waterfalls and ocean views, may affect this niche opportunity under climate change.



Figure 5.22—Wildfires burn canopy cover, for example this tree in the Santa Monica Mountains, reducing shade and increasing sun exposure and heat risks to outdoor recreationists. Photo by Tony Valois, USDI National Park Service, Santa Monica Mountains National Recreation Area.



Figure 5.23—Native plant communities along the trails of the Santa Monica Mountains. Photo by Tony Valois, USDI National Park Service, Santa Monica Mountains National Recreation Area.

Not all climate change effects are negative. When wildfires are followed by rainfall, unusual and beautiful wildflower displays often emerge, increasing the scenic beauty and attracting recreationists (fig. 5.24). When followed by dry periods, however, wildfires and then extreme drought have led to further dieback of native species. Postfire recovery may slow under climate change given these conditions (Federico et al. 2012).

Recreation groups vary in their response to these conditions. For example, mountain bikers, a common

visitor group to the area, enjoy exercise and thrills. Key contacts interviewed from the National Park Service suggested that mountain bikers will be less concerned about climate change effects, so long as trails are maintained and accessible.

Key contacts from the National Park Service said that they viewed surrounding residential communities as having a considerable role in the future resilience of the Santa Monica Mountains National Recreation Area by maintaining vegetation on their properties and



Figure 5.24—Postfire wildfire blooms in the Santa Monica Mountains. Photos by Mark Mendelsohn, USDI National Park Service, Santa Monica Mountains National Recreation Area.

supporting National Park Service actions to minimize adverse climate change effects. The urban populations near national park boundaries influence management options for vegetation and risk. Park boundaries abutting urban development will be a continuing challenge because of climate change effects (Hall et al. 2018).

Following the Woolsey Fire (2018), National Park Service resource managers developed several initiatives focused on revegetation, planting, and wildlife populations, especially mountain lions (*Puma concolor*). The Woolsey Fire affected the mountain lion population, but most were able to relocate and thrive despite modification of their habitat. There has been greater investment in the development of wildlife crossings (e.g., the Wallis Annenberg Wildlife Crossing at Liberty Canyon) (Pittman 2021) than projects involving clearing of vegetation, so efforts vary based on primary values targeted for conservation. It would be unusual for recreationists to encounter a mountain lion during day use, but climate

change and shifts in vegetation and prey may increase the likelihood of encounters. Visitor education on mountain lions in the Santa Monica Mountains National Recreation Area aims to mitigate negative wildlife encounters and enhance visitor safety.

San Bernardino National Forest

San Bernardino National Forest has 153,931 acres of designated wilderness area, 620 miles of trails, 15 developed picnic areas, and 24 developed campgrounds (USDA FS 2020d) (fig. 5.25). Natural features include 266 lakes and ponds, 778 miles of rivers and streams, and 30 miles of wild and scenic rivers. The forest spans Riverside and San Bernardino Counties. These two counties account for the top U.S. based visitor origins reported. More than one-fourth (29.0 percent) of visitors traveled more than 100 miles to visit San Bernardino National Forest (USDA FS NVUM 2021e). Annual recreation visitation has been estimated at more than \$157 million in value to recreationists (USDA FS 2020d).

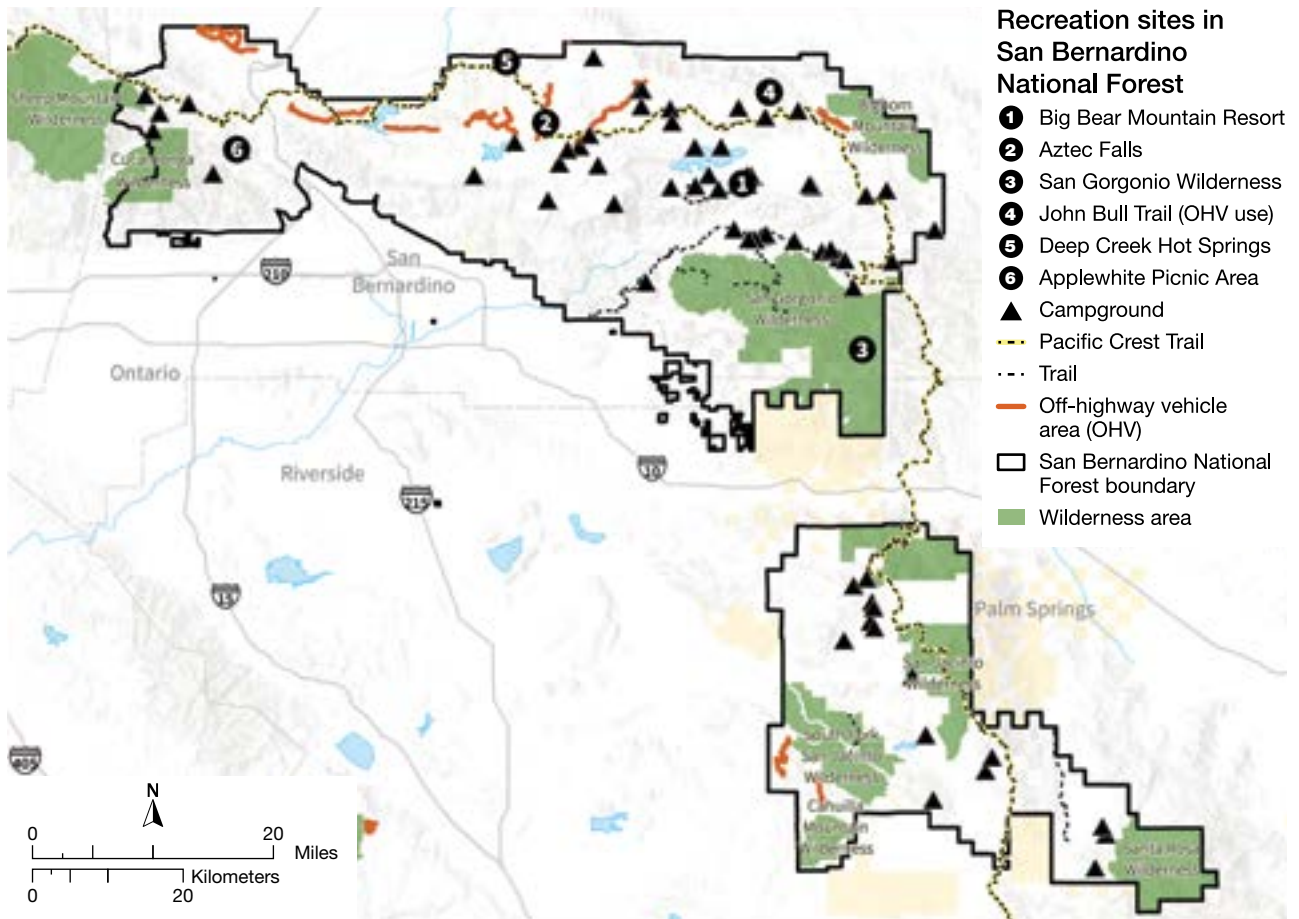


Figure 5.25—Niche recreation map of the San Bernardino National Forest. Map by Micha Solomon, USDA Forest Service, Pacific Southwest Region.

Niche Recreation Area: Big Bear Mountain Resort

Downhill skiing is a key component of the diverse winter outdoor recreation activities available in San Bernardino National Forest. Winter-season recreation is higher there than in the other management units in the SOCAAP assessment area, with most visits in higher elevation conifer forests (Garnache et al. 2018). Big Bear Mountain Resort (fig. 5.25: area 1) includes two downhill ski areas with chair lifts, Bear Mountain and Snow Summit. The resort offers additional winter snow sports including snowboarding, cross-country skiing, and snowshoeing.

An analysis of snowpack and precipitation projected a median decline in snowpack of 70 percent for the Bear Mountain and Snow Summit ski areas by the 2070s because of projected temperature increase and precipitation decline (Blickenstaff et al. 2013) (chapter 3). Blickenstaff et al. (2013) noted considerable variation in different model projections, but the analysis implies that it would likely be beneficial to consider the effects of shifting snowfall patterns on winter outdoor recreation. Although snowmaking capabilities can likely sustain some winter sports, reduced snow may affect uses outside of developed runs (Sawyer et al. 2014). For example, cross-country skiing opportunities as well as developed snowplay areas for tubing and sledding will likely be affected.

A key contact that we interviewed for San Bernardino National Forest offered additional insights on snow-based opportunities and climate change effects on outdoor recreation. Seasons of unusually heavy snowfall because of erratic patterns, such as Thanksgiving of 2019, challenged residents and visitors alike with its effects on accessible roads, maintenance of power resources, lost cell service, and downed trees. Opportunities that were still open and accessible saw increased traffic and crowding. He noted that cross-country skiing outfits are struggling with shortened seasons and decreased snowfall, such that some have remained shuttered across multiple years. Although snowmaking helps some resorts during low-snow years, recreationists may need to travel farther to enjoy similar opportunities. He also noted that some resorts have adapted by providing warm-season opportunities, such as mountain biking. For example, Summit Bike Park offers an extensive system of trails, natural and built, and riders can take the chairlift up the mountain.

Niche Recreation Area: Aztec Falls

Following snowmelt, a Santa Ana wind event blew over many trees, leading to the closure of multiple locations, including Heaps Peak Arboretum, Switzer Park Picnic Area, and Baylis Picnic Area; the latter remains closed at the time of writing this report. Closures of popular recreation locations have also occurred because of crowding in recent years; this includes the 2.5-mile stretch of Deep Creek in the Lake Arrowhead area and Aztec Falls (fig. 5.25: area 2). The San Bernardino National Forest implemented this closure in May 2020, which was still in effect at the time of writing this report (box 5.8). Our key contact from the San Bernardino National Forest cited this niche opportunity as an example of a high-use location that requires innovative management approaches. Issues of concern include parking, environmental effects, visitor safety, and effects on the adjacent community.

Users of stream systems can encounter dangerous conditions during high-precipitation events in San Bernardino National Forest. An up-channel thunderstorm miles away can result in unexpected flash flooding in an otherwise sunny area, and evacuation may not occur in time. Loss of life has occurred on the forest during flash-flooding events. An increase in erratic storm patterns and heavy rain can elevate the dangers involved. Increasing the public's awareness of emergency responses may help increase climate resilience (WRCOG 2019).

Many threatened and endangered species in San Bernardino National Forest depend on riparian habitat. As surface-water levels continue to decline, protecting habitat for listed species, including riparian vegetation, will further increase the challenges around providing for high-quality recreation experiences and species protection (chapter 3). At the same time, higher temperatures and more high-heat days will result in more individuals coming to the forest and to riparian zones to seek respite. Climate change is likely to further complicate meeting the multiple-use mandate on the forest.

Niche Recreation Area: San Gorgonio Wilderness

Year-round high demand for outdoor recreation in designated wilderness led to the San Gorgonio Wilderness becoming one of the first such units to mandate a year-round visitor-use permit for day and overnight uses (fig 5.25: area 3). Although sections of this wilderness that the Bureau of Land Management manages, along with a section of the Pacific Crest Trail, do not require

Box 5.8**Overcrowding Causes Deep Creek and Aztec Falls to Remain Closed**

Deep Creek and Aztec Falls in San Bernardino National Forest have garnered significant outdoor recreation attention. When open, visitors would often come to this location to hike, play in the water, and dive from the cliffs (Weber, n.d.) On warm days, the site was extremely popular. The trail from the small parking area crossed the Pacific Crest Trail for about 1 mile. A hike on a steep trail down to the water was necessary to view the falls. Recreationists would jump from the surrounding cliff ledges into the creek below.

This location was one of southern California's most popular swimming holes. Before its closure in May 2020,

visitors posted firsthand accounts online about crowding, difficulty finding parking, and trash along the trail and at the creek (Marsh 2025). Visitor safety and emergency response were key factors in the closure. In recent years preceding 2020, there had been multiple incidents requiring emergency response (e.g., The Sun 2016, Wesson 2017). Although the closure is supposed to be temporary, managers continue to explore effective approaches to managing this high-demand location to ensure quality recreation experiences, visitor safety, and ecological sustainability. As climate change causes average temperatures to increase at lower elevations, locations with similar opportunities may face similar challenges.

permits, most of the area that the Forest Service manages has this requirement. San Gorgonio Wilderness includes San Gorgonio Mountain, the highest peak in California (11,499 feet) south of the Sierra Nevada.

San Gorgonio Peak can be the destination endpoint for hikers on Vivian Creek Trail, a 19-mile roundtrip journey from the Forest Falls community. The trail is challenging, and hikers may underestimate the snow depth encountered, even in spring. The 81 miles of trails in San Gorgonio Wilderness include a section of the Pacific Crest Trail and several other trails, including those which have been the focus of outdoor recreation studies that examine the use of urban-proximate wilderness (Winter 2013).

The San Gorgonio Wilderness Association provides the Forest Service with volunteers year round to help manage the permit system and provide visitor information to improve visitor awareness of rules and safety-related issues.

As the effects of climate change elevate issues, such as water availability in the backcountry, information provided by volunteers and managers can help to improve visitor awareness, safety, and enjoyment (chapter 3). Overall, climate change threatens San Gorgonio Wilderness use because of too many stems per acre (individual trees or woody plants), the effects of insects, less money for fuels

treatments, and fewer tools to fight fires, according to a key contact interviewed for San Bernardino National Forest.

Niche Recreation Area: John Bull Trail

San Bernardino National Forest offers an extensive, designated OHV trail-riding network for four-wheel-drive vehicles, such as all-terrain and utility task vehicles, as well as motorcycles. In keeping with agency regulations, a motor-vehicle use map displays designated routes. The forest does not have open-use areas but has more than 900 miles of sports utility vehicle routes and 226 miles of off-road routes for advanced and beginner riders. An example is the John Bull Trail (fig. 5.25: area 4), one of the most challenging 4×4 roads on San Bernardino National Forest. Trail users report many large rocks, advise against driving it solo, and have offered comparisons to the Rubicon Trail in the Sierra Nevada AllTrails, LLC 2010–2025.

OHV use accounts for 6.8 percent of outdoor recreation participation on San Bernardino National Forest (USDA FS NVUM 2021e). According to a key contact, an uptick in OHV sales during the COVID-19 pandemic and increased use on the forest created concerns for some long-term users (Hickey 2020). Environmental effects contributed to perceptions that loss of use would result.

Increased recreation demand associated with increased population projections for the region could add to ecological and social effects, although a large volunteer network strives to maintain experience quality. In the case of closures, limited opportunities may place more pressure on areas that remain open.

Niche Recreation Area: Palms to Pines and Rim of the World Scenic Byways

Driving for pleasure accounts for about one-third (30.5 percent) of recreation participation on San Bernardino National Forest. Visitors may choose to travel the Palms to Pines Scenic Byway from Palm Desert to Banning Pass, while enjoying the Lower Sonoran region ecosystems. They might also travel the Rim of the World Scenic Byway, a 110-mile route traversing the San Bernardino Mountains from Cajon Pass to San Geronio Pass. The Rim of the World Scenic Byway passes Big Bear Lake and Lake Arrowhead along the route. Although it's open year round, heavy snowfall may preclude access, and fog sometimes makes the drive challenging.

In December 2021, a washout of California State Highway 18 after heavy rains caused a closure and emergency repairs. The closure affected residents of nearby mountain communities as well as holiday season recreationists. The route is a major thoroughway to ski resorts in San Bernardino National Forest, and traffic was diverted to other routes for mountain access by residents and visitors. The full road closure began on December 23 and ended when repairs were completed on January 20, 2022. With a pattern of erratic storm events, highway closures require advance planning, timely communications, adequate resources to make repairs, and flexibility in recreation plans for visitors heading to the mountains. Redundant transportation routes are increasingly needed to mitigate the effects of closures of critical routes (WRCOG 2019). Such measures allow continued access, maintain normal function within communities, and improve visitor safety.

Niche Recreation Area: Deep Creek Hot Springs

Deep Creek Hot Springs (fig. 5.25: area 5) provides a niche opportunity on the San Bernardino National Forest that outdoor recreationists use heavily. This area has several thermal pools and connects to the Deep Creek drainage. The deep thermal pools, wildlife, diverse vegetation, and connection to the Pacific Crest Trail provide for a unique recreation experience. Crossing the stream

to reach the location from one access route can be cold, and the steep, rocky terrain on the hike out can be difficult; some recreationists have needed to be rescued.

Organic pollution and high levels of human use in the Deep Creek drainage have caused high bacterial levels and contamination risk from *Naegleria fowleri*, a thermophilic, free-living amoeba that can cause primary amoebic meningoencephalitis (Harden et al. 2003), a rare but almost always fatal infection. Recreationists are advised to avoid submerging their heads in the pools to prevent bacteria from entering the nasal cavity. Factors affecting the proliferation of the amoeba are high ambient temperatures, high water temperatures, and low precipitation (Harden et al. 2003). Elevated temperatures projected under climate change paired with extended periods of drought may increase the risk to recreationists in this location (Gompf and Garcia 2019). Maciver et al. (2020) and Gompf and Garcia (2019) reported a likely increase in *N. fowleri* associated with climate change. Elevated temperatures are already a risk resulting in warnings to visitors to bring ample drinking water and make other preparations for the sometimes higher than 100 °F ambient temperatures at the location. The projected increase in average temperatures may require additional adaptation measures to maintain a quality recreation experience for this location.

Niche Recreation Area: Applewhite Picnic Area and Campground, Lytle Creek

Another water-based area in San Bernardino National Forest noted for its high recreational use is Applewhite Picnic Area, Lytle Creek (fig. 5.25: area 6). The location is a large picnic area that can accommodate 184 vehicles in the developed site, which requires an additional fee for day use (fig. 5.26). Nearby are the Applewhite Campground (fig. 5.27), Lytle Creek dispersed use recreation area (fig. 5.28), and the Lytle Creek Firing Line Shooting Range. The picnic area has been the focus of social science research to inform a re-development plan as well as subsequent modifications to the area (Chavez 2002, Chavez et al. 1995). Initial concerns were recreation-use effects to the creek, surrounding private properties, and adjacent community, as well as meeting needs of the ethnically diverse visiting public that was mostly Hispanic.

The Climate Change Resource Center (2021) recently examined recreation improvements to address recreation at Lytle Creek in response to anticipated climate change effects. Higher average temperature and more high-heat



Figure 5.26—Applewhite Picnic Area, Lytle Creek. Some sites accommodate a larger group with multiple tables and trash bins while others are designed for smaller groups. Photos by Jacob Winter.



Figure 5.27—Applewhite Campground, Lytle Creek. Photo by Patricia L. Winter.

days are expected to increase outdoor recreation demand along Lytle Creek, which is already a heavily affected dispersed use recreation area (chapter 2). Resource managers have also expressed concern about drought and streamflow changes, extreme precipitation events, wildfire activity, and the effects they could have on the ecosystem and visitor safety (Climate Change Resource Center 2021). Community safety is a concern because

timely evacuation of residents in the canyon near the creek may be needed during emergencies, such as heavy rainfall, flooding and sediment movement, and wildfires. Managers used the *Climate Change Adaptation Workbook* (Swanston et al. 2016) to inform project planning in Lytle Creek. Goals included strategies to divert recreation use away from high-risk areas, relocate infrastructure and opportunities away from areas at high-risk

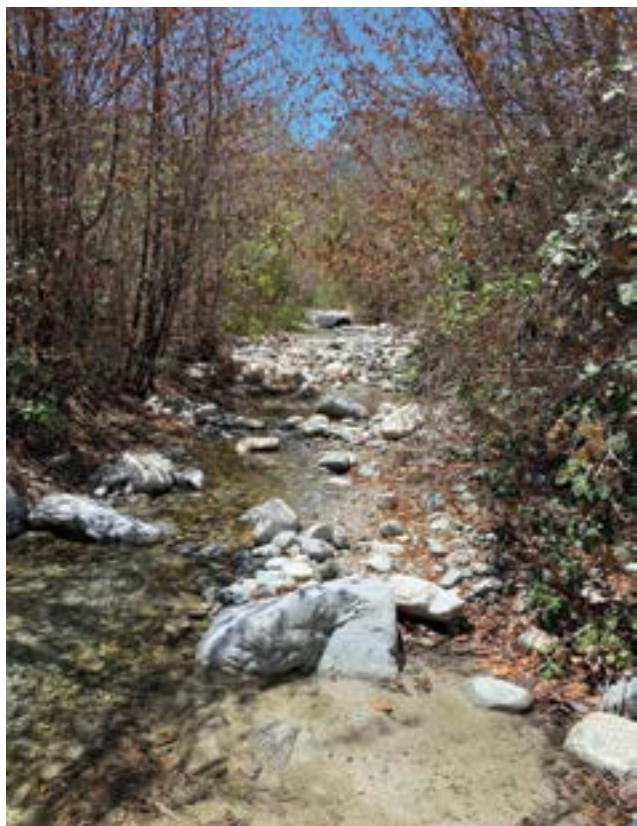


Figure 5.28—Lytle Creek dispersed use recreation area. The creek splits off into branches or watercourses depending on the season and volume of water flowing. Recreationists may hike across unshaded branches of Lytle Creek to get to the shaded section beyond. Photos by Patricia L. Winter.



from climate-induced damage, and improve public awareness around climate change and associated risks. The public awareness strategy included improved telecommunications access in the canyon to support emergency communications. Erecting shade structures over picnic areas away from the creek and diverting water into dry channels to distribute recreation use were listed as adaptation tactics.

Elements of the Lytle Creek adaptation strategy are similar to those considered for the 1995 development at Applewhite—specifically, shifting picnicking to grassy shaded areas away from the creek, development of creekettes, or small gravity-fed creek extensions (Chavez et al. 1995), and development of an interpretive trail at the ranger station. Another element proposed for Lytle Creek is a shuttle or transportation system to reduce parking demand and its effects in the canyon (fig. 5.29). Transportation system designs consider multiple factors, including effects on resources as well as social and economic effects (Spernbauer et al. 2022). Ongoing

adaptive management has characterized this popular recreation setting, where attention to effects on climate are essential to the provision of quality outdoor recreation experiences, while sustainably managing the forest.

Cleveland National Forest

Cleveland National Forest spans 460,000 acres, with 77,960 acres of wilderness area, 336 miles of trails, 6 developed picnic areas, and 15 developed campgrounds (USDA FS 2020b) (fig. 5.30). Natural features include 406 lakes and ponds, and 561 miles of rivers and streams. The forest spans sections of Orange, Riverside, and San Diego Counties, with the latter two counties accounting for the top U.S. based visitor origins reported in the NVUM survey (USDA FS NVUM 2021c). Only 8.3 percent of visitors traveled more than 100 miles to visit Cleveland National Forest (USDA FS NVUM 2021c). Annual recreation visitation is estimated at more than \$53 million in value to recreationists (USDA FS 2020b). Most recorded visits are to chaparral ecosystems during the spring



Figure 5.29—A parking area at Lytle Creek dispersed use recreation area. Photo by Patricia L. Winter.

months, although some visitation occurs year round (Garnache et al. 2018).

Niche Recreation Area: Santiago Peak

Trabuco Canyon, one of the earliest and smallest forest reserves in southern California, was established in 1893 and later became a portion of Cleveland National Forest. The Trabuco Ranger District spans Orange and Riverside Counties and contains the highest peak in Orange County, Santiago Peak (fig. 5.30: area 1). Getting to the trailhead requires travel along a dirt road (more suited for four-wheel-drive or OHV use). The peak is accessed from the Holy Jim Trail. The area offers challenging hiking with a steep ascent through the Santa Ana Mountains. Hikers need to bring water and appropriate clothing, and cooler seasons are the best time to hike the area as it can become quite warm outside the tree canopy cover. On a clear day, hikers are rewarded with views of the ocean and vistas overlooking cities below. Mortality of large, mature oak trees caused by the goldspotted oak borer (*Agrilus coxalis*) and exacerbated by drought will make shade less abundant and sites less hospitable according to key contacts from Cleveland National Forest.

Niche Recreation Area: Holy Jim Falls

Visitors can hike directly to Holy Jim Falls, a relatively

easy 3-mile journey from the parking lot (fig 5.30: area 2). A longer journey follows the historical trail markers found along the trail, winding through the canyon and along the creek. In the spring, the California Department of Fish and Wildlife stocks Trabuco Creek for fishing with rainbow trout. The full course of the creek is part of a restoration effort to remove barriers along the creek and eventually reintroduce native trout. At the time of writing this report, the area above the falls was closed to recreation to allow for restoration and safety-related improvements. Low rainfall and extended drought may result in a dry creek and falls, or low water flow (chapter 3). The area burned in the Holy Fire (2018) and is still recovering.

Trabuco Canyon Road is unpaved and popular for OHV use. The Trabuco Creek Picnic Site is nearby. Access to the fishing area is along the same road favored for OHV use, so a four-wheel-drive or high-clearance vehicle is needed. According to history of the area, the last wild grizzly bear (*Ursus arctos*) in Orange County was shot and killed in Holy Jim Canyon in 1908.

Niche Recreation Area: Observatory Trail

The Palomar Ranger District is home to camping (e.g., Observatory Campground) and hiking (e.g., Observatory Trail [a designated national recreation trail]) (fig. 5.30: area 3, fig. 5.31). Developed camping accounts for 7.5 percent of outdoor recreation visits in Cleveland

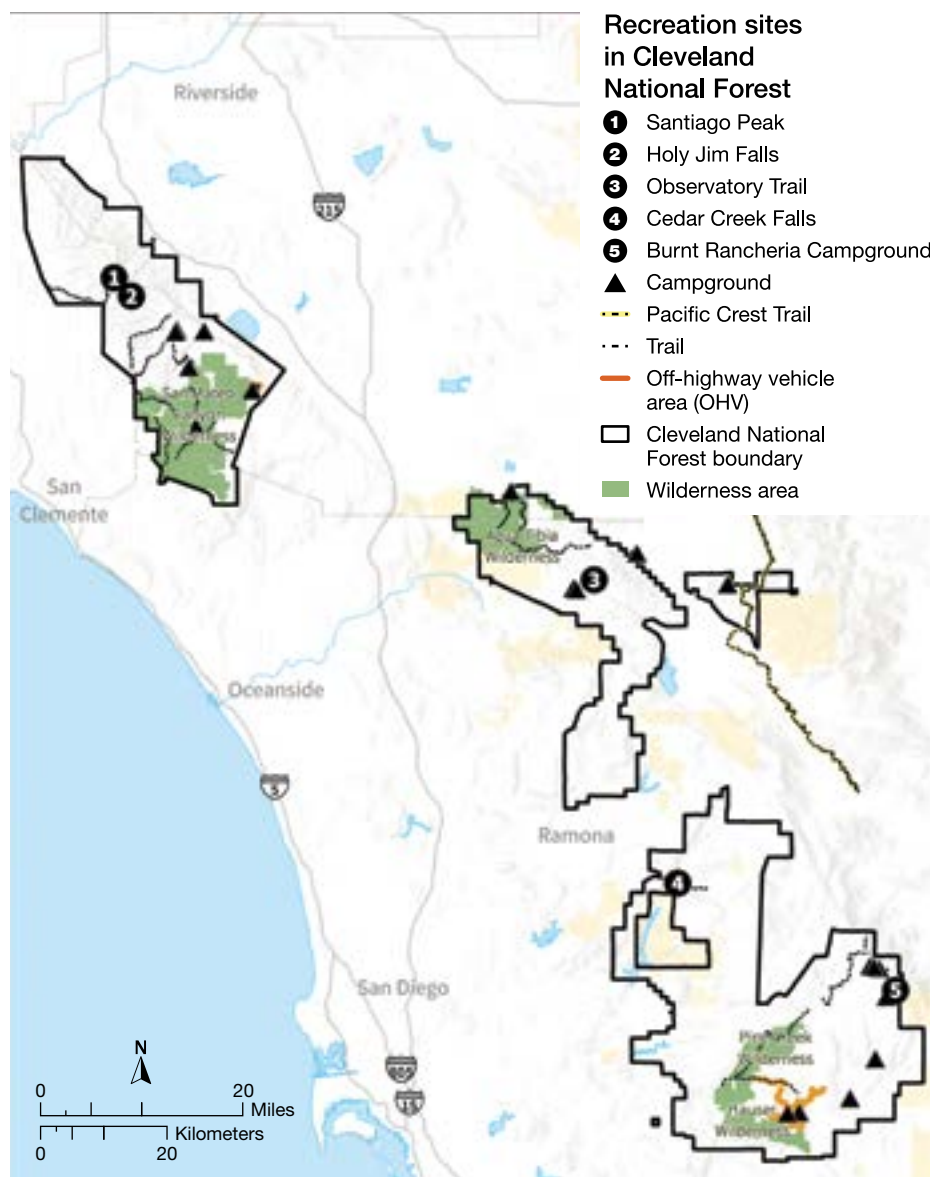


Figure 5.30—Recreation niche map of the Cleveland National Forest. Map by Micha Solomon, USDA Forest Service, Pacific Southwest Region.

National Forest (USDA FS NVUM 2021c). Observatory Campground remains a popular location for stargazing, and bright lights are restricted after 9 p.m. in some campground sections to facilitate better viewing. Observatory Trail is unique in its canopy cover and surrounding trees of pine, fir, and cedar along the 4.4-mile route (fig. 5.32). Hikers can travel between Observatory Campground and Palomar Observatory (operated by California Institute of Technology). Natural features, such as the Laguna Mountains skipper butterfly (*Pyrgus ruralis lagunae*) and lichen growth offer additional scenic beauty and opportunities for nature study. Native wildflowers are seasonally abundant along the trail and highways leading into the area (fig. 5.33). Climate change and extended drought may cause the decline of some sensitive plant species over time.

Visitors to Observatory Trail are reminded to watch for mountain lions, rattlesnakes (*Crotalus* spp.) and poison oak. Poison oak is common throughout California and causes an allergic response in most exposed individuals. Recreationists, outdoor workers, and firefighters face risk from exposure (CDC NIOSH, n.d.) although fast action can mitigate the rash and itching caused by exposure. Some research suggests that higher concentrations of ambient carbon dioxide can promote the growth of poison oak and the toxicity of urushiol (its irritant oil) (Mohan et al. 2006). Its function as habitat for pollinators and other wildlife, its native abundance, and some application in postburn recovery plantings make this an important plant that may warrant increased precautions among recreationists (California Native Plant Society, n.d.).



Figure 5.31—Observatory Trail in Cleveland National Forest is a designated national recreation trail. Photo by Patricia L. Winter.

hike to Cedar Creek Falls is moderately challenging and best undertaken in the fall or spring. Hiking the 6.6-mile trail requires the online purchase of a permit for a modest fee from the website Recreation.gov (USA 2025). The trail and site offer a beautiful backcountry experience on the Palomar Ranger District for well-prepared visitors. Hiking accounts for 73.3 percent of outdoor recreation in Cleveland National Forest (USDA FS NVUM 2021c).

Water flow is severely reduced because of recent drought and scarce water flow over the 80-foot drop in the summer months; as water flow decreases, the water at the bottom of the falls fills with algae. The challenge of the hike and heat-related risks prompted forest officials to post an infographic to improve visitor preparation and awareness (fig. 5.34). High-heat days ($\geq 95^{\circ}\text{F}$) now involve closures to this trail and the general location (box 5.9). Multiple incidents of heat-related emergencies and evacuations have occurred in the recent past. For example, in July 2019, a family of five suffering from heat exhaustion on a 90-degree day were air lifted from the area. As average temperatures increase along with the number of high-heat days, it is likely that additional closure days will occur in the future (see chapter 2).

Niche Recreation Area: Cedar Creek Falls

Water-based activities represent a small proportion of the overall recreation use in Cleveland National Forest (Garnache et al. 2018). Nevertheless, there are popular areas on the forest that surround water, such as Cedar Creek Falls (fig. 5.30: area 4) and Three Sisters Falls. The



Figure 5.32—The shaded Observatory Trail is home to large pine, fir, and cedar. Photos by Patricia L. Winter.



Figure 5.33—Wildflowers along the Observatory Trail and roads leading to the trail and Observatory Campground are seasonally abundant, including the widethroat yellow monkeyflower (*Mimulus brevipes* Benth.) and Scarlet bugler (*Penstemon centranthifolius* Benth.). Photos by Patricia L. Winter.



Figure 5.34—Infographic for Cedar Creek Falls, Cleveland National Forest, to improve visitor safety. Credit: USDA Forest Service, Cleveland National Forest.

Niche Recreation Area: Burnt Rancheria Campground

Burnt Rancheria Campground (fig. 5.30: area 5) is a popular campground in the Descanso Ranger District, within the Laguna Mountain Recreation Area. The Descanso Ranger District is the southernmost region of the SOCAAP assessment area, only 5 miles from the U.S.-Mexico border. The campground is typically open from spring to early November, depending on the weather, and contains multiple developed sites, each with a table and campfire ring. The campground has restrooms and a coin-operated shower facility. A mix of tent, trailer, and larger recreational vehicle camping are supported, with a total of 109 developed campsites. Hiking and wildlife viewing are also available, surrounded by oaks and pines. The shade is a welcome feature during the summer.

Hikers departing from the campground can connect to the Pacific Crest Trail and take a short hike to the Desert View Picnic Site. The scenic overlook provides a panoramic view of the desert, and on clear days, the Salton Sea. San Diego State University hosts stargazing programs at the campground. The Laguna Mountain Volunteer Association hosts several programs seasonally on the forest, including at Burnt Rancheria Campground. Aside from these programs, association volunteers help monitor

Box 5.9**Elevated Temperatures and Challenges for Outdoor Recreation Management**

With consistent forecasts of increasing temperatures across much of the Southern California Adaptation Partnership (SOCAAP) assessment area, current and projected effects of increased temperatures are important to highlight (Hall et al. 2018, Joe et al. 2016). Both average and maximum temperatures have increased, emerging as a common concern across management areas.

Higher than average temperatures in shoulder seasons can extend the outdoor recreation season and may create recreation opportunities that were previously unavailable in colder seasons, as has been the case at Chilao Campground in Angeles National Forest. Elevated average temperatures in the summer and other seasons may further increase demand, especially in shaded areas, areas near water bodies, and at higher elevations. Forests may serve as natural cooling stations during extended heat waves.

Forest visitors and outdoor workers supporting recreation opportunities are also at risk of health effects caused by rising temperatures, high-heat days, and extended heat waves. When paired with extended drought, higher elevation experiences are transformed (NDIS 2019). On the Pine Ridge Trail in Los Padres National Forest, wilderness hikers note the loss of perennial water sources and the need to prepare by bringing adequate drinking water for the full hike, with extra water to ensure adequate hydration on warmer days. At lower elevations, visitors typically visit water bodies to relax by the water's edge and in the water. Managers reported lower

visitation numbers and diminished experience quality because water levels have decreased. If wildfire burns away tree canopy cover, as some worry may occur in Santa Monica Mountains National Recreation Area and Angeles National Forest, there will be greater concern over the effects of increased sun and heat exposure to visitor comfort and safety.

Visitor safety and quality experiences are already challenged by elevated temperatures across the SOCAAP assessment area. In San Bernardino National Forest, visitors to Deep Creek Hot Springs are at risk from high temperatures, sometimes reaching ≥ 100 °F. High-temperature events are also a concern for Lytle Creek. The Santiago Peak Trail in Cleveland National Forest, with little canopy cover at higher elevations, is avoided for safety reasons on high-heat days. When temperature is forecasted at >90 °F, some locations are closed to outdoor recreationists (e.g., Cedar Creek Falls).

High temperatures are a significant threat to human well-being, both physical and psychological, and heat waves associated with climate change are considered the most deadly of climate-related disasters (CDC NCEH 2020, Clayton et al. 2021, Hall et al. 2018, Joe et al. 2016). Increasing temperatures represent a pervasive and growing threat, and unlike extreme events, no return to baseline is anticipated (Clayton et al. 2021: 13). In the future, increased average temperatures and more high-heat days projected under climate change (chapter 2) will likely increase the frequency and magnitude of stressful conditions for outdoor recreation and recreation management (Joe et al. 2016).

trails and serve as trail ambassadors by answering questions from visitors. Knowledgeable volunteers are a valuable resource as climate change effects continue to affect recreation settings. Volunteers can improve visitor safety by redirecting potentially lost hikers; this can decrease the risk of being away from established trails and water-access points on unusually warm days and improve information

flow under variable environmental conditions, (e.g., in anticipation of heavy precipitation). The Descanso Ranger District experiences frequent wildfires that can spread quickly through the chaparral ecosystem and rough terrain. Visitor education to decrease disturbance and reduce wildfire risk is an important climate change adaptation measure for chaparral and scrub systems (EcoAdapt 2017c).

Adapting Recreation to the Effects of Climate Change

Although several effects from climate change are anticipated, and some have already occurred to varying degrees, many options are available for adapting to climate change. In this chapter, we have explored prominent climate change effects, offering a local perspective throughout the SOCAAP assessment area. We now consider how adaptation options can reduce negative outcomes (see also chapter 7). Accounts from management units in the assessment area exemplify the approaches already recommended or applied by managers, partners, and visitors. Varying degrees of challenge and opportunities were also revealed in these place-based accounts.

A robust systems approach for incorporating socio-ecological linkages and the willingness to use diverse sources of information is needed to develop appropriate climate change responses. Additional research focused on the intersection of climate change and recreation is needed to better understand short- and long-term, and direct and indirect effects (Brice et al. 2017). Beyond the effects, an improved understanding of the effectiveness of various adaptation strategies and tactics requires study over time. For example, the influence of substitution behaviors (e.g., going elsewhere for the same or a different activity) and their degree of effectiveness in maintaining the myriad benefits of recreation, or the nudging of visitation and activities to improve climate resilience, require additional study (Miller et al. 2022). Working with other entities outside of natural resource specialties may help mitigate negative exchanges that improve resilience in one system but have costs for another (Czech et al. 2014). To prevent these negative outcomes, multisector and transdisciplinary approaches can be focused on longer time horizons and setting of adaptable approaches, as well as use of monitoring and research (Czech et al. 2014, Jardine and Long 2014, Selin et al. 2020).

Adaptation by Recreation Participants

Recreationists benefit from searching information resources to plan visits to national forests and other locations, thus elevating the value of “know before you go” messaging. This allows them to develop alternative plans in case unexpected events render an area or opportunity unavailable. Substitution of alternative locations

and activities is complex and may be less inviting to recreationists with a personal or family connection to a location or activity, an identity associated with that place or activity, or a belief that the activity and location are unique in a way that cannot be replaced elsewhere (Winter et al. 2014a).

Although recreation visitors are most likely to adapt to short-term patterns where the primary forest location is not available for a planned recreation activity and visit, longer term effects on recreation experience quality, recreation benefits, and place attachments are not well understood (chapter 6). Recreationists may go elsewhere for the same activity, although most substitution occurs within a planned 50-mile radius of home. If the desired activity is not available within that commuting distance because of large-scale effects, such as widespread reductions in snowpack, or multiforest and park area closures due to wildfire risk, then substitution would involve switching planned activities and experiences rather than finding an alternative site nearby (chapters 2 and 3).

If an activity is linked to identity, loss or threats to that activity may be more impactful (Schneider and Winter 1998). If a specific place holds significance beyond the activity or opportunities provided, such as cultural importance or attached memories with significant others (cultural identity or place meanings), shifting to other areas for a similar activity may lessen benefits in ways not well understood. Flexibility of expectations may become more important under continuing climate effects. If recreation providers can broadly message alternative opportunities offering comparable settings and activities, the effects of closures or restrictions in a specific zone will likely be lessened. Recreation providers may also be able to message alternative activities within a zone to help visitors identify options. Thus, adaptation by recreationists can be eased when facilitated by managing agencies and partners.

Recreationists are also responsible for gathering information to adequately prepare for a visit. For example, additional water may be needed when a specific water source is no longer available. They may need to shift their route to follow open trails or roads while traveling to a site and while recreating onsite. They may also alter their behavior as advised for safety reasons at Deep Creek Hot Springs (see above). To address additional

risks, recreationists can practice improved notification to a person not accompanying them on the visit, describing areas they will visit and when they plan to return (check-in and check-out with a trusted person).

Recreationists can improve safety by recreating with at least one person who can assist if an emergency arises. Alternate travel routes can be considered in advance, should the main route become inaccessible. In some cases, these alternate routes rely on managing agencies, as well as transportation management entities (chapter 4). These adaptations are best viewed in an interactive system among parties concerned with natural resource-based recreation.

The NVUM survey indicates that communities adjacent to recreation areas take advantage of nearby opportunities, with most users traveling less than 50 miles to recreate. Loss of recreation opportunities by forest-proximate residents affects community well-being through decreased activity participation and diminished personal and community benefits. Closures and limits also contribute to a loss of community character when local businesses focused on serving recreation visitors suffer from lower demand for services. The overlapping identities of forest recreationist and community member may compound effects that are complex to overcome.

Supporting equipment may increase safety and improve the recreation experience—sun protection gear, sunblock, and other materials improve response to increased sun exposure, lessened shade, and higher temperature. Smartphone applications that facilitate visitor information and planning can communicate safety information and timely updates. Although smartphone access and technologies have improved, recreationists can ensure that they have downloaded maps and even printed backups in case cellular connectivity is lost or a cellular phone battery is expended. Myriad locations on the forests have zones where cellular access is lost. This may increase the importance of recreating with at least one other person and practicing check-in and check-out as described above.

Equity considerations are important in discussions of recreation participant adaptations (Miller et al. 2022). The need to shift to areas farther away may require additional transportation resources that are not equitably available to all potential visitors. Because some underserved communities may have limited access to

information, managing agencies need to be attentive to adverse burdens on those communities. Closures that tend to affect areas frequented more often by underserved groups, or other limitations for shifting use effects on higher demand zones, will likely benefit from assessment and monitoring to ensure equitable access is provided. It may not be reasonable to expect that all groups will have appropriate equipment or access to alternate transportation routes. Considering effects on vulnerable populations and giving attention to mitigation measures that support socioecological resilience will likely be a key element of sustainable outdoor recreation management in the future.

Adaptation by Public Land Managers

The Forest Service, National Park Service, and other natural resource recreation providers will need an expanded portfolio of approaches to address uncertainty surrounding climate change effects (Aplet et al. 2010). Agencies are implementing shifts to green practices (e.g., recycling, powering down computers when not in use) (Ma et al. 2020, Winter and Burn 2010), helping to mitigate climate effects associated with recreation management and delivery. Recreation is expected to continue to increase across the SOCAAP assessment area, and adequate staffing and resources will be needed to manage for a diversity of high-quality recreation opportunities. Additional personnel can help deliver recreation opportunities, help to maintain visitor safety, and improve the protection and restoration of affected settings. Federal staffing can be augmented through increased participation of volunteers and expansion of internships, although these programs require effective management and coordination to be successful.

Climate change will likely extend the season for warm-weather activities and increase the variability of conditions for snow-dependent recreation. More extreme weather events and wildfire will likely limit the availability of recreation infrastructure and transportation systems, consolidating outdoor activities in the fewer remaining locations. These shifts in recreation patterns will likely necessitate adjustments in seasonal opening periods as well as resources and staffing (Miller et al. 2022). Flexibility in redeploying staff and resources to areas with higher demand or those that can remain open may be especially important for sustainable management.

Pivoting to keep an area open based on atypical seasonal weather may not always be possible, but more flexibility in staffing and provision of opportunities can enhance visitor experiences and access. Sites may need to increasingly offer alternate opportunities, such as mountain biking in ski areas or disc golf courses as with Angeles and San Bernardino National Forests. These types of shifts can be challenging for federal agencies, but alternate uses of an area to accommodate ecological shifts will be a useful strategy for agencies. Some shifts may prove less successful if demand for the activity wanes, although engagement of surrounding communities, local recreationists, and researchers can improve outcomes through advanced identification of alternatives with greater potential success (Miller et al. 2022, Winter et al. 2020b).

Limits on visitation through determination of carrying and social capacity may be increasingly necessary, as may be approaches that incorporate messaging around alternative areas and activities, and warnings about potential crowding and capacity issues. Visitor capacity and monitoring guides (IVUMC 2019a, 2019b) may be useful in addressing these challenges. However, it may be most effective to place such limitations thoughtfully, as loss of recreational experiences results in loss of benefits to individuals, communities, and society. Alternative transportation systems that limit the number of personal vehicles moving into and through an area reduce the number of individuals in some areas, while also reducing vehicle emissions (Spernbauer et al. 2022). Increasing access for underrepresented groups may provide an additional gain in some circumstances.

According to key contacts interviewed from the Angeles National Forest, pilot transportation programs intended to increase access to the forest recreation sites showed mixed success when evaluated. Access for underserved groups was not increased to the degree initially hoped when the pilots were designed. Further, group transportation revealed unique challenges when planning for emergency evacuations of forest recreation sites.

Strategies can be targeted to aid visitors in decision processes surrounding destinations and activities. When environmental hazards are high (e.g., when air quality or water quality are degraded), messaging can inform visitors, particularly those with sensitivities, to avoid locations or activities until hazards are diminished or

resolved. Some sites have reservation systems for access to high-demand locations. Increased reliance on such systems may characterize future management even more than it does now. It can be important to provide accessible platforms that convey information in multiple languages,¹² as well as to consider alternate forms of access for recreationists who may not have access to technology. Collaborative work with community-based partners in crafting solutions to equity challenges can be important, and clear messaging about the benefits of various management actions to ecosystems and visitors may ease acceptance. Seasonal closures can be implemented where communications and staffing cannot adequately mitigate risks or ensure visitor safety. Closures implemented in recent years have been both situational (e.g., projected high-heat days for a specific location) and broader on a geographic scale.

In some locations, redesign or site modification may be necessary to address the complex interactions of ecological conditions, climate change, visitor demand, and shifting interest in high-demand locations. Examples include adding fencing to limit access, increasing signage and onsite contacts, and redesigning areas to support recreation uses and protect natural features. Examples from the Applewhite Picnic Area, Lytle Creek dispersed use recreation area, and the adaptive management area at San Gabriel Canyon demonstrate past, current, and future shifts in site features and provision of opportunities. In the future, modifications may incorporate green designs, such as installation of solar panels or cool-surface technologies to reduce heat transfer.

Current platforms used to communicate availability of recreation opportunities, such as agency websites and smartphone applications, will likely be increasingly important tools for maintaining visitor awareness of specific seasons, closures, and limits to recreation uses. Social media platforms may be useful for a subset of interested parties seeking forest updates, although social media that visitors use and rely upon is diverse, changes rapidly, and requires investment and frequent updating to remain relevant (Ballew et al. 2015). Smartphone

¹² Conveying information in multiple written languages aids the public whose primary reading language is something other than English. Not only does this increase likelihood of understanding but it conveys elevated customer service, a sense of welcome, and serving individuals from diverse cultural and linguistic backgrounds (Roberts et al. 2009).

applications are a more recent innovation that the Forest Service uses and can be an essential tool in the agency communication portfolio if updated in a timely way.

Partnerships and volunteer programs will continue to aid federal agencies with providing and managing for diverse recreation opportunities and settings. Partnerships and volunteers have been instrumental in providing recreation and in restoring areas (e.g., the Gabrielino Trail, as described earlier) (Cardine 2018). These opportunities provide benefits to participating volunteers and partners, although considerable variation exists among national forests (Winter 2014b). Partnerships among agencies and institutions, resource management agencies, and others focused on resource sustainability will be important for supporting information needs and informing adaptive responses (CIRMOUNT Committee 2006). Onsite visitor interactions and support through partners and volunteers are already essential aspects of outdoor recreation management. Reliance on partnerships, collaboratives, and volunteers will likely increase in necessity under climate change effects.

Where recreation access is of elevated benefit to populations who are otherwise at risk, preserving high-quality opportunities and access is a cornerstone of sustainable recreation delivery (Winter et al. 2019). Collaborative monitoring of effects, identification of the most urgent needs and values to protect, and crafting of culturally competent solutions with partners and communities may be necessary to achieve sustainable recreation management (Adger et al. 2012, Winter et al. 2020b). Managing agencies and partners may need to be nimbler by transforming policies (e.g., around seasonal hiring) and increasing resources to meet the challenges of climate change (Miller et al. 2022, Selin et al. 2020). Long-term planning timeframes; interdisciplinary teams; and collaboration among agencies, recreation providers, nonprofit organizations, and communities of place and interest will likely be key elements of this approach (Miller et al. 2022).

There is likely an upper limit to the ability of social and ecological systems to adapt to climate change, beyond which system alterations become permanent (Felgenhauer 2015), likely requiring that adaptation responses be continually modified in response to climate change. As noted by one of our key contacts, current

forest conditions may be relics of a bygone era. Therefore, managing for a desired future condition may involve assessing where it has been determined the system should go, rather than where it has been. These forms of decisions apply well beyond ecological conditions to the social realm in assessing future outdoor recreation under continuing climate change.

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Chapter 6: Effects of Climate Change on Ecosystem Services in Southern California

José J. Sánchez, Matthew R. Sloggy, and Christopher Huber¹

Introduction

National forests provide various ecosystem service benefits to people. Ecosystem services are the goods and services individuals and communities receive from natural resources and amenities, including carbon sequestration, recreation opportunities (chapter 5), and water quantity and quality (chapter 3), among others. The key ecosystem services examined in this Southern California Adaptation Partnership (SOCAAP) climate change vulnerability assessment were identified through a series of semistructured interviews with staff from Angeles, Cleveland, Los Padres, and San Bernardino National Forests and Santa Monica Mountains National Recreation Area (fig. 6.1).

Although there have been other attempts to classify ecosystem services into well-defined groups, a frequently referenced organizational scheme is the United Nations' Millennium Ecosystem Assessment (MEA 2005) report, which categorized ecosystem services into four groups:

- **Cultural services** provide aesthetic, recreational, and spiritual benefits.
- **Provisioning services** provide fiber, food, timber, biodiversity, and water runoff.
- **Regulating services** provide erosion and flood control, temperature regulation, and water quality.
- **Supporting services** provide nutrient cycling, photosynthesis, and soil formation.

The SOCAAP assessment area contains large areas of chaparral ecosystems, which provide a wide range of ecosystem services. Underwood et al. (2018a) mapped five ecosystem services in southern California (fig. 6.2)—groundwater recharge, water runoff, sediment erosion retention, carbon storage, and biodiversity—but they did not include clean air, grazing lands, cultural and heritage value, and others. None of the four southern California national forests had all five ecosystem services considered in their study. Los Padres and Angeles National Forests have the highest number of ecosystem services concentrated within their boundaries, according to Underwood et al. (2018a).

Climate change is expected to affect the quantity, quality, and diversity of benefits that individuals and communities receive from public lands, with considerable variation in effects among ecosystem services and in different locations. We present a framework that conceptually links management actions and external factors (including the effects of climate change) to change in the ability of an ecosystem to provide ecosystem services (adapted from Keeler et al. 2012) (fig. 6.3). How climate change affects a given ecosystem service depends on how it responds to changes in temperature, precipitation, and the pattern of disturbances resulting from climate change.

For southern California, projected climate change effects on the ecosystem include more frequent and intense droughts, more concentrated but less frequent periods of increased minimum temperature, increased frequency and extent of wildfires, and altered distribution of chaparral vegetation (Molinari et al. 2018) (chapter 2). Wildfire patterns will continue to be a major influence on ecosystem services in the SOCAAP assessment area (chapter 2), with some locations potentially transitioning from chaparral to grassland (Syphard et al. 2018). In addition, higher minimum temperature (chapter 2) and longer drought conditions (chapter 3) are expected to affect the provision of ecosystem services that can be linked to human well-being (e.g., water quantity for irrigation or household uses).

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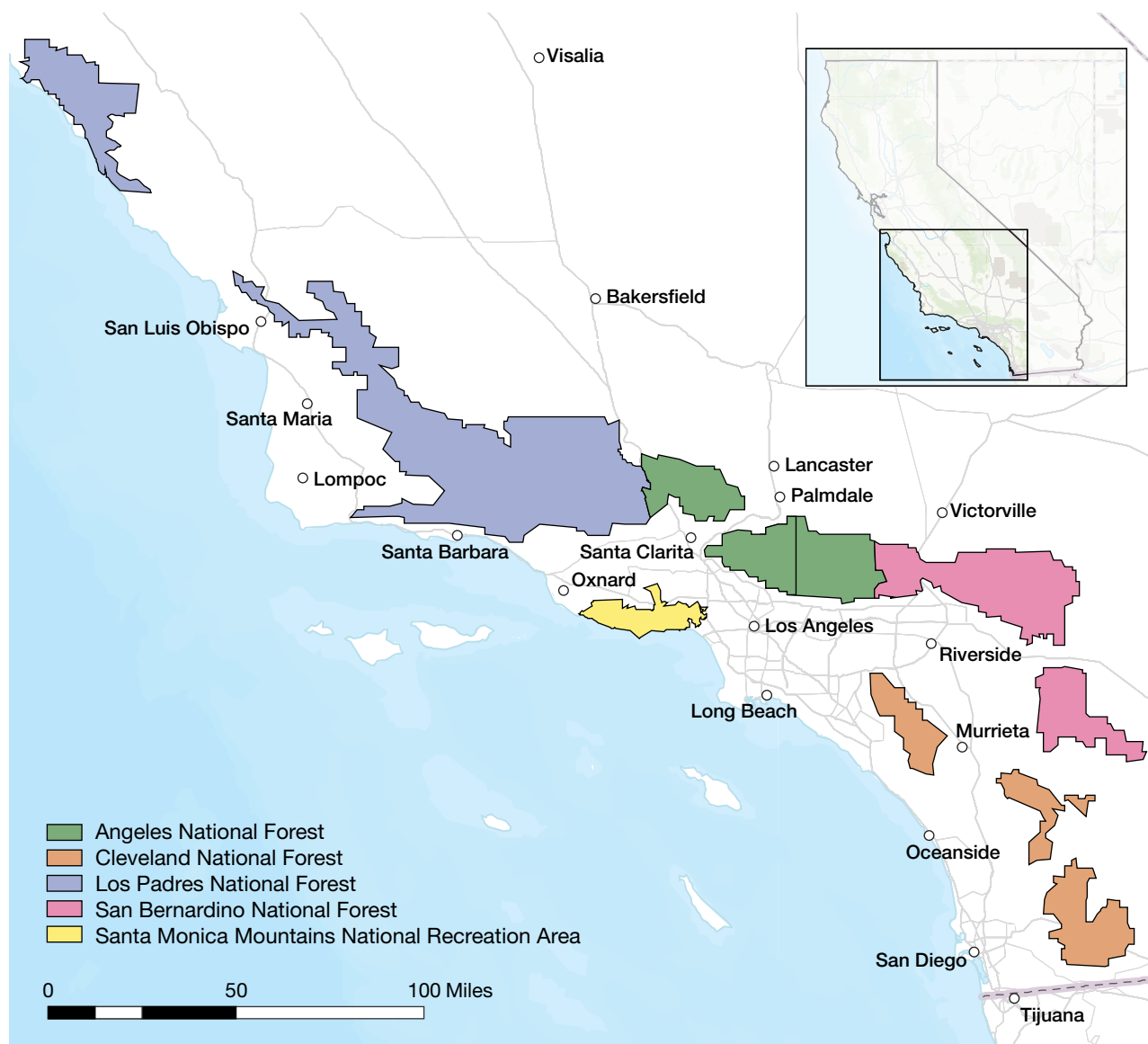


Figure 6.1—Southern California Adaptation Partnership assessment area, which includes Angeles, Cleveland, Los Padres, and San Bernardino National Forests and Santa Monica Mountains National Recreation Area.

This chapter focuses on ecosystem services from landscapes within the four national forests and Santa Monica Mountains National Recreation Area that compose the SOCAAP assessment area (fig. 6.1), with the objective of providing public land managers with the best-available science about interactions between ecosystem services and climate change. This will support current and future decision making about the design of mitigation and adaptation strategies for enhancing the sustainability of

ecosystem services in these landscapes. In this chapter, we identify general trends and strategies for adaptation, rather than specific prescriptions. Furthermore, the information provided in this chapter provides information to help fulfill the requirement of the U.S. Department of Agriculture, Forest Service's 2012 Planning Rule, which mandates that the agency address ecosystem services in planning (USDA FS 2012).

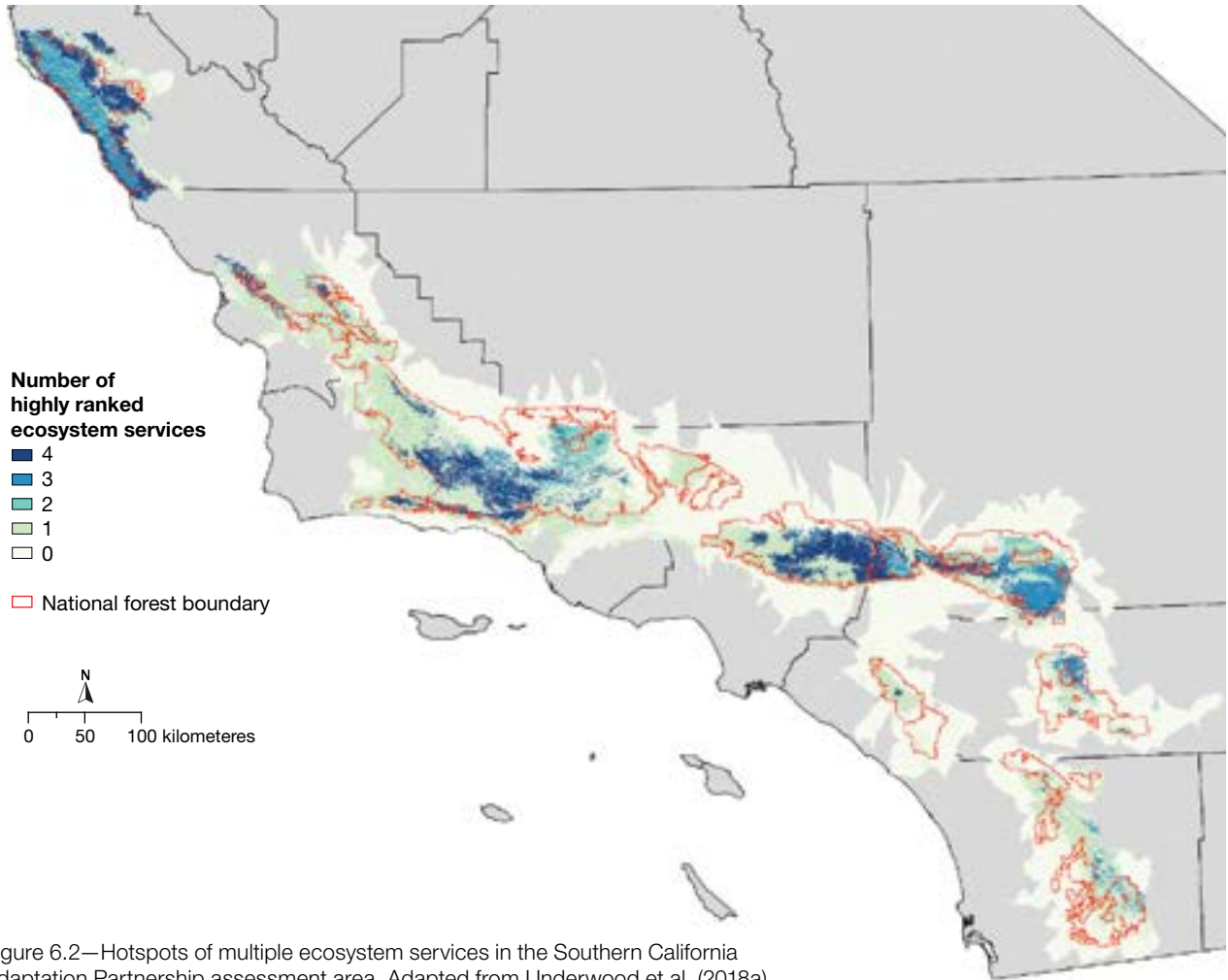


Figure 6.2—Hotspots of multiple ecosystem services in the Southern California Adaptation Partnership assessment area. Adapted from Underwood et al. (2018a).

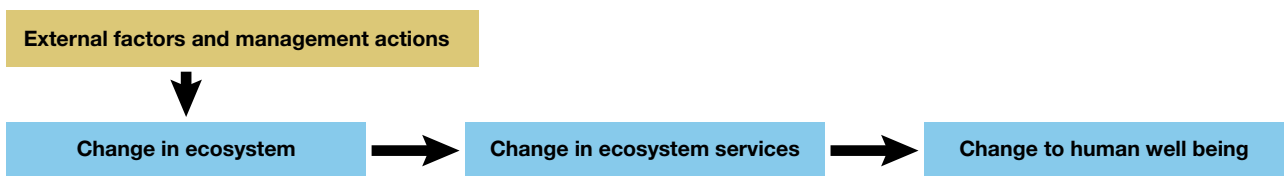


Figure 6.3—Framework for linking management actions and external factors (such as climate change) to values for ecosystems services in the Southern California Adaptation Partnership assessment area.

Ecosystem Services in the Southern California Adaptation Partnership Assessment Area

The four national forests and national recreation area experience a Mediterranean climate, which shapes the biogeography and ecosystem services of southern California. This region is dominated by chaparral vegetation, with forest and alpine systems at higher elevations. In consultation with staff from Angeles, Cleveland, Los Padres, and San Bernardino National Forests and Santa Monica Mountains National Recreation Area, we identified key ecosystem services to examine in the SOCAAP assessment area. The ecosystem services discussed in this chapter include the following:

- Carbon sequestration
- Clean air and local pollution abatement and mitigation
- Cultural, traditional, spiritual, and heritage values
- Grazing and rangelands
- Soil regulation
- Surface and ground water availability
- Water quality
- Biodiversity (including genetic diversity)

We provide an understanding of the current supply and user groups for these ecosystem services and discuss their vulnerabilities and adaptation capacities in the face of a changing climate. We do not discuss outdoor recreation, which is covered as a standalone topic in chapter 5.

Information Gaps, Monitoring, and Adaptation Strategies

There are many ecosystem services not covered in this chapter that are still important to the SOCAAP assessment area. For example, pollinator services (a supporting ecosystem service) affect agricultural production (Porto et al. 2020) and are understudied. Further research is needed to fully understand the benefits of pollinators to plant products, plant reproduction, and ecological and cultural values in the SOCAAP assessment area. In addition, pollinator populations will need to be monitored to understand climate change effects, providing a foundation for management strategies to revegetate public

lands that support pollinator conservation and health. Additional research and management activities would help satisfy strategic priorities established by the Federal Pollinator Health Task Force (USDA FS 2021).

Extraction of oil and minerals (a provisioning ecosystem service) is understudied in the SOCAAP assessment area (Campbell and Brown 2012), even though it can have large effects on other ecosystem services (Boldy et al. 2021). Mining opportunities are available within the SOCAAP assessment area, although extraction rates and locations of mines are mostly unknown. Mining operations typically require large amounts of water (Wessman et al. 2014), so an increase in mining activity will not only disturb the landscape but also consume valuable water resources (Northey et al. 2016) that may be scarcer in a warmer climate.

Uncertainty is an inherent component of climate projections based on multiple models (Lehner et al. 2020, Murphy et al. 2004), including in this assessment in which precipitation and temperature projections differ among models (chapter 2). The provision of ecosystem services, notably water resources, depends on the quantity and timing of precipitation in the region. Although the mean change in precipitation across all models is small, some models show large decreases, or increases, in the quantity of precipitation (chapter 2). Management that allows for this degree of uncertainty in climate and weather will likely facilitate a robust adaptive approach in preparation for a variety of outcomes.

Monitoring is used to track the provision of ecosystem services over time. Unfortunately, the quantity and quality of ecosystem services are typically not monitored effectively on federal lands (Lovett et al. 2007). Additional monitoring activities on federal lands are needed to inform resource management about data gaps for ecosystem services and opportunities to improve the scientific foundation (e.g., a combination of on-the-ground monitoring and remote sensing) for long-term provision of ecosystem services (e.g., Berhan et al. 2011).

The provision of ecosystem services can also facilitate additional investment in landscape management. Payments for ecosystem services occur when private partners pay for management that increases the provision of ecosystem services, such as water, carbon, or biodiversity (Alix-Garcia and Wolff 2014). These investments can increase the pace and scale of management

on federal lands (Martin et al. 2014, USDA FS 2021). In addition, these activities can reduce susceptibility to wildfire, insect outbreaks, and other climate-related factors that could pose risks to nearby communities. It is vital to estimate outcomes of management for payments for ecosystem services programs. This allows outcomes to be compared with costs to evaluate effectiveness of investments.

This chapter discusses a subset of the entire portfolio of ecosystem services that landscapes in southern California may produce. As our ability to monitor and observe ecosystems improves, future work can focus on incorporating ecosystem service values into natural capital accounts, and the range of ecosystem services monitored can be expanded. This will help to accurately assess the economic value of public land. In addition, to quantify the effects of management activities on ecosystem services, one will need to consider a more expansive

portfolio. Ecosystem services included in this chapter are summarized in table 6.1, which also includes several ecosystem services that are not addressed in this chapter, to describe the scope of our assessment.

Surface Water and Groundwater

The availability of water resources is vital for human communities in southern California, as well as for the health and stability of ecosystems (Carle 2015). A considerable amount of water is sourced from federal lands in the SOCAAP assessment area (Joyce et al. 2009), where demand for water is high because of several large metropolitan areas (Maggioni 2015). Southern California is semiarid; water availability varies in this region more than it does in most other parts of the country (Loik et al. 2004). Increasing populations are likely to compound the high demand for water resources in the assessment area (chapter 5).

Table 6.1—Ecosystem service types, categories, and functions identified in the Southern California Adaptation Partnership assessment area

Ecosystem service	Category	Ecosystem function	Addressed in this chapter
Water provision	Provisioning	Water resources for human consumption	Yes
Water filtration	Regulating	Cleaning water resources for ecological uses and human consumption	Yes
Climate regulation from carbon sequestration	Regulating	Sequestering atmospheric carbon that contributes to climate regulation	Yes
Air filtration	Regulating	Filtering harmful pollutants from air	Yes
Biodiversity and genetic diversity	Provisioning	Ecosystem resilience, potential medical applications, scientific value	Yes
Cultural services	Provisioning	Direct spiritual or cultural resources, such as plants, animals, or places providing important connections for people	Yes
Grazing land	Provisioning	Grazing rangelands for cattle production	Yes
Soil retention	Regulating	Protecting against erosion	Yes
Recreation	Provisioning	Recreational resources	No
Disturbance regulation	Regulating	Maintaining regular disturbance intervals	No
Climate regulation from other greenhouse gas exchanges (e.g., methane)	Regulating	Maintaining temperature and precipitation patterns	No
Pollination	Provisioning	Pollination services for plants and crops	No
Biological control	Regulating	Defending against invasive species	No
Food production	Provisioning	Production of edible plants and animals	No
Minerals, timber, and other materials	Provisioning	Raw materials used by humans for a variety of purposes	No
Waste treatment	Regulating	Removing waste products from air and water	No
Nutrient cycling	Regulating	Maintaining nutrient levels in the soil	No

Climate change is expected to increase the frequency of droughts (Dettinger et al. 2015) and the occurrence of extreme precipitation events (Kim 2005) (chapter 3). Precipitation may become more concentrated in fewer events, a process known as “wet season sharpening” (Swain 2021). Climate models project negligible changes in total precipitation, although the amount of the water that reaches water bodies may increase if extreme rain events saturate the soil and produce more surface water.

Consumptive uses of water resources in the SOCAAP assessment area are diverse. The largest use is municipal water consumption, although hydroelectric power and agriculture are also big consumers. Table 6.2 summarizes water use by category and source (national forest or recreation area) (see chapter 3). The data in the table are from the Forest to Faucets dataset (Mack et al. 2021), which is then mapped to a given forest using a shapefile of the national forest administrative boundaries.

The Forest to Faucets dataset reports water use by category for Hydrologic Unit Code (HUC)-12 watersheds. Domestic use refers to water used for drinking, bathing, washing, and any other uses within the household. Industrial use includes water used for fabrication, washing, and other production processes. Irrigation and livestock use refers to water used for crops and animal husbandry, respectively. Mining use refers to water used for mineral extraction, including oil. Thermoelectric

use refers to water used in steam turbines for electricity generation. Public supply refers to water obtained and then distributed by water service providers (including domestic, industrial, and other uses). Aquaculture refers to water used to farm fish, shellfish, or other aquatic life. We converted numbers in the database from thousands or billions of gallons per day to percentages to illustrate the distribution of uses from each forest.

The largest proportions of water (both groundwater and surface water) provided by Angeles, Cleveland, and San Bernardino National Forests (62.3, 49.8, and 83.6 percent, respectively) are distributed to public supply. The largest proportions of water provided by Los Padres National Forest (84.8 percent) and Santa Monica Mountains National Recreation Area (59.6 percent) are devoted to crop irrigation.

Domestic Use

Angeles and San Bernardino National Forests provide a considerable amount of water for domestic use because of their proximity to some of the largest urban areas in the country—the cities of Los Angeles (box 6.1), San Diego, and San Bernardino. In contrast, water from Los Padres National Forest is not heavily relied upon for domestic use. This national forest is distant from large population centers, and its relative closeness to the ocean means that runoff has less opportunity to seep into aquifers and other storage structures, either natural or manufactured.

Table 6.2—Combined surface water and groundwater devoted to each use category by national forest and recreation area in the Southern California Adaptation Partnership assessment area

Category	Los Padres National Forest	Angeles National Forest	San Bernardino National Forest	Cleveland National Forest	Santa Monica Mts. NRA
PERCENT					
Domestic	0.15	2.20	3.12	0.43	0.99
Industrial	0.20	6.52	7.50	0.72	3.28
Irrigation	84.84	27.21	5.73	41.78	59.59
Livestock	0.56	0.04	0.03	0.45	0.04
Mining	0.28	0.00	0.00	0.48	0.02
Thermoelectric	0.56	0.00	0.01	0.86	0.00
Aquaculture	0.30	1.68	0.00	5.50	4.30
Public supply	13.11	62.34	83.60	49.80	31.79

We converted data from thousands or billions of gallons per day to percentages. Domestic refers to water used within households; public supply refers to water obtained and distributed by water service providers (including domestic, industrial, and other uses); aquaculture refers to water used to farm fish, shellfish, or other aquatic life.

NRA = National Recreation Area.

Source: Forest to Faucets dataset (Mack et al. 2021).

Box 6.1**Water for the City of Los Angeles**

Water conservation efforts have reduced water consumption in the City of Los Angeles over the past 20 years, despite the population increasing by 1 million people (Peters 2022). However, demand for water is expected to grow to 200 million gallons per day in the future (Los Angeles Sanitation 2021).

Watersheds in Angeles National Forest, other national forests, and other forested lands provide 68.7 percent of the drinking water for the Los Angeles region (Liu et al. 2022). Climate change will likely decrease many water supplies, including the portion of Colorado River water used by the City of Los Angeles (Christensen et al. 2004). Consequently, there will be a heightened emphasis on management efforts in Angeles National Forest and other source forested areas to maintain and enhance water flow in vital watersheds supporting the city.

Industrial Use

Along with serving a large metropolitan area, federal lands in southern California provide water to a large base of industrial production (e.g., manufacturing and fabrication in Los Angeles). These resources are vital for economic productivity and industrial output of the region. Following a pattern similar to water for domestic use, a larger proportion of the water from San Bernardino National Forest is used for industrial use (7.5 percent), followed by Angeles National Forest (6.5 percent) and Santa Monica Mountains National Recreation Area (3.3 percent). Cleveland and Los Padres National Forests have a small proportion (0.7 and 0.2 percent, respectively) because of their distance from large urban centers.

Irrigation and Livestock

Los Padres National Forest provides substantially more surface water and groundwater for agricultural irrigation and livestock categories (85.4 percent total for both

categories) than other federal lands in the SOCAAP assessment area. Angeles and Cleveland National Forests and Santa Monica Mountains National Recreation Area also provide large amounts of water for agricultural irrigation and livestock uses (totals for both categories of 27.2, 42.2, and 59.6 percent, respectively). San Bernardino National Forest provides only 5.8 percent.

Public Supply

For Angeles, San Bernardino, and Cleveland National Forests, public supply is the largest use of water (62.3, 83.6, and 49.8 percent, respectively). This is the second largest use of water for Santa Monica Mountains National Recreation Area (31.8 percent) and Los Padres National Forest (13.1 percent). Most of this water is allocated to domestic use in households, as well as some commercial applications, although the specific uses are not quantified.

Other Uses

Other water uses reported in table 6.2 include mining, thermoelectric power generation, and aquaculture. Amounts of water used for these categories are negligible, with thermoelectric power generation having the largest proportion at 0.56 percent for Los Padres National Forest. Aquaculture is the largest “other use” of water for Angeles and Cleveland National Forests and Santa Monica Mountains National Recreation Area (1.7, 5.5, and 4.3 percent, respectively).

Effects of Climate Change and Population Growth

The effects of climate change on water resources will be influenced by various factors (see chapter 2), and as noted previously, will vary across the landscape. Minimum temperatures are likely to increase, leading to higher rates of evapotranspiration from vegetation and evaporation in water-storage facilities. Although changes in annual precipitation will likely be negligible, the timing of precipitation may change. More frequent high-precipitation events will result in more runoff into streams because of higher amounts of soil saturation (chapter 3). In addition, the region might experience higher frequency and extent of wildfires (Swain 2021, Westerling et al. 2011), which would also affect water supply by removing vegetation that would otherwise buffer runoff. At the same time, population growth may

create more pressure on water needs. In this section, we will discuss expected effects of climate change and population growth on use categories in table 6.2.

Domestic Use

Although water supplied from national forests may increase in a warmer climate, there will be additional pressure on water resources as the population increases (Ashoori et al. 2016). The population of southern California is forecasted to increase nearly 10 percent across the counties surrounding the assessment areas (chapter 5), which could make water more expensive for domestic use or lead to restrictions on some uses, such as watering lawns.

Industrial Use

Continued pressure on water resources and an expanding population is likely to make water use for industrial purposes more expensive and scarcer. This could limit economic expansion in the region depending on the water requirements of the industry in question. Therefore, interactions among water, population growth, and industrial activity will influence the effects of climate change on both natural resources and local economies. Constraints on population expansion in southern California could lead to shortages of labor for some industries.

Irrigation and Livestock

Given the large amount of water devoted to agricultural irrigation and livestock across the region, and that water rights for urban users are typically prioritized, agricultural output may be at risk of water shortage in a warmer climate. Curtailed water rights have the potential to affect agricultural production by different mechanisms. For example, many crops (e.g., almonds, pistachios, grapes) grown in southern California need large amounts of water, so decreased water supply will likely cause price increases. As temperatures rise, demand for agricultural water will rise as well (Thomas 2008). However, some research has suggested that some crops can be used for flood-protection zones and water storage (Wyatt 2022), which would be a secondary benefit.

Public Supply

As a category of water use with mixed uses (e.g., domestic, industrial), public supply will face pressure from a growing population. In addition, climate change might pose risks to water infrastructure if increased wildfire

frequency causes sedimentation and destroys structures in burn zones (Lee et al. 2022). Public supply infrastructure, sedimentation, and damage and contamination from wildfire may interrupt deliveries at irregular intervals. However, some opportunities for mitigation exist; for example, agricultural land can be used as green infrastructure for flood mitigation and water storage (Wyatt 2022).

Other Uses

Many of the same pressures faced by the other categories in this section will also play a role in affecting uses not explicitly discussed above. For example, the thermoelectric category, which refers to water used in steam turbines to generate electricity, will likely face pressure with larger populations and higher temperatures, both increasing demand for electricity.

Adaptive Capacity

Climate projections indicate that precipitation will likely be the same or slightly higher, but that it will not be distributed as equally across the year as in the past. This poses a challenge for storing and using the water within and between years. Even if more water is available, there will be periods when it will be necessary to conserve water. Behavioral changes of water users (i.e., water conservation) have the potential to alleviate pressure on water resources in the long term. Several studies have examined the effectiveness of communication campaigns, alternative designs, and urban water-conservation campaigns (Gleick et al. 2003, Luthy et al. 2020, Vivek et al. 2021). If behavioral changes are achieved, this could reduce the burden placed on water supplies for urban consumption and other uses.

Increasing adaptive capacity for providing and conserving water resources on federal lands is a key element of long-term sustainability in the SOCAAP assessment area. For example, removal of invasive species that consume lots of water can retain water within mediterranean ecosystems (McNeely 2001). Maintenance and restoration of riparian areas through tree plantings and other activities can reduce evapotranspiration and moderate stream temperatures (Singh et al. 2021). Restoration of wetlands and other vegetated areas can help buffer extremes in the timing of water deliveries (Hunt et al. 2018). However, planting excess vegetation (more than environmental norms) should be avoided

to reduce the possibility of higher water consumption (Ricciardi et al. 2022).

The potential for a higher frequency of high-rain events has important implications for the timing of water supplies and water use in southern California, which has a combination of a generally arid climate and high population. Therefore, it will be necessary to adapt to changes in both the quantity and timing of water resources. Enhancing water storage can help distribute water supplies through time as well as control flooding (Zhuo et al. 2019). Furthermore, combining flood-control efforts with water storage to minimize the amount of water flowing back into the ocean might be necessary to address water shortages.

Several studies have highlighted the potential of water markets to help alleviate pressure on water supplies by allowing transfers from less productive uses to more productive uses (e.g., Chong and Sunding 2006, Schwabe et al. 2020). It is plausible that better functioning water markets have the potential to increase efficiencies and adapt to changes in water supply, especially with respect to transfers from agricultural to urban uses (Arellano-Gonzalez et al. 2021).

Water Quality

Both human populations and wildlife habitat depend on the health of water resources in the SOCAAP assessment area (Berg et al. 2004). National forests in the assessment area, especially Angeles and San Bernardino National Forests, provide large amounts of drinking water. Drinking water depends heavily on the quality of the water being transported to households, and any poor-quality water must either be treated, or not be used at all. Water quality is also critical for water-based recreation. Outdoor recreation involving water resources is common in the region (chapter 5), especially in San Bernardino National Forest, which contains Big Bear Lake and Lake Arrowhead, both of which host activities such as swimming, boating, water skiing, kayaking, and paddleboarding (Estrada 2022).

Effects of Climate Change

Climate change has the potential to degrade water quality (Whitehead et al. 2009), which then influences the provision of drinking water (Ekstrom et al. 2017), including increasing costs of water treatment (Valdivia-Garcia et al. 2019). Degradation of water quality might

also affect public health (Michalak 2016). Furthermore, degraded water quality can affect recreational opportunities as harmful algal blooms may become more common (Gobler 2020). Changes in water quality may also degrade aquatic habitat for fish and other animals (Missaghi et al. 2017).

Higher air temperature in the assessment area (chapter 2) is expected to increase water temperature in lakes and streams. Higher temperatures in drinking water supplies can degrade water quality by increasing the quantity of phytoplankton, thus decreasing dissolved oxygen in the water (Ducharne 2008). Warmer water can also contribute to a higher incidence of harmful algal blooms (Wells et al. 2020), which can increase water-treatment costs (Anderson et al. 2000) as well as public-health costs (Kouakou and Poder 2019). Warmer temperatures will also reduce the suitability of habitat for fish species that require relatively cool temperatures (Jardine et al. 2020). Wildfires are also a potential source of water contamination (Whitney et al. 2015).

Drought conditions can also affect water quality, causing reduced reservoir levels throughout the year, regardless of whether average precipitation remains unchanged. The lower quantity of water at some points of the year may result in higher pollution levels as less water is available to dilute pollutants (Sun and Lockaby 2012). Similar to water quantity, the factors influencing water quality are dynamic, leading to variations in the provision of water quality over time.

More frequent high-precipitation events may result in increased sedimentation in streams (Puntenney-Desmond et al. 2020), which can reduce water quality through increasing turbidity, metals, and other dissolved solids. More frequent high-intensity wildfires can also degrade water quality via production of runoff and sedimentation in streams (Hohner et al. 2019, Mann et al. 2016, Nyman et al. 2015, Smith et al. 2011). In some cases, wildfire suppression chemicals can be washed into streams, causing nutrient enrichment and potentially leading to algal blooms and oxygen depletion (Kalabokidis 2000). For fires that enter urban areas, contamination from destroyed infrastructure, such as buildings and plastic piping, can pollute drinking water (Odimayomi et al. 2021).

Water quality in some streams has been shown to decline during droughts (Mosley 2015), including

an increase in salinity (Mosley et al. 2012, Wilbers et al. 2009). A decline in water quality associated with droughts is usually caused by increased concentrations of chemicals regularly found in the waterways (Mosley 2015). In other words, sources of pollution become more concentrated when less water is available.

Adaptive Capacity

There is an opportunity to invest in landscape modification and conservation to mitigate the effects of climate change on water quality. Providing forest cover in riparian zones has been shown to cool water temperatures (Justice et al. 2017). Species conservation and other landscape modification may be enough to manage the movement of water and sediment caused by altered precipitation patterns by allowing additional, steadier flows of water into waterways (Spathelf et al. 2018). Water quality can be managed through this treatment as well (Price and Heberling 2018). Increased capacity and ability to treat water may be necessary as climate change results in lower quality drinking water overall (Lipczynska-Kochany 2018). In addition to public investment in water treatment, household investments in water treatment (e.g., purchasing water filters) may be needed to maintain acceptable drinking water (Zivin et al. 2011).

Grazing and Rangelands

California contains a large quantity of rangeland (Biggs and Huntsinger 2021), some of which is public land. Some agencies allow grazing by cattle, goats, and other livestock on some of this public land, including national forests (Lewin et al. 2019). The rangeland provided by national forests contributes to local economies (Sloggy et al. 2023) (box 6.2). Although the provision of grazable rangeland is itself an ecosystem service, it also has implications for other ecosystem services on the landscape, such as degradation of water quality (Hubbard et al. 2004) and competition with other habitats, leading to potential declines in biodiversity (Huffman 2019), emission of greenhouse gases (Godde et al. 2020), and in some cases, increased fire risk (Davies et al. 2022). As a result, rangeland on national forests represents a mixture of benefits and costs to the provision of other ecosystem services.

Grazing is allowed in national forests in the SOCAAP assessment area but not in Santa Monica Mountains

National Recreation Area. The unit of measure for grazing is an “animal unit month.” The expansion or contraction of the number of animal unit months within any given national forest is related to several factors, including historical precedent, economic and environmental conditions, and the availability and quality of pastureland.

Using data from the Forest Service (USDA FS 2022), we quantified the area and quantity of grazing for national forests within the SOCAAP assessment area (table 6.3). These data do not contain the acreage of closed allotments, which is reported as zero in the database. Most of the grazing occurs in Los Padres National Forest in terms of the number of allotments and number of acres. Cleveland National Forest has the second highest number of allotments, but its acreage is about the same as for San Bernardino National Forest. Vacant allotments indicate the amount of available grazing that is not assigned to a specific grazing activity. Thus, national forests with more vacant allotments might be able to more quickly expand grazing on the landscape. Los Padres and Cleveland National Forests have the most vacant allotments. Angeles National Forest does not have a large amount of grazing, but it has the most closed allotments. The trend of shutting down allotments in Angeles National Forest is not likely to change, as it is typically impractical to reopen closed allotments.

Although the provision of rangeland for grazing is considered a supporting ecosystem service (Sala et al. 2017), grazing itself can affect other ecosystem services. First, grazing can alter carbon sequestration. Although some grazing operations can increase soil carbon (Ingram et al. 2008), greenhouse gas emissions from cattle might outweigh soil sequestration (Franzluëbbers 2020). Grazing can thus be considered carbon cycling, because carbon sequestered in plants is converted to methane and carbon dioxide through digestion. Second, grazing also might degrade the quality of water resources near the grazing operation (Wagner et al. 2021). Third, grazing might have a mixed effect on biodiversity (Metera et al. 2010). Fourth, grazing has a mixed relationship with reducing or increasing the threat of fire. As such, grazing is part of a dynamic flow of ecosystem services. Similarly, the provision of grazing habitat is dynamic, because it is influenced by other ecosystem services, such as soil health and water quantity, that vary through time.

Box 6.2
Economic Effects of Grazing

In addition to acting as a fuel treatment option (Bruegger et al. 2016, Lovreglio et al. 2024, Vaillant et al. 2009), grazing on federal lands contributes to local economies. Sloggy et al. (2023) evaluated the effects that specific grazing allotments on federal lands had on the number of jobs, the income from those jobs, and the economic output by state based on data collected in December of 2017. The study found that for every 1,000 animal unit months (a measure of grazing volume) in California, there was one additional job, \$9,353 in labor income, and \$70,616 in economic output from cattle grazing (both in 2016 U.S. dollars). For grazing by goats or sheep,

the numbers are even higher, with 1,000 animal unit months resulting in 4.8 jobs, \$15,114 in labor income, and \$86,040 in economic output.

Los Padres National Forest contains 33,345 reported animal unit months of grazing, most of which is cattle grazing. Therefore, we estimate that the economic effect of grazing in this national forest is 33 jobs, with \$317,944.58 in labor income, and an economic output of \$2,354,690. Although grazing can affect other ecosystem services, such as water quality (Hubbard et al. 2004), expanding the amount of grazing in Los Padres National Forest, especially goat or sheep grazing, could provide additional economic benefits to local communities aside from reducing wildfire risk.

Table 6.3—Number, acreage, and status of grazing allotments by national forest in the Southern California Adaptation Partnership assessment area

Status	Los Padres National Forest	Angeles National Forest	San Bernardino National Forest	Cleveland National Forest
	ACRES			
Active allotments	48	1	4	13
Active acres	461,588	2,703	57,452	63,005
Vacant allotments	43	2	9	13
Vacant acres	368,371	4,156	122,794	64,678
Closed allotments	2	6	1	1
Closed acres	0	0	0	0

Grazing by cattle, sheep, and goats has been used to manage fire risk in some parts of southern California (Davies et al. 2022). Although potentially harmful to some ecosystem components (Roche et al. 2013), grazing is a proven means of reducing fuel loads, which can in turn minimize losses of ecosystem services (e.g., reduced fire damage to infrastructure) (Vaillant et al. 2009).

Effects of Climate Change

Research on the effects of climate change on grazing typically focuses on the environmental conditions necessary

to sustain grazing (Hanson et al. 1993, Holechek et al. 2020). However, climate change might intensify the ecological effects of grazing (Ghahramani et al. 2019). In some cases, carbon fertilization (Coonan et al. 2019) and higher temperature (Patton et al. 2007) might increase rangeland productivity and the capacity for grazing. The potential effects of precipitation on grazing in the SOCAAP assessment area are unknown, but altered precipitation can lead to changes in plant composition of rangelands (Chambers and Pellant 2008) and available water for cattle (Havstad et al. 2007). In addition,

as climate change increases the sensitivity of some ecosystems to disturbances, such as wildfire and invasive species (Lenihan et al. 2008), the effects on and caused by grazing could be negative. For example, as water resources become more valuable (Brown et al. 2019), grazing effects on water quality (e.g., increased nitrate levels from cattle waste) (Hubbard et al. 2004) might be more costly, and erosion (and sedimentation) associated with vegetation loss could increase (Yamazaki et al. 2020).

Adaptive Capacity

Grazing can be used to address other changes on the landscape, such as fire risk (Davies et al. 2022). Good grazing practices can help avoid negative effects on ecosystem services. In some cases, curtailment of grazing might be used to protect ecosystems (Côté and Darling 2010). Los Padres National Forest, which currently features considerable grazing, has room to further expand grazing (table 6.3). San Bernardino National Forest, which has a moderate amount of grazing, also has capacity to expand grazing into vacant allotments.

Although climate change might increase the productivity of grasslands and make grazing a more attractive alternative to landscape management, it may also increase the effects of grazing on other ecosystem services. Detrimental effects of grazing can be balanced with the economic and fire reduction benefits of grazing in the assessment area. Potential interactions of decisions about grazing can consider how it affects local economies (box 6.2).

Carbon Sequestration

Sequestration of carbon in biological systems, the uptake and storage of carbon in wood products and in vegetation and soil, is an important ecosystem service provided by forests. Carbon sequestration is considered a regulating ecosystem service as it helps to mitigate greenhouse gas emissions in the atmosphere by removing and capturing carbon dioxide. Therefore, forest carbon storage is an important service for society at local to global scales.

Forested ecosystems sequester significant amounts of carbon. In North America, forests are carbon sinks because more carbon is absorbed in them than is released (Pan et al. 2011). The federal government manages 190

million acres of land, 29 percent of which is forested (Smith et al. 2019). Federal forest lands sequester an estimated 17.2 petagrams of carbon (Pg C), of which 13.8 Pg C are from national forests (Smith et al. 2019). The National Forest System, which contains 22 percent of all forested land area in the contiguous United States, sequesters 24 percent of total carbon stored in all forests in the lower 48 states (USDA FS 2022b). Although discussed here as carbon stock, the carbon within a landscape is constantly fluxing between different carbon sinks—soil, biomass, and the atmosphere—through natural processes, including wildfires, insect outbreaks, and decomposition of woody biomass.

Since 2012, national forests have been required to identify baseline carbon stocks for consideration in planning and management under the Forest Service's 2012 Planning Rule (USDA FS 2012). Carbon stock estimates are based on forest inventory data from the Forest Service Forest Inventory and Analysis (FIA) program. The FIA carbon stock estimation procedure is continuously being upgraded; current refinements target improvements in estimating soil carbon, belowground biomass and carbon, carbon in understory vegetation, and better delineations between woodland and forest carbon pools. We summarized the Forest Service FIA carbon estimates (USDA FS 2025) and a dataset and estimation procedure for total carbon stock values for the same assessment area (Schrader-Patton and Underwood 2021).

Southern California national forests contain grassland, shrubland or chaparral, woodland, and forest at higher elevations (Underwood et al. 2018b, 2019). The literature on the magnitude of soil carbon sequestration in chaparral versus coniferous forests is equivocal. Jenerette et al. (2018) cite studies that indicate chaparral sequesters more carbon and nitrogen than coniferous forests. Luo et al. (2007) found that chaparral-dominated ecosystems can absorb more carbon than old-growth forest in wet years. However, more research is needed in chaparral-dominated systems to understand deep-soil carbon storage as well as the effects of very dry years.

The FIA carbon stock estimates are provided from 2005 to 2023 for the four national forests in the SOCAAP assessment area (see USDA FS 2025). These estimates indicate that Los Padres National Forest stored the most carbon in the region, and Cleveland National Forest stored

the least carbon. During this period, Angeles, Los Padres, and San Bernardino National Forests generally saw a decrease in forest carbon stocks because of disturbances (e.g., wildfire, insect outbreak, and extreme weather) and change in land use (USDA FS 2025). Cleveland National Forest did not see a change in total carbon stock in all carbon pools and had the lowest carbon density of all national forests in California (USDA FS 2025).

Forests sequester carbon in seven primary stocks (USDA FS 2015):

- Aboveground live trees—all live woody vegetation at least 2.5 centimeters in diameter at breast height (DBH). Some estimates also separate aboveground and belowground stocks in live trees, in which case, belowground includes coarse living roots >2 millimeters in diameter.
- Belowground live trees—difference between whole live trees and aboveground live trees only.
- Understory—all live herbaceous and woody vegetation ≤2.5-centimeters DBH.
- Standing dead trees—nonliving standing dead trees that are otherwise defined the same as standing live trees, including estimates for belowground roots >2 millimeters in diameter.
- Down dead wood—all nonliving woody biomass with a diameter of ≥7.5 centimeters at transect lying on the ground.
- Forest floor—litter, fomic and humic layers, and all nonliving biomass with a diameter <7.5 centimeters at transect intersection lying on the ground above the mineral soil.
- Soil organic carbon—all organic material in soil to a

depth of 1 meter but excluding the coarse roots of the carbon pools mentioned above.

Related research by the U.S. Department of the Interior (USDI), National Parks Service and U.S. Geological Survey found that Santa Monica Mountains National Recreation Area sequesters 0.2 million tonnes of carbon per year, ranking it as one of the top 20 U.S. national parks in terms of annual carbon sequestration (Richardson et al. 2014). The annual carbon sequestration estimate for Santa Monica Mountains National Recreation Area is a measure of flow over time.

Because uncertainties persist regarding total carbon stock estimates in Mediterranean ecosystems, researchers are developing models that will provide more accurate estimates of carbon storage in southern California. A recent study estimated the amount of carbon stored in aboveground live biomass during 2010 in southern California to be 45 teratonnes of carbon (Underwood et al. 2019). Schrader-Patton and Underwood (2021) used remote-sensing data, which improves the accuracy of biomass estimates.

To better understand the amount of total carbon stock for each of the four national forests in the SOCAAP assessment area, we used the raw aboveground live biomass estimated by Schrader-Patton and Underwood (2021) to convert to carbon stock storage. Schrader-Patton and Underwood (2021) estimated the total biomass for all four forests in the SOCAAP region. We combined the biomass estimates from Schrader-Patton and Underwood (2021) using a coefficient of 0.47 from Eggleston et al. (2006) that converts biomass to carbon across several carbon pools to estimate the mean carbon storage in kilograms per square meter for shrub, non-shrub, and a combined all vegetation category in the SOCAAP assessment area

Table 6.4—Baseline mean aboveground carbon stocks in three carbon pool types for national forests in the Southern California Adaptation Partnership assessment area

National forest	Shrub type	Nonshrub type	All vegetation types
KILOGRAMS PER SQUARE METER			
Los Padres	1.65	2.73	1.97
San Bernardino	1.41	2.21	1.83
Cleveland	1.08	2.16	1.18
Angeles	1.08	2.26	1.41

Note: Values are mean; therefore, they must be multiplied by the area of each forest to calculate the total carbon storage for each forest. Vegetation types are based on Mayer and Laudenslayer (1988).

(table 6.4). The vegetation classes are based on California Wildlife Habitat Relationships vegetation data (Mayer and Laudenslayer 1988): shrub (mixed chaparral, chamise-redshank chaparral, coastal scrub, montane chaparral, and sagebrush), nonshrub (montane hardwood, pinyon-juniper, Sierran mixed-conifer, coastal oak woodland, montane chaparral-Jeffrey pine [*Pinus jeffreyi* Balf.], annual grassland, and eastside pine), and all California Wildlife Habitat Relationships vegetation types. The values reported in table 6.4 are means per square meter;

therefore, they must be multiplied by the area of each forest to calculate the total carbon storage for each forest.

Effects of Climate Change

Climate change effects on forest carbon storage are already evident in the SOCAAP assessment area (chapter 2, box 6.3), and further change is anticipated. Many factors affect the magnitude and distribution of carbon, and some uncertainty exists regarding carbon stocks because different vegetation and climate models

Box 6.3

Wildfire and Bark Beetle Effects on Carbon

Wildfires, droughts, insects, and other disturbances have reduced forest carbon stocks on U.S. forest lands to about half of their theoretical maximum storage

potential (Williams et al. 2016). Marcos-Martinez et al. (2022) evaluated the effects of bark beetle outbreaks and wildfires on forest carbon emissions in the Western United States using an ensemble of aboveground biomass datasets and regional field data to compile tree mortality by forest type and fire intensity. Figures 6.4 and 6.5

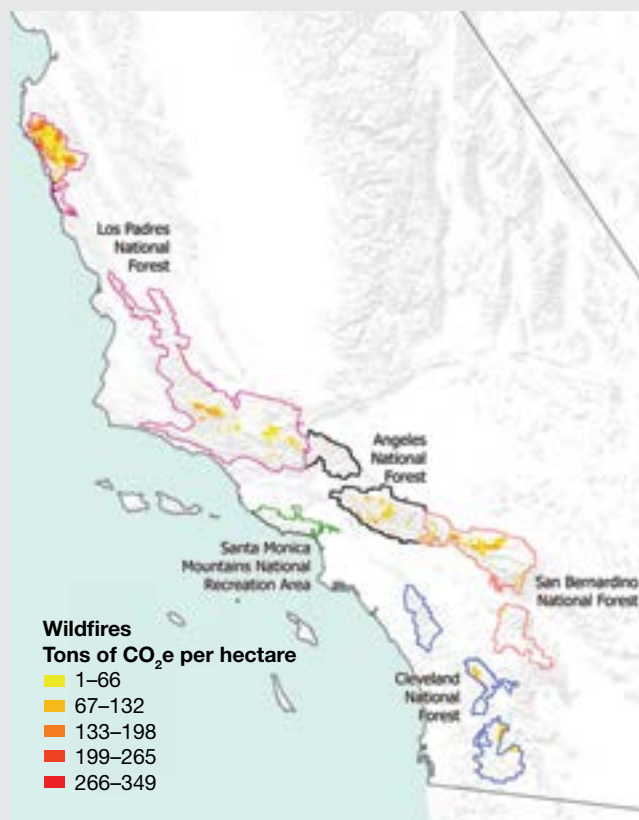


Figure 6.4—Cumulative carbon dioxide (CO₂) emissions from biomass loss due to wildfires in the Southern California Adaptation Partnership assessment area, 2003–2012. Modified from Marcos-Martinez et al. (2022).

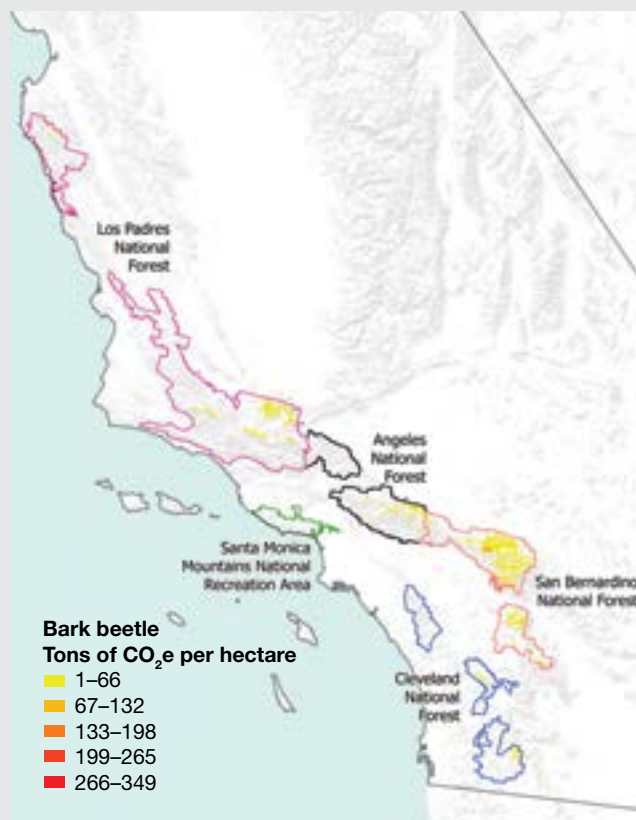


Figure 6.5—Cumulative carbon dioxide (CO₂) emissions from biomass loss due to bark beetles in the Southern California Adaptation Partnership assessment area, 2003–2012. Modified from Marcos-Martinez et al. (2022).

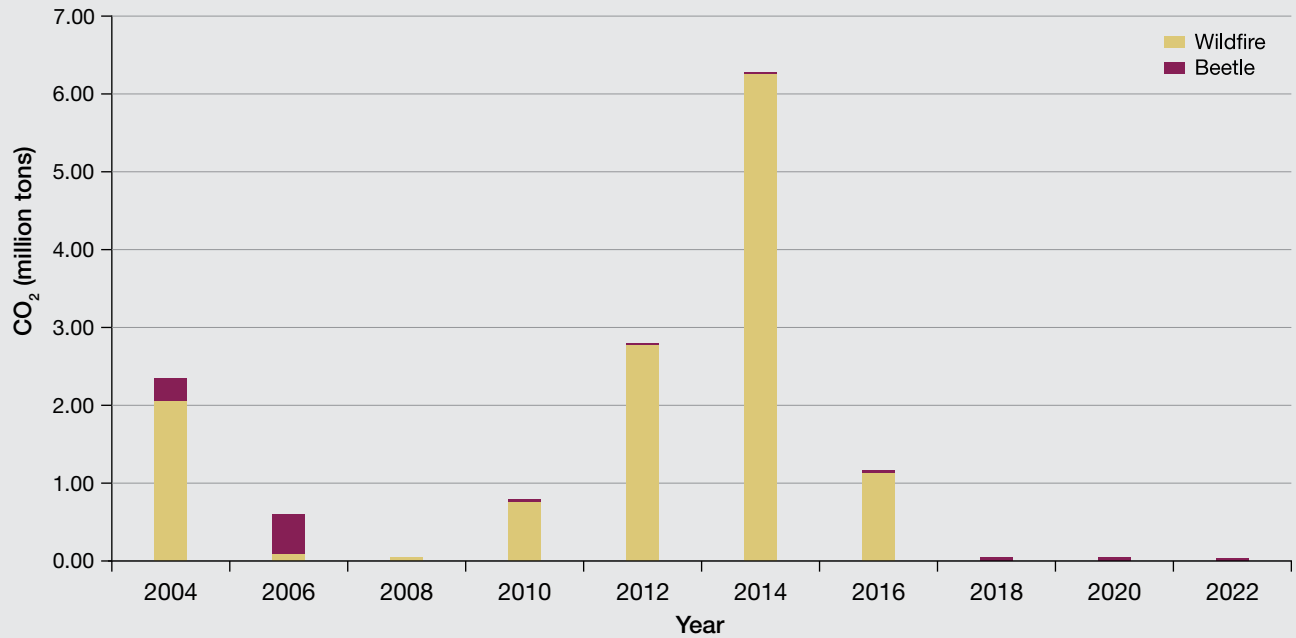


Figure 6.6—Total carbon dioxide (CO₂) emissions from wildfire and bark beetle outbreaks in the Southern California Adaptation Partnership assessment area, 2003–2012. Modified from Marcos-Martinez et al. (2022).

were modified from Marcos-Martinez et al. (2022) to show cumulative carbon dioxide (CO₂) emissions from wildfires and bark beetles for the Southern California Adaptation Partnership (SOCAAP) assessment area. The highest emissions from wildfire occurred in the northern part of Los Padres National Forest, whereas the highest concentration of emissions per land area from bark beetle outbreaks was in San Bernardino National Forest. Wildfires cause most CO₂ emissions, with the highest emissions in 2008 (fig. 6.6). This trend is continuing as we have seen an increase in the frequency and extent of wildfires in the past few years (chapter 2). Both wildfires and bark beetle outbreaks have significantly affected carbon sequestration in the SOCAAP assessment area (fig. 6.7). This pattern may continue with warming in the future (chapter 2).

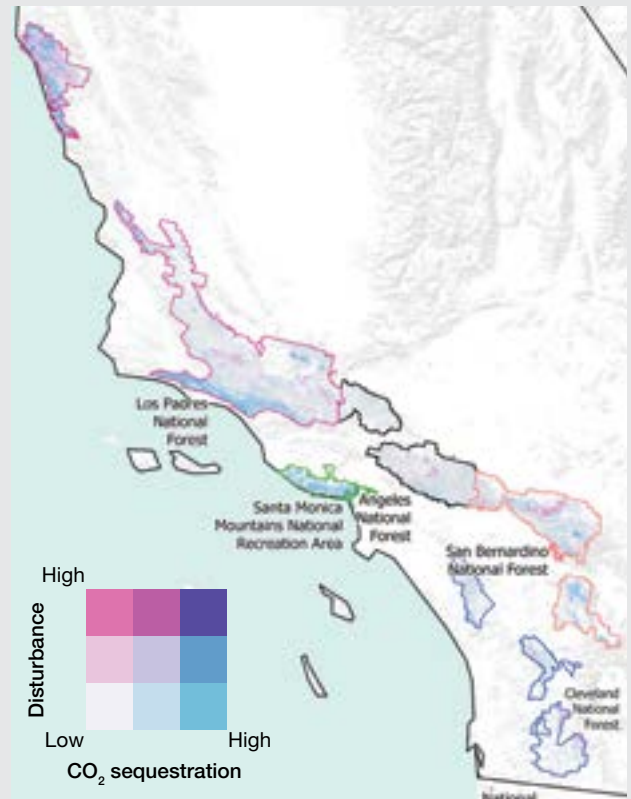


Figure 6.7—Interaction between mean annual tree biomass mortality (2003–2012) and carbon dioxide (CO₂) sequestration (2001–2020). Modified from Marcos-Martinez et al. (2022).

project different outcomes. This is particularly true for the portion of the assessment area that is mostly chaparral for which belowground carbon is difficult to estimate. Type conversion can have significant effects on carbon sequestration. Petrie et al. (2015) found that chaparral land cover sequesters more carbon than grasslands, implying that land use conversion from one to the other may have substantial effects on carbon sequestration. As more frequent wildfires convert native chaparral to nonnative grasslands (Spyhard et al. 2018), there are likely substantial reductions in carbon sequestration driven by reduced plant cover and root depth from grasslands (Jenerette et al. 2018). Nonnative grasses, which do not capture water at depths below their roots, might alter other ecosystem services such as groundwater recharge (Williamson et al. 2004). New methods and models using remote sensing may provide a better understanding of biogeochemical dynamics in chaparral ecosystems (Jenerette et al. 2018).

Adaptative Capacity

Shorter wildfire-return intervals may cause long-term effects on carbon in the SOCAAP assessment area (Fried et al. 2004). The use of prescribed fire for fuel reduction in forests may help mitigate the severity of some large wildfires that influence vegetation life-form conversions, thus avoiding large pulses of carbon emissions. In addition, prescribed fires may increase carbon storage in grasslands as they stimulate grass growth and increase root biomass (Pellegrini et al. 2022). Other vegetation management practices, such as grazing, are being explored in Los Padres National Forest.

The SOCAAP assessment area is likely to experience warmer minimum temperatures, leading to longer periods of drought stress for tree species (Bentz et al. 2010). As the level of drought stress increases, several species of trees in the SOCAAP assessment area may become more susceptible to beetle infestations (Dobbertin et al. 2007) and wildfire (Littell et al. 2016), which can increase carbon emissions. Past management practices have reduced bark beetle damage—thinned forests eliminated competition among trees, allowing them to produce enough sap to fight beetle outbreaks (Hood et al. 2016). The ability to adapt carbon sequestration strategies to climate change will be linked to effective management of all large-scale disturbance events.

Clean Air and Local Pollution Abatement and Mitigation

From an ecosystem services perspective, benefits of clean air and local pollution abatement and mitigation provided by the national forests and national recreation area in the SOCAAP assessment area are in the form of avoided impacts to human health outcomes. There are two sources of benefits from these public lands: (1) the flow of the natural environment cleaning the air of existing pollution and particulate matter, and (2) the avoided damage to human health provided by reduced smoke

inhalation during wildfires. In the latter case, the ecosystem service is generated by avoiding health impairment.

Although air quality has improved in southern California in recent decades, this region still has some of the poorest air quality in the United States (Yaya et al. 2020). Ozone and particulate pollutants monitored by the U.S. Environmental Protection Agency are largely caused by emissions from industrial activities, automobiles, lawnmowers, and other emissions from people's daily activities. Other sources of particulate pollution include wildfire and burning wood for heat. These emissions combined with high temperatures and consistent sunlight contribute to the formation of tropospheric ozone, for which concentrations peak during the summer months. People of color, people experiencing poverty, children, older adults, and people with underlying health conditions are considered high-risk groups for exposure to poor air quality (American Lung Association 2022). Because southern California has a large residential population, a substantial portion of that population is at risk of exposure to harmful air quality conditions. In addition, poor air quality can obstruct views, damaging the economic value of viewsheds (Rodriguez Mendez et al. 2003).

Smoke is a major contributor to poor air quality, especially in southern California (Aguilera et al. 2021). Particulate matter from wildfire smoke can cause significant health effects, especially for sensitive and high-risk groups of people with underlying health conditions. Past studies have shown links between wildfire smoke and higher asthma rates (Kiser et al. 2020), cancer (O'Dell

Table 6.5—Number of smoke days and percentage of change for two periods in counties adjacent to a national forest in the Southern California Adaptation Partnership assessment area, 2006 through 2013 and 2014 through 2021

County	2006–2013	2014–2021	Change
	NUMBER OF DAYS	PERCENT	
Los Angeles	37	55	49
Monterey	44	67	53
Orange	20	35	79
Riverside	52	62	20
San Bernardino	44	59	35
San Diego	45	57	28
San Luis Obispo	40	62	56
Santa Barbara	32	51	59
Ventura	32	50	57

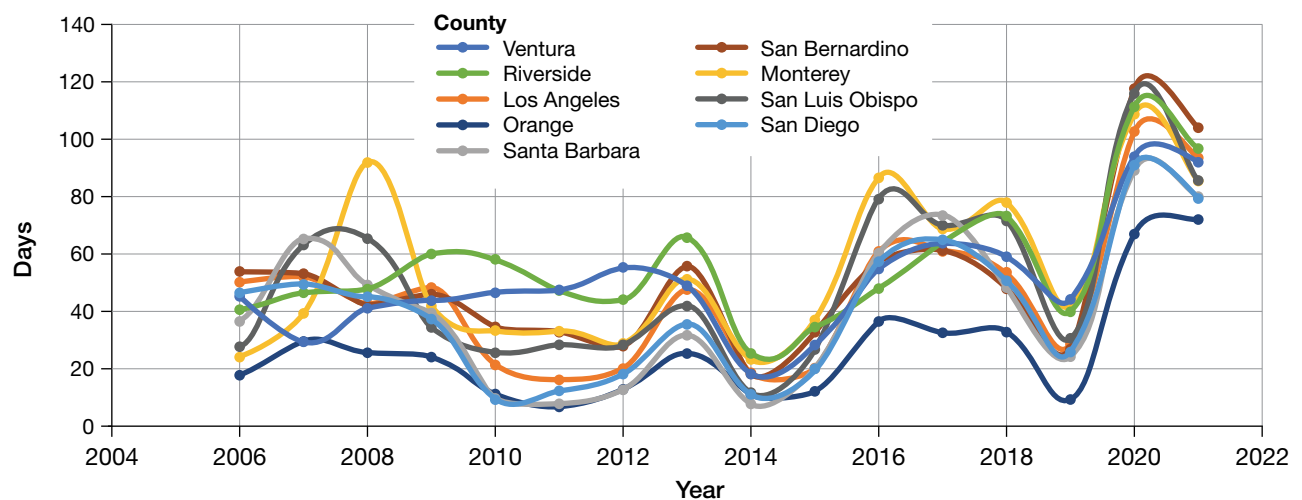


Figure 6.8—Annual smoke days for each county adjacent to a national forest in the Southern California Adaptation Partnership assessment area, 2006–2021.

et al. 2020), and other negative health outcomes (Reisen et al. 2015). Wildfire smoke affects populations adjacent to a fire as well as far away (e.g., hundreds of kilometers), depending on air currents (Schweizer et al. 2017). Health effects from wildfire smoke exposure (e.g., difficulty breathing and other symptoms during the 2008 Station Fire in Angeles National Forest) can translate to economic damage (Richardson et al. 2012).

Some evidence suggests that the number of days with smoke (i.e., smoke days) is increasing. Using data from the U.S. Department of Commerce, National Oceanic and Atmospheric Administration's *Hazard Mapping System Fire and Smoke Product* (USDC NOAA 2022), we calculated the number of smoke days in counties adjacent to the four national forests in the SOCAAP assessment area for 2006 through 2021 (table 6.5). Orange County had the highest percentage increase over the period of study (79 percent), whereas San Diego County had the lowest percentage increase (28 percent). We did not differentiate between the intensity of smoke or height of the smoke plume, so the data in table 6.5 might not match other reported smoke day information. A plot of the time series of smoke days for each county shows an overall increasing trend, with 2020 having the most annual smoke days for all the counties (fig. 6.8).

Effects of Climate Change

Climate change is expected to exacerbate wildfire frequency and extent, which will increase health-related effects from exposure to wildfire smoke. The trend of increasing smoke days in our assessment (table 6.5) is expected to continue. In addition, wildfire smoke will likely impair outdoor recreation opportunities and

people's ability to exercise outside during periods of poor air quality (chapter 5). Table 6.5 highlights the dynamic nature of air quality, which is affected by multiple processes that vary through time. The expected increase in smoke days is likely to translate to increased exposure for residents with health conditions, reducing their physical activities and increasing medical costs.

Adaptive Capacity

There may be opportunities to reduce health symptoms by increasing the flexibility with which forest managers plan management activities, such as prescribed burns. This may include creating contingency plans for unexpected shifts in outdoor recreation use and establishing protocols for when to close public land access points to reduce exposure to poor air quality. Improved communication about air quality, including real-time data, will provide timely information to the public so it can prepare for periods of poor air quality.

Soil Regulation

The Forest Service recognizes the importance of "any ecological service, role, or task that soil performs" (USDA FS 2009). As noted by Underwood et al. (2019) and Hansen and Ribaud (2008), the ecosystem service provided by soil regulation is the avoided loss of soil. The soil itself provides several provisioning ecosystem services, such as biodiversity (Bennett 2010) and carbon sequestration (Lal 2016). According to a 2009 Forest Service soil management directive (USDA FS 2009), soil functions also include (1) soil biology, (2) soil hydrology, (3) nutrient cycling, (4) carbon storage, (5) soil stability and support, and (6) filtering and buffering. From an

Box 6.4

Wildfire and Landslides

The number of extreme precipitation events is projected to increase under climate change (Touma et al. 2022). Extreme precipitation events following fires can destabilize soils and produce destructive landslides. Southern California has had several recent experiences with landslides, including the destructive landslides following the 2017–2018 Thomas Fire in Santa Barbara and Ventura

Counties (Lukashov et al. 2019). The mudslides affected human populations significantly, taking 21 lives and injuring many people, destroying hundreds of structures, and displacing thousands of individuals (Langdon et al. 2019). As climate change increases the frequency of wildfire and extreme precipitation events (Touma et al. 2022), soil health and stability will continue to be affected, which will potentially degrade natural resource conditions and damage human communities.

ecosystem services perspective, soil regulation indirectly supports these soil functions and many other ecosystem services. This suggests that soil regulation can serve as an indirect input to most ecosystem services in the SOCAAP assessment area.

Southern California has some of the world's most erodible soils, which leads to sediment removed from upland areas and deposited in lowlands (Jansson 1988). Soil erosion can pose a threat to infrastructure, water quality, cultural sites, and outdoor recreation sites. See chapter 4 for a discussion on the role that erosion and soil retention play with respect to built infrastructure. The two main causes of excessive erosion are increased water runoff and lack of ground cover over the soil. These factors depend on a site's topography, geology, soils, vegetation cover, and rainfall patterns (Wohlgemuth and Lilley 2018). Increased storm frequency and precipitation intensity combined with changes to vegetation cover (e.g., conversion from chaparral to nonnative grasses) can exacerbate erosion (Puntenney-Desmond et al. 2020). Vegetation type influences soil regulation and is affected by fire regimes. Fire regimes influence water quality (Hohner et al. 2019, Smith et al. 2011) through runoff and sedimentation following fires (Nyman et al. 2015).

Effects of Climate Change

Soil erosion is tied to many forces on the landscape that are affected by climate change, including increased wildfire frequency, more intense storms, and the transition of vegetation cover from native species to nonnative grasses. As each of these factors changes, the potential for reduced soil regulation from erosion is expected. If precipitation extremes increase, the number of landslides will increase because landslides are sensitive to changes in the intensity of precipitation. Small landslides are expected to occur nearly every year in southern California, and large landslides capable of damaging structures are expected every 10 to 13 years (Kean and Staley 2021). For additional discussion on the effects of extreme precipitation events, see box 6.4. It is also possible that increased frequency and extent of wildfires will promote vegetation types with weaker soil retention properties (Obrist et al. 2004).

Adaptive Capacity

Because more intense storms and increased runoff promote soil movement, erosion, and sedimentation to local water courses, maintaining soil regulation to prevent erosion is an important adaptation strategy. Maintaining vegetative ground cover and reestablishing vegetation after wildfires can be effective treatments to prevent erosion during storm events. Management of soil erosion requires prevention of short-term erosion from exposed soil and control of long-term erosion through establishment of vegetation. Revegetation projects can use grasses, brush, chaparral, and trees for ground cover, root strength, and soil protection.

Given the semiarid climate of much of southern California, drought-tolerant native species of vegetation are more likely to sustain revegetation in bare-soil areas. In addition to species selection, soil preparation may be required in areas with soil compaction, low soil organic matter, and low fertility. Some types of grazing regimes might provide an additional avenue for adaptation. Grazing has a measurable influence on the plant species present on a landscape (Lezama et al. 2014), and depending on how grazing is managed, it can support or restrict species that provide additional soil regulation (e.g., Fick et al. 2020, Li et al. 2019).

Biodiversity and Genetic Diversity

The four national forests and national recreation area in the SOCAAP assessment area comprise a wide range of ecosystems, including mixed-conifer forests, oak woodlands, pinyon-juniper forests,² chaparral, and semidesert areas (Underwood et al. 2019). Elevation and climate influence the range of ecosystem types and species richness found in southern California. As a result, the SOCAAP assessment area contains high biodiversity. The definition of biodiversity has been debated for decades (DeLaplanche and Picasso 2011). However, there is general agreement that biodiversity corresponds with species richness—both the number of species and uniqueness of species supported by the landscape. Because this can be difficult to quantify, proxies are often used, such as the provision of habitat for species or the amount of

² Pinyon-juniper forests include singleleaf pinyon (*Pinus monophylla* Torr. & Frém.) and California juniper (*Juniperus californica* Carrière).

Table 6.6—Threatened or endangered flora and fauna species by national forest and recreation area unit in the Southern California Adaptation Partnership assessment area

Unit	Common name	Scientific name	Taxonomic authority
Angeles National Forest	Arroyo toad	<i>Anaxyrus californicus</i>	Camp, 1915
	California condor	<i>Gymnogyps californianus</i>	Shaw, 1797
	California red-legged frog	<i>Rana draytonii</i>	Baird and Girard, 1852
	Coastal California gnatcatcher	<i>Polioptila californica californica</i>	Brewster, 1881
	Mountain yellow-legged frog	<i>Rana muscosa</i>	Camp, 1917
	Santa Ana sucker	<i>Pantosteus santaanae</i>	Snyder, 1908
	Southwestern willow flycatcher	<i>Empidonax traillii extimus</i>	A.R. Phillips, 1948
	Thread-leaved brodiaea	<i>Brodiaea filifolia</i>	S. Watson
Cleveland National Forest	Arroyo toad	<i>Anaxyrus californicus</i>	Camp, 1915
	Coastal California gnatcatcher	<i>Polioptila californica californica</i>	Brewster, 1881
	Cushenbury oxytheca	<i>Acanthoscyphus parishii</i> var. <i>goodmaniana</i>	(Ertter) Reveal
	Hermes copper butterfly	<i>Lycaena hermes</i>	W.H. Edwards, 1870
	Laguna Mountains skipper	<i>Pyrgus ruralis lagunae</i>	Scott, 1981
	Munz's onion	<i>Allium munzii</i>	(Ownbey & Aase ex Traub) McNeal
	Nevin's barberry	<i>Berberis nevinii</i>	A. Gray
	Quino checkerspot butterfly	<i>Euphydryas editha quino</i>	Behr, 1863
	San Bernardino bluegrass	<i>Poa atropurpurea</i>	Scribn.
	San Diego thornmint	<i>Acanthomintha ilicifolia</i>	A. Gray
	Southwestern willow flycatcher	<i>Empidonax traillii extimus</i>	A.R. Phillips, 1948
	Thread-leaved brodiaea	<i>Brodiaea filifolia</i>	S. Watson
	Vail Lake ceanothus	<i>Ceanothus ophiochilus</i>	Boyd, Ross & Arnseth
	Arroyo toad	<i>Anaxyrus californicus</i>	Camp, 1915
Los Padres National Forest	California condor	<i>Gymnogyps californianus</i>	Shaw, 1797
	California red-legged frog	<i>Rana draytonii</i>	Baird and Girard, 1852
	Conservancy fairy shrimp	<i>Branchinecta conservatio</i>	Eng, Belk and Eriksen, 1990
	Least Bell's vireo	<i>Vireo bellii pusillus</i>	Coues, 1866
	Purple amole	<i>Hooveria purpurea</i>	Brandege
	Southwestern willow flycatcher	<i>Empidonax traillii extimus</i>	A.R. Phillips, 1948
	Vernal pool fairy shrimp	<i>Branchinecta lynchi</i>	Eng, Belk and Eriksen, 1990
	Western snowy plover	<i>Charadrius nivosus nivosus</i>	Cassin, 1858

Continued on next page.

habitat that can support a certain level of species richness (Bartkowski et al. 2015).

Genetic diversity—the provision and support of genetic material within an ecosystem—is a key component of biodiversity (Bartkowski et al. 2015) that sometimes provides economic benefits (e.g., pharmaceutical applications) (Hanley and Perrings 2019, Jump et al. 2009). Underwood et al. (2019) described how species richness

can serve as an input to generating or supporting other ecosystem services but also as an asset on its own. This includes the societal value of preserving unique species, including threatened and endangered species (Richardson and Loomis 2009). A meta-analysis by Harrison et al. (2014) found that few studies have confirmed an association between biodiversity and fishing or timber harvest and that the studies were typically associated with a

Table 6.6—Threatened or endangered flora and fauna species by national forest and recreation area unit in the Southern California Adaptation Partnership assessment area (continued)

Unit	Common name	Scientific name	Taxonomic authority
San Bernardino National Forest	Arroyo toad	<i>Anaxyrus californicus</i>	Camp, 1915
	Ash-grey paintbrush	<i>Castilleja cinerea</i>	A. Gray
	Bear Valley sandwort	<i>Eremogone ursina</i>	(B.L. Rob.) Ikonn.
	California taraxacum	<i>Taraxacum californicum</i>	Munz & I.M. Johnst.
	Coachella Valley milk-vetch	<i>Astragalus lentiginosus</i> var. <i>coachellae</i>	Barneby ex Shreve & Wiggins
	Cushenbury buckwheat	<i>Eriogonum ovalifolium</i> ssp. <i>vineum</i>	(Small) S. Stokes
	Cushenbury milkvetch	<i>Astragalus albens</i>	Greene
	Mountain yellow-legged frog	<i>Rana muscosa</i>	Zweifel, 1955
	Parish's daisy	<i>Erigeron parishii</i>	A. Gray
	Peninsular bighorn sheep	<i>Ovis canadensis nelsoni</i>	Merriam, 1897
	Quino checkerspot butterfly	<i>Euphydryas editha quino</i>	Behr, 1863
	San Bernardino bluegrass	<i>Poa atropurpurea</i>	Scribn.
	San Bernardino Merriam's kangaroo rat	<i>Dipodomys merriami parvus</i>	Rhoads, 1894
	San Bernardino Mountains bladderpod	<i>Physaria kingii</i> ssp. <i>bernardina</i>	(Munz) O'Kane & Al-Shehbaz
	Santa Ana sucker	<i>Catostomus santaanae</i>	Snyder, 1908
	Southern mountain wild buckwheat	<i>Eriogonum kennedyi</i> var. <i>austromontanum</i>	Munz & I.M. Johnst.
	Southwestern willow flycatcher	<i>Empidonax traillii extimus</i>	Audubon, 1828
	Thread-leaved brodiaea	<i>Brodiaea filifolia</i>	S. Watson
Santa Monica National Recreation Area	Braunton's milk-vetch	<i>Astragalus brauntonii</i>	Parish, 1903
	California red-legged frog	<i>Rana draytonii</i>	Baird and Girard, 1852
	Lyon's pentachaeta	<i>Pentachaeta lyonii</i>	A. Gray
	Tidewater goby	<i>Eucyclogobius newberryi</i>	Girard, 1856
	Western snowy plover	<i>Charadrius nivosus nivosus</i>	Cassin, 1858

Source: USDI USFWS (2022).

single species of fish or tree, respectively.

The USDI Fish and Wildlife Service has spatial data for critical habitat of threatened or endangered species (USDI USFWS 2022). Using these data, we identified the threatened or endangered species for the four national forests and national recreation area in the SOCAAP assessment area (table 6.6). Angeles National Forest has eight threatened or endangered species, including Santa Ana sucker (*Pantosteus santaanae*), California red-legged frog (*Rana draytonii*), and California condor (*Gymnogyps californianus*). Cleveland National Forest has 13 threatened or endangered species, including Nevin's barberry (*Berberis nevinii*), arroyo toad (*Anaxyrus californicus*),

and Quino checkerspot butterfly (*Euphydryas editha quino*). Los Padres National Forest has nine threatened or endangered species, including California condor, western snowy plover (*Charadrius nivosus nivosus*), and purple amole (*Chlorogalum purpureum*). San Bernardino National Forest has 18 threatened or endangered species, including Peninsular bighorn sheep (*Ovis canadensis nelsoni*), and California taraxacum (*Taraxacum californicum*). Santa Monica National Recreation Area has five threatened or endangered species, including Braunton's milk-vetch (*Astragalus brauntonii*), Lyon's pentachaeta (*Pentachaeta lyonii*), and tidewater goby (*Eucyclogobius newberryi*). In all, Santa Monica National Recreation

Area contains habitat for more than 50 federally recognized threatened or endangered plants and animals (USDI NPS 2022).

California Native Plant Society (2022) has developed a broader list beyond those listed as threatened or endangered. This plant inventory identifies 89 plant species that are considered rare in Santa Monica National Recreation Area, which also provides habitat connectivity for carnivorous wildlife such as mountain lion (*Puma concolor*), bobcat (*Lynx rufus*), and coyote (*Canis latrans*) (USDI NPS 2021). For example, owing to its location immediately adjacent to the Los Angeles metropolitan area, National Park Service research has found that Santa Monica National Recreation Area serves an important role in providing habitat to larger wildlife, such as mountain lions, in a highly fragmented urban setting (Riley et al. 2021). Current stressors include habitat fragmentation and large-scale disturbances, such as wildfire and bark beetle outbreaks. Species with small population sizes, fragmented habitats, and low genetic variability are more vulnerable and less resilient to disturbances such as wildfire and insect and disease outbreaks (Jennings 2018).

Effects of Climate Change

Changes in temperature and precipitation may alter the distribution and abundance of species, including those that are considered rare, threatened, endangered, or a species of concern. Climate change is expected to have several effects on plant and animal species. Altered climate,

disturbance regimes, and vegetation composition will combine to affect species habitat in southern California. Increasing temperatures and changing precipitation will have direct effects on some species. For example, heavy rainfall following the 2018 Woolsey Fire filled streams with mud and silt, destroying most of the California red-legged frog habitat (USDI NPS 2024). Other species may be affected indirectly through shifts in habitat ranges and modified interactions with other species. These effects are expected to interact with existing stressors, such as wildfire, leading to complex responses of plant and animal species that are difficult to anticipate.

Adaptive Capacity

Increased monitoring of habitats, species populations, and human-use patterns can help inform management, planning, and postdisturbance restoration activities. For example, the National Parks Service has studied mountain lion, bobcat, coyote, and gray fox (*Urocyon cinereoargenteus*) movement in Santa Monica National Recreation Area and throughout the Los Angeles metropolitan area (USDI NPS 2021). These data provide insights on the effects of urban expansion on wildlife. Regarding public access for recreation and other uses, it may be possible to identify locations where closures can be enacted to protect sensitive habitat and avoid disturbance of critical life stages of certain species. There may also be opportunities to implement wildlife reintroduction projects in the restoration of habitats that have been severely affected

Box 6.5

Traditional Ecological Knowledge

Traditional ecological knowledge is based on relationships among humans, animals, landscapes, natural phenomena, and plants (Jantarasami et al. 2018). Berkes (2008) defines traditional ecological knowledge as “a cumulative body of knowledge, practice, and belief evolving by adaptive processes and handed down through generations by cultural transmission, about the relationships of living beings (including humans) with one another and with their environments.”

American Indian tribes regard plants that evolved with frequent low-intensity fire as living cultural

resources because they provide many benefits (Long and Lake 2018). Incorporating traditional ecological knowledge into research can help managers understand how fire and management practices may affect tribal cultural resources and values. The chaparral plant species used by tribes depend on fire to maintain desired growth and quality. Lack of fire can reduce the suitability of some plants for traditional cultural uses (Long and Lake 2018). Landscapes that supported American Indian communities prior to European settlement provide ecosystem services that still sustain cultures and preserve traditional activities.

by disturbances. For example, Santa Monica National Recreation Area has several reintroduction sites for the California red-legged frog, whose habitat was degraded by the 2018 Woolsey Fire (USDI NPS 2024). This has resulted in the recovery of the frog population to prefire breeding numbers (USDI NPS 2024).

Cultural, Traditional, Spiritual, and Heritage Values

Cultural ecosystem services are the nonmaterial benefits individuals obtain from ecosystems, which include connections between people and the land, such as aesthetic, recreational, and spiritual benefits (MEA 2005). Federal lands in southern California provide many cultural ecosystem services, including cultural heritage values for significant species, locations, and landscapes; traditional values for the type of knowledge developed by cultures (box 6.5); and sense of place associated with recognized features of the environment (MEA 2005). American Indians in California have used plants found in chaparral ecosystems as a source of food, medicine, ceremonial items, clothing, material for baskets, and tools (Anderson and Keeley 2018). American Indian tribes chewed manzanita (*Arctostaphylos* spp. Adans.) leaves to relieve nausea and upset stomachs and drank manzanita tea to relieve diarrhea (Joye 2023).

Other Native tribes have used yerba buena (*Micromeria douglasii* (Benth.) Benth.) to treat parasitic worm infections (Reid et al. 2009). Tribes from the Palm Springs area used manzanita trunk wood for tools and used the stems of pointleaf manzanita (*A. pungens* Kunth.) for smoking pipes (EthnoHerbalist 2020). Native tribes in California have also made cooking baskets and water jugs from the

flexible deergrass (*Muhlenbergia rigens* (Benth.) Hitchc.) plant (Reid et al. 2009). Many of these tribes still practice traditional gathering and hunting that have been passed down from generation to generation. For example, tribes still make foods and drinks for guests at social events using chaparral plants such as California Mormon tea (*Ephedra californica* S. Watson), laurel sumac (*Malosma laurina* (Nutt.) Nutt. ex Abrams) berries, yerba buena tea, and manzanita cider (Anderson and Keeley 2018). These products are part of a landscape that has been inhabited for thousands of years (box 6.6) and contribute to the cultural values of the landscape.

People develop connections to specific locations or features of a landscape and develop a place attachment, place identity, or sense of place (Brown and Raymond 2007). For example, Brown and Raymond (2007) measured place attachment by asking participants to map special places where they found high values for aesthetic, wilderness, therapeutic, family connection, home, heritage, and spiritual qualities. Memories, experiences, interactions, and history play a role in people's attachment and cultural connections to the land. For example, Lewicka (2011) found that experience with an area and spending more time in the place intensified emotional bonds as well as more attachment.

The quality of viewsheds and aesthetics can serve as a proxy for many values. Forest aesthetics are considered in planning and management activities and often influence forest policies, such as by limiting the size of clearcut timber harvests (Gan and Miller 2001). In addition, visual quality of the landscape may influence human mental well-being (Kandziora et al. 2013). Furthermore, Franco et al. (2017) found that viewing nature provided benefits, such as reducing anxiety and stress, reducing the length

Box 6.6

Tribes in the Southern California Adaptation Partnership Assessment Area
Carbon dating places the earliest known settlements in Angeles National Forest at 7675 Before Present (5725 Before Christ) (USDA FS ANF 2025). In San Bernardino National Forest, two communities existed within the

current forest boundary: the Cahuilla in the Mount San Jacinto area, and the Serrano in the San Bernardino Mountains (USDA FS SBNF 2025). Today, Indigenous groups use the landscape to preserve cultural practices, traditions, and knowledge systems. For example, traditional burning practices and other land management practices facilitate the preservation of forest conditions (Lake 2007).

of hospital stays, and lowering heart rate. Individuals also received enjoyment from scenic viewshed access while recreating in natural settings.

Studies in the San Jacinto Wilderness Area (San Bernardino National Forest) showed that recreationists derived the greatest values for mountain peaks because peaks provide the best visibility and can be seen from several trails (Baerenklau et al. 2010, Sánchez et al. 2020). The visual benefits of air quality provided by natural landscapes in southern California were formally recognized in the legislation that authorized Santa Monica National Recreation Area (National Parks and Recreation Act of 1978). This act authorized the Secretary of the Interior to manage the recreation area to preserve and enhance its scenic, natural, and historical setting and its public health value as an airshed for the southern California metropolitan area, while providing for the recreational and educational needs of the visiting public.

Nontimber forests products (NTFPs) are products made from plant materials and fungi found in aboveground vegetation and forest soil. NTFP harvesters are diverse, coming from different cultural groups, social sectors, and generations (Chamberlain et al. 2018). NTFPs are collected for personal enjoyment, commercial gain, and cultural and spiritual importance. The Forest Service (USDA FS 2001) defines NTFPs as follows:

Products collected from National Forest System land that include, but are not limited to, bark, berries, boughs, bryophytes, bulbs, burls, Christmas trees, cones, epiphytes, fence material, ferns, firewood, forbs, fungi (including mushrooms), grasses, mine props, mosses, nuts, pine straw, posts and poles, roots, sedge, seeds, shingles and shake bolts, transplants, tree sap, rails, and wildflowers. Special forest products do not include animals, animal parts, cull logs, derrick poles, house logs, insects, minerals, non-saw log material removed in log form, pulpwood, rocks, sawtimber, small roundwood, soil, telephone poles, water, and worms.

A forest product permit is needed to collect some NTFPs from national forest lands, such as pinecones, manzanita, mushrooms, firewood, and seeds.

The Forest Service National Visitor Use Monitoring (NVUM) survey includes NTFP gathering as a recreational activity. Among the four national forests

surveyed in SOCAAP assessment area, NTFP gathering accounted for 0.29 percent of total visits (chapter 5). San Bernardino National Forest had the highest percentage of such visitation (0.6 percent) (USDA FS 2019), and Angeles National Forest had the lowest (0.04 percent) (USDA FS 2016). Some people do not consider NTFP gathering as a recreational activity, but as an activity that contributes to subsistence or spiritual values. Therefore, these categories may not be captured in NVUM data, thus underestimating the true value of NTFP harvest.

Effects of Climate Change

Climate change effects on cultural and heritage values could be substantial, more so in cases where access to places people value is diminished or lost. When a wildfire or other disturbance displaces people from highly valued places, or their cultural or historic site is destroyed, there is strong evidence that cultures are endangered or diminished (Adger et al. 2013). For example, the 2018 Woolsey Fire destroyed several cultural and historic sites, including the Sepulveda Adobe, an architectural landmark (one of the oldest structures was built in 1863) (Knight 2020). It was destroyed weeks before the long-awaited reopening (Malibu Creek State Park 2022). The same fire also destroyed much of the Paramount Ranch, a historic site that was used for film making and television production (Stromberg 2018). Substitutes rarely exist for unique sites that have distinctive cultural or historical importance, sense of place, or personal attachment that individuals or communities build over time.

Climate change negatively affects cultural practice, such as gathering, hunting, and human well-being (Díaz et al. 2019). American Indian communities could face disproportionate effects from climate change compared to other groups because of their proximity to ecologically sensitive regions, unique cultural and traditional ties to the land, strong connections to surrounding environments, and various socioeconomic factors. In addition, the decline of certain plant and animal species may endanger ceremonial items, which could lead to erosion of culture and tradition. For example, Mucioki et al. (2021) found that climate change would create uncertainty around access and harvest of culturally important foods by tribal members in the Klamath River Basin. Altered precipitation and higher minimum temperatures might increase variability in timing and abundance of food, fiber, and medicinal species of plants used for ceremonies and cultural practices.

Increased wildfire frequency and extent can influence vegetation through plant mortality, a shorter period of dormancy, and altered distribution of some species (Mucioki et al. 2021). Fire-return intervals for some locations in the SOCAAP assessment area are now less than 10 years (Keeley and Syphard 2018). More frequent fire can result in conversion from chaparral shrublands to nonnative grasslands leading to the loss of some habitats, altered plant biodiversity, and higher water runoff (Syphard et al. 2018). As a result, cultural food sources and ceremonial items may be more difficult to access or may no longer be available on the landscape.

Adaptative Capacity

Incorporating traditional ecological knowledge and cultural burning into land management practices can help forest management adapt to climate change. Cultural burning contributes to community livelihoods

by conserving landscape heterogeneity and resilience. Furthermore, the use of cultural burning can help improve the growth and production of edible aboveground (e.g., seeds and berries) and belowground (e.g., corms and rhizomes) plant parts, promote the growth of basket-weaving materials, reduce insects and pathogens on valued plants, and reduce surface fuels (Anderson and Keeley 2018). Collaboration among tribal governments, federal and state forest managers, and local communities is needed to improve forest management practices that address tribal needs and maintain cultural traditions. Long and Lake (2018) provide examples of successful collaborations between national forests and tribes that help forest managers understand which habitats, specific plants, and other natural resources are valued by tribes.

Summary and Conclusions

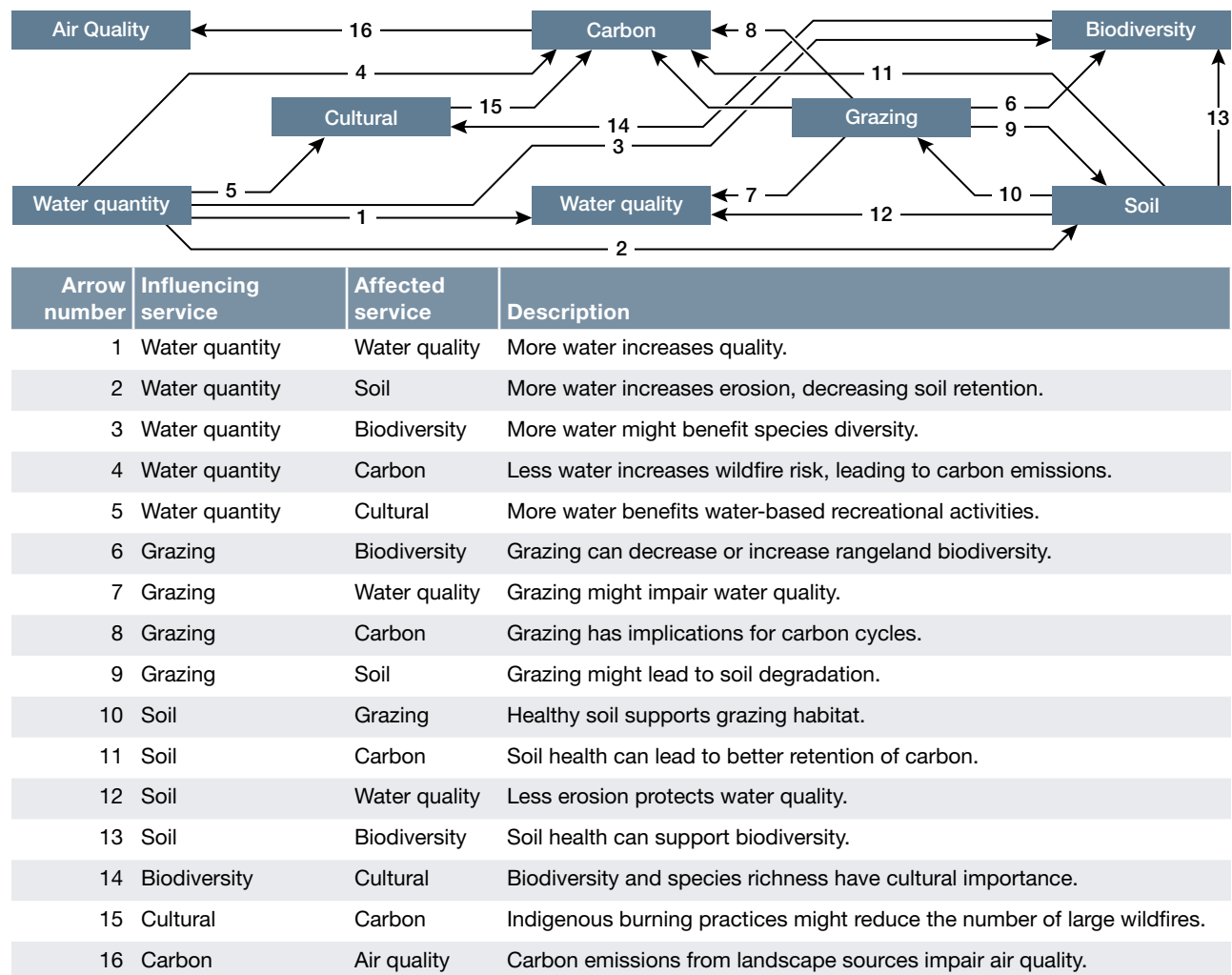


Figure 6.9—Conceptual framework of interrelations.

Ecosystem services are the benefits that people derive from natural functions and processes provided by the landscape. Federal lands that compose the SOCAAP assessment area provide many ecosystem services to many communities, ranging from local to global. In this assessment, we focus on carbon sequestration, clean air, cultural and heritage values, grazing, soil regulation, and water quantity and quality. Figure 6.9 shows the conceptual framework of interrelations between the different ecosystem services discussed throughout this chapter. The ecological condition of these landscapes, their susceptibility to fire, and their resilience to drought conditions or extreme precipitation and other disturbances, directly affect their ability to provide clean water,

carbon sequestration, and other ecosystem services.

From our review of the literature, together with analysis of the current knowledge of ecosystem services, we have identified important ways that climate change will likely affect the provision of ecosystem services. With increasing minimum temperatures and more variable precipitation events, we expect the provisioning of several ecosystem services to decline as the provisioning of other ecosystem services increase. Adaptation actions on federal lands can help to take advantage of any increases in the provisioning of ecosystem services, and they may help to reduce negative effects of climate change on valued ecosystem services (see chapter 7).

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Chapter 7: Adapting Infrastructure, Recreation, and Ecosystem Services in Southern California to Climate Change

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Introduction

Climate change is projected to affect forests across the United States (Vose et al. 2018), and climate change adaptation strategies aim to reduce negative effects and take advantage of positive changes (McCarthy et al. 2001). To prepare for the effects of climate change, resource managers working for the U.S. Department of Agriculture, Forest Service are required to integrate climate change science into land management planning (USDA FS 2012). In practice, climate change adaptation options are an integral component of effective land management under climate change.

Several frameworks have been proposed that help researchers and managers describe adaptation approaches. Two popular frameworks are Resistance, Resilience, Response, Transition (Millar et al. 2007) and Resist, Accept, Direct (Schuurman et al. 2020, Thompson et al. 2021). At one end of the spectrum, “resistance” or “resist” adaptation options encompass management actions that attempt to maintain ecosystem status quo (Millar et al. 2007, Schuurman et al. 2020). Similarly, resilience strategies focus on maintaining ecosystem conditions by building in capacity for ecosystems to rebound after climate change effects (Millar et al. 2007).

At the opposite end of the spectrum, “transition” or “direct” refers to management responses that aid ecosystem transformation to a desirable new condition (Peterson St-Laurent et al. 2021, Thompson et al. 2021). Ecosystems may also transform to a new condition if managers allow or “accept” climate change transformation with no management interference (Schuurman et al. 2020, Thompson et al. 2021). These strategies may be

used in tandem to manage different aspects of the same ecosystem (Thompson et al. 2021).

Ultimately, the most suitable climate change adaptation strategy for each situation will balance ecological, financial, and social feasibility to achieve success (Lynch et al. 2021). Adaptation strategies that fall in the resist/resistance, resilience, and transition/direct categories will likely require some active management and resources to accomplish, while those in the accept category will likely be less resource intensive. Some ecosystems are already moving beyond feasible implementation of resist/resistance options, suggesting that strategies resulting in higher levels of ecosystem change may become more favorable in the future (Lynch et al. 2021).

This chapter describes climate change adaptation options for infrastructure, recreation, and ecosystem services practitioners developed during a series of adaptation workshops. An overview of climate change effects and vulnerabilities provides context for these adaptation options. We provide documentation from these workshops as a scientific foundation for resource management.

Climate Change Vulnerability Assessment and Adaptation in National Forests

Climate change vulnerability assessments are central to climate change adaptation in the National Forest System (Timberlake and Schultz 2019). Since 2010, the Forest Service has completed 43 “climate change vulnerability assessments and adaptation partnerships,” a process designed to assess potential climate change effects and adaptation options across national forests (USDA FS 2022). Climate change vulnerability assessments and adaptation partnerships may vary to meet local needs, but they typically consist of four steps (Peterson et al. 2011):

1. Synthesize relevant local climate change science (review)
2. Determine the priority of identified local climate change vulnerabilities (rank)

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3. Develop and implement adaptation options (resolve)
4. Monitor the effectiveness of the adaptation options that have been implemented (observe) and adjust as needed

The Southern California Adaptation Partnership (SOCAAP) began in the summer of 2021. It is a partnership with Angeles, Cleveland, San Bernardino, and Los Padres National Forests; Santa Monica Mountains National Recreation Area; the Forest Service's Pacific Southwest Region; and Western Wildland Environmental Threat Assessment Center. For this assessment, regional priorities led to a focus on hydrology, infrastructure, recreation, and ecosystem services. The assessment complements the Sierra Nevada Climate Change Vulnerability Assessment and Adaptation Partnership (Halofsky et al. 2021) and furthers the objectives of the Forest Service, Pacific Southwest Region's Climate Change Integration Team to incorporate climate change science into regional management practices.

An effective adaptation workshop format must meet the specific needs and preferences of the stakeholders involved (Peterson et al. 2011), which in this instance primarily included the abovementioned partners. Therefore, a series of four climate change adaptation workshops were held in April 2022 to optimize stakeholder engagement. The first workshop reviewed vulnerability assessment findings, and the ensuing three workshops were centered on each of the three resource areas (i.e., infrastructure, recreation, and ecosystem services). The workshop that focused on infrastructure also included climate change effects on hydrology and hydrologic effects on infrastructure. The ecosystem services workshop included discussions on soil regulation, water quality and quantity, and biodiversity. During the resource-specific workshops, participants were encouraged to first identify high-priority climate change vulnerabilities, followed by adaptation strategies, or broad responses to the identified vulnerability (Peterson et al. 2011, Soderquist and Halofsky 2022). For each strategy, participants then discussed possible adaptation tactics, or specific actions that can be implemented by managers (Peterson et al. 2011, Soderquist and Halofsky 2022).

This chapter focuses on the adaptation options discussed during those workshops; resource area

chapters (chapters 4, 5, and 6) provide additional vulnerabilities and adaptation options. A full list of adaptation options described in other climate change vulnerability assessments can be accessed in the *Climate Change Adaptation Library for the Western United States* (Adaptation Partners 2019).

Overview of Climate Change Projections

The southern California region has a Mediterranean climate with hot, dry summers and mild, wetter winters. The ocean heavily moderates temperatures along the coast, with inland areas experiencing more extreme temperatures (Abatzoglou et al. 2009). The region has complex topography, which contributes to high microclimatic variability and transitions between ecosystems across short distances. In this section, we discuss general trends and projections in climate change effects; for a more complete discussion, see chapters 2 and 3.

Climate change is expected to lead to warming throughout southern California. Specific projections for the assessment area were generated using data from *California's Fourth Climate Change Assessment* (Pierce et al. 2018). Of the forests in the SOCAAP assessment area, San Bernardino and Angeles National Forests are projected to have the largest increase in mean annual maximum temperatures (9.4 °F; Representative Concentration Pathway [RCP] 8.5) by late century (2065–2099) compared to historical baselines (1961–1990). The smallest increases under RCP 8.5 are projected for Santa Monica Mountains National Recreation Area (7.9 °F) and Los Padres National Forest (7.8 °F) (chapter 2). There is high uncertainty around projected precipitation, with a slight decrease projected for most forests in the SOCAAP assessment area (chapters 2 and 3).

In addition to changes in climatic averages, the region is also expected to experience more extreme events. For example, the number of days with extreme heat is projected to rise, and extreme precipitation events may become more common. Southern California is also projected to experience an increase in drought conditions (Swain et al. 2018). Under most climate change scenarios, wildfire probability will increase in much of the SOCAAP assessment area (chapter 2). The hottest, driest climate scenarios are projected to increase burn probability across the entire region, particularly in the southernmost forests.

Additional factors may affect climate change vulnerability in southern California (chapter 2). Sea-level rise in coastal areas could reach 11.8–23.6 inches by 2050, leading to the loss of estuarine ecosystems. Changes in Santa Ana wind patterns, important drivers of fire events in the region, are uncertain. Changes in coastal fog patterns, which moderate coastal temperatures, are also uncertain. These considerations, and uncertainty associated with all climate change projections, can be accounted for in adaptation planning.

Overview of Infrastructure, Recreation, Ecosystem Services, and Associated Vulnerabilities

Infrastructure

Infrastructure includes any built environment or structure that helps maintain the desired uses and functions for the national forests and national recreation area. In the national forests, a substantial amount of infrastructure is already present, including 4,788 miles of roads, 41 road bridges, 39 dams, and more than 2,250 buildings and administrative sites. An additional 3,211 miles of trails, 44 trail bridges, 150 developed campgrounds, and 74 developed picnic areas provide recreation opportunities. Combined, the investment represented by this infrastructure is over \$1 billion (chapter 4). In addition to standard maintenance, these infrastructure resources may require modifications and repairs because of changes in extreme events and use patterns under climate change.

Wildfire is the greatest risk to forest infrastructure in the region (chapter 4). Fire is already common in southern California ecosystems and is driven by many factors, including the characteristic hot, dry summers, as well as Santa Ana winds and land-use patterns (Keeley et al. 1999, Langridge 2018, Syphard et al. 2007). Most climate change scenarios suggest that burn probability will increase throughout the region (chapter 2), making future fire risk a high priority when assessing infrastructure vulnerability. Most forest infrastructure is vulnerable to fire (e.g., culverts, timber bridges, signs), and recreation and administrative facilities are at particularly high risk of burning during fire events (chapter 4). Indirect effects from fire, such as increased runoff and erosion after a fire event, can damage roads, bridges, and culverts (chapter

4). Independent of fire, changes in extreme precipitation events (chapters 2 and 3) can lead to increased runoff and associated complications, such as washouts, plugging, overtopping, and erosion (chapter 4).

In addition to extreme events, a warmer, drier climate can affect forest infrastructure. For example, milder winters may lead users to access roads, trails, and campgrounds further into the shoulder seasons (spring and fall) (chapters 4 and 5). However, milder winters may also have some infrastructure benefits, including decreased costs for snow removal, and an extended construction season in places where snow might otherwise limit repairs and improvements (chapter 4). A drier future climate can also affect water resources and associated infrastructure, such as dams and campground water systems, and may require management of dust on roads and facilities (chapter 4).

Infrastructure resources play a crucial role in realizing the intended use and function of federal lands. These resources are particularly vulnerable to extreme events that will likely increase in frequency with changing climate. Adapting forest infrastructure will be necessary to reduce negative climate change effects and facilitate continued recreation opportunities and ecosystem services (chapters 5 and 6).

Recreation

The management units in this assessment provide 7.8 million recreation visits per year, which are valued at more than \$500 million by recreationists (chapter 5). Most visitors are from the local area and live within 50 miles of the national forests and within 35 miles of the national recreation area (chapter 5). In the national forests, recreation sites include day- and overnight-use areas, wilderness areas, viewing corridors (e.g., roads and other travel corridors), and other general forest areas such as trailheads (English et al. 2002). Most recreational visits (86 percent) are warm-weather oriented, with hiking, walking, and cycling being the most popular (chapter 5). Although snow is limited to high elevations in the assessment area, snow-based recreation, such as skiing and snowmobiling, are popular cold-weather activities (chapter 5). Los Padres National Forest and Santa Monica Mountains National Recreation Area both have coastline with recreational beach opportunities (chapter 5).

Recreation in southern California faces several vulnerabilities related to climate change, including changing recreation patterns, changes in user satisfaction, and increased risk to recreationists in some cases. Higher temperatures (chapter 2) could result in higher demands for shady places and water-based recreation activities (chapter 5). Increasing temperatures will also lead to an extended warm-weather recreation season, providing some users with year-round recreation opportunities (chapter 5). Increased temperature and changing precipitation patterns will likely influence winter recreation activities. Both snowpack and snow-residence time are expected to decrease in the SOCAAP assessment area (chapter 3), and less predictable snow events may leave forest staff unprepared for unexpected influxes of recreationists (chapter 5). In some cases, recreation sites may need to be closed following extreme events, such as floods or wildfires, resulting in altered use patterns.

In addition to changing use patterns, climate change may affect user satisfaction and user safety. Some vulnerabilities include degraded views from smoke during wildfire events and a perception of overcrowding due to high use from increased visitation (chapter 5). However, some climate change effects may lead to increased user satisfaction, including wildflower blooms following extreme precipitation (chapter 5). In some cases, user risk may also increase as extreme precipitation events, extreme heat, and fire become more common (chapters 2 and 5). For example, an increase in the number and intensity of extreme precipitation events can lead to flooding (chapters 2 and 3), resulting in increased user risk during water-based recreation (chapter 5). Recreation opportunities are an important resource in southern California, and adaptation strategies can help maintain user safety and satisfaction in a changing climate.

Ecosystem Services

Ecosystem services are most broadly defined as the benefits people derive from ecosystems (MEA 2005). Participants in the adaptation workshop series identified water quality and quantity, soil regulation, and biodiversity for discussion, and thus we focus on these ecosystem services in this chapter. However, additional consultations with staff from the four national forests and the national recreation area identified grazing; carbon sequestration; air quality/pollution abatement;

and cultural, traditional, spiritual, and heritage values as other critical ecosystem services. See chapter 6 for further discussion of these additional ecosystem services.

Southern California is semiarid with areas of high population density, so water availability and quality are vital. Water in the region is mostly used for domestic, agricultural, and industrial purposes, with smaller amounts used for mining, power generation, and aquaculture (chapter 6). The assessment area is projected to experience an increase in droughts and more erratic precipitation (chapter 2), potentially disrupting the provisioning of adequate quality and quantity of water resources (chapter 6). For example, water quality can be reduced by drought, which can lead to higher concentrations of water pollutants (Mosley 2015), and by heavy precipitation, which can cause soil erosion. In addition, the potential for increased wildfire (chapter 2) could negatively affect water quality as a result of increased runoff with subsequent precipitation events (chapter 6).

Workshop attendees also identified continued provisioning of soil regulation as a high-priority ecosystem service. Soil regulation is important both for reducing landslides and reducing erosion that negatively affect water quality. Much of southern California has highly erodible soils (chapter 6). Soil erosion is linked to precipitation events (Underwood et al. 2019), and more erratic and extreme precipitation events are projected throughout the SOCAAP assessment area (chapters 2 and 3). Erosion may also be worsened by fire events that remove vegetation, and the associated roots that absorb water and hold soil in place (chapter 6). These fire events may also promote vegetation changes (chapter 2) that exacerbate erosion (Underwood et al. 2019).

Many native ecosystems in southern California contribute to high levels of biodiversity (chapters 2 and 6). In addition to being important for recreation resources (chapter 5), biodiversity may also be important in maintaining ecosystem stability and function in a changing environment (Loreau and de Mazancourt 2013). Each national forest is home to at least 15 threatened, endangered, or sensitive species, and Santa Monica Mountains National Recreation Area contains habitat for 50 threatened, endangered, or sensitive species (chapter 6). A large percentage of high-biodiversity areas, particularly at high elevations, are at risk of increased water stress (Underwood et al. 2019) that could negatively

affect some species. Additional climate change effects on biodiversity include altered life history, range shifts, and species interactions, including the spread of invasive plants, insects, and pathogens (chapter 6). These stressors may also interact, leading to exacerbated negative effects on biodiversity.

Vulnerabilities Across Resource Areas

The resource areas addressed in this assessment are interconnected, with components of each integral to the use and function of the others. Infrastructure (e.g., roads and bridges) is needed for visitors to access most aspects of recreation. Other types of infrastructure (e.g., trails and campgrounds) are the basis of some forms of recreation, such as hiking and camping. In addition, recreation is a type of cultural ecosystem service (MEA 2005). Infrastructure is also required for the provisioning of many ecosystem services, such as reservoirs that support water supplies (chapters 4 and 6). Roads and reservoirs may also offer recreation opportunities (chapter 5).

The interconnectedness of the resource areas also means they share many of the same climate change vulnerabilities; for example, changes to extreme events (chapter 2) can affect infrastructure, recreation, and ecosystem services. Flooding can damage infrastructure, such as roads and bridges, and recreation areas, such as trails and campgrounds. These areas are often located near streams or in floodplains, putting them at risk for flood effects. Streams and floodplains are also important for the continued provisioning of water resources. Wildfire is a common vulnerability across resource areas, as fire events can close recreation areas, damage infrastructure, increase runoff that causes soil erosion and degrades water quality, and release carbon stored in vegetation biomass. Increasing temperatures and number of extreme heat days (chapter 2) will likely also affect all resource areas. For example, demand for recreation in shaded areas and near water resources will likely increase (chapter 5), and this increased visitation could burden current infrastructure or sensitive biodiversity resources in these areas. Visitors will also require access to drinking water, a high-priority ecosystem service in the SOCAAP assessment area.

For this assessment, we discuss each resource area separately to take advantage of subject-matter expertise by resource managers. In addition, each resource is often

managed separately within management units. However, addressing climate change vulnerabilities will often require a holistic approach that considers effects across resource areas.

Adaptation Options for Infrastructure

During the workshops, attendees identified high-priority climate change effects on infrastructure that result from extreme fire and altered precipitation events, both of which can result in direct and indirect effects. Direct effects damage infrastructure, whereas indirect effects may increase risk to infrastructure or affect natural resources that, in turn, reduce the function or capacity of infrastructure.

Adapting Infrastructure to Fire

Of major concern are direct effects of wildfire events on facilities, including damage to housing units, administrative buildings, vault toilets, campgrounds, and ranches. Adaptation options for this vulnerability focus on increasing resistance to fire damage on current structures, including hardening (using materials resistant to ignition) and increasing defensible space (areas around a structure with minimal vegetation or other combustible materials) (table 7.1). However, even structures built and managed with these precautions may be at risk of damage from wildfires (Syphard and Keeley 2019). An alternative adaptation option is to relocate high-priority, high-risk facilities to new locations where they will be less vulnerable.

Indirect effects on infrastructure from fire events include increased runoff, erosion, and landslides in some cases (chapter 4). Areas within, downstream, or downslope from burn scars with vegetation loss and hydrophobic soils are particularly at risk. Prominent examples of recent fire events in this region are the 2020 Dolan Fire and 2018 Thomas Fire that caused significant damage to nearby infrastructure after subsequent high-rainfall events (chapter 4). Although participants did not explicitly discuss runoff and erosion in the context of fire during the adaptation workshops, adaptation strategies used to address these vulnerabilities are similar to those used for mitigating effects from extreme precipitation events (see below).

Table 7.1—Adaptation options for infrastructure in the Southern California Adaptation Partnership assessment area

Sensitivity to climate change	Adaptation strategy	Adaptation tactics
Wildfires can cause damage to facilities, including housing units, administrative buildings, vault toilets, ranches, and campgrounds.	Increase resilience of infrastructure and existing facilities to fire.	Modify existing buildings and facilities using hardening techniques. Remove vegetation from building perimeters; build structures in areas with defensible space. Relocate facilities to areas less susceptible to fire.
Increased magnitude of short-duration storms can cause erosion and subsequent channel widening.	Promote resilience of streambanks to erosion.	Build flexibility into structures so they can be modified under changing conditions. Build infrastructure in places where channel mobility or migration is less likely to occur, rather than on alluvial fans. Increase the use of bridges versus low-water crossings. Perform geomorphic studies of sites to ensure bridges and fords are large enough to be resilient to new conditions. Implement buffers in adjacent riparian areas.
Precipitation changes can reduce water availability and quality at campsites and downstream locations.	Consider methods to buffer water availability and storage.	Evaluate future water trends and supplies. Improve runoff storage and make water more available for human consumption. Enable settling of alluvial material in strategic places. Implement water conservation measures, such as decreasing use and demand via signage, special use permits, and public education.
Shifts in precipitation patterns and associated flooding can damage recreation facilities near streams and drainages	Make recreation sites less vulnerable; identify vulnerabilities in advance.	Implement channel improvements and modify channels to redirect flow. Move campsites upslope to less flood-vulnerable locations. Control the timing of facility use based on high-risk seasons and forecasted events. Harden sites to be more resilient to erosion and scour. Conduct debris flow and hazard analysis. Conduct watershed management and restoration postfire. Use an early warning system to notify visitors of forecasted hazards and storms.

Adapting Infrastructure to Changes in Precipitation

Workshop participants identified direct effects of flooding associated with extreme precipitation events as a major vulnerability to climate change (table 7.1). Bridges, culverts, roads, and campgrounds, particularly those located near streams and channels susceptible to erosion, are at high risk during flood events. Channel modification and improvement projects were identified as adaptation options that could help mitigate erosion effects and would likely need to be implemented in degraded areas. Other adaptation options include modifying the built structures affected by high-water events, such as low-water crossings, bridges, and culverts, to withstand possible future conditions; moving crossings is another option. Infrastructure designed to encourage the settling of debris flow in strategic locations would also be beneficial. For these projects, high-priority sites include those

that have experienced past damage. Stakeholders also suggested that additional research to assess whether current and proposed structures would withstand future conditions could also help improve adaptation planning.

Workshop participants also identified indirect effects of projected drought and unpredictable precipitation events (chapters 2 and 3) as high-priority vulnerabilities for infrastructure. Top concerns included potential effects on availability and quality of water resources (table 7.1), especially in inland areas that lack the moderating effects of coastal fog (chapter 2). Participants determined that further evaluation of future water trends and supplies would be valuable for adaptation planning. Adaptation options to mitigate water shortage included modifying or building infrastructure to store water runoff generated during times of high precipitation and developing signage and education programs to promote responsible and strategic water use by visitors.

Adaptation Options for Recreation

When identifying recreation-based climate change vulnerabilities, resource managers and stakeholders identified two broad categories: changing temperature baselines and extreme-climate events. Both factors could alter user demand, satisfaction, and safety. To mitigate effects, stakeholders provided adaptation options to modify management and facilities and to help users modify their own behaviors. Here we discuss examples in each of these categories and adaptation options to address vulnerabilities.

Adapting Recreation to Changing Climate Baselines

Mean annual minimum and maximum temperatures are projected to increase across the SOCAAP assessment area (chapter 2). This will likely influence demand for warm-weather-based recreation opportunities, which are already popular (chapter 5). Visitation patterns may be extended during spring and fall, and even through winter

in some areas (chapter 5). In these cases, adaptation options include increasing the number of staff and the duration of their appointments to meet more year-round demand (table 7.2). Keeping some facilities open year round may require fewer resources because opening and closing facilities can be costly (chapter 5).

In addition to seasonal changes in visitation patterns, workshop participants identified an overall increase in demand for recreation activities as a key vulnerability, with emphasis on increased demand for recreation opportunities in shaded areas and areas in or around water (table 7.2). Adapting to this change will require more staff resources in some areas and potential use of permit and reservation systems in high-demand areas (table 7.2). In some cases, visitors might prefer a reservation system to maintain the quality of the recreation experience (Atzori 2020). Indeed, high-visitation off-road vehicle areas in the SOCAAP assessment area have already successfully implemented reservation systems (chapter 5), but access to reservation systems by all potential users can be an issue with this tactic (chapter 5). In addition, increased demand may bring novice users into management units.

Table 7.2—Adaptation options for recreation in the Southern California Adaptation Partnership assessment area

Sensitivity to climate change	Adaptation strategy	Adaptation tactics
Higher temperatures can result in increased demand for recreation opportunities.	Ensure sustainable outdoor recreation opportunities that meet social and ecological needs.	Ensure adequate staffing to meet high levels of demand. Provide education for novice users to ensure visitor safety and mitigate ecological effects. Implement permit and reservation systems where necessary. Provide shuttles and public transportation to recreation areas. Analyze data on use patterns to determine sustainability at current recreation sites; create sites at new locations if needed.
Decreased snow and erratic snow events can decrease snow-based recreation.	Ensure provision of snow-based activities where possible.	Manage snow-based recreation traffic using shuttles, local ordinances, and strategically placed parking areas. Use surveillance and enforcement systems to reduce driving in dangerous conditions. Provide education and outreach regarding snow recreation safety and recreation opportunities.
Higher temperatures can lead to higher rates of heat-related illness.	Support user resilience.	Increase the number of recreation opportunities in shaded areas. Increase the number of potable water resources, while maintaining current resources. Provide visitor education regarding heat-related illnesses. Close areas during extreme heat events. Modify pavement in recreation areas to be more resilient to heat and radiate less heat.
Extreme events can disrupt recreation opportunities.	Maintain the resilience of recreation opportunities.	Remove hazard trees after fire events. Require groups to complete an ignition mitigation plan before recreating. Direct people to other recreation opportunities in lower-risk areas.

In this case, adaptation options include providing education to users about appropriate activities that help protect ecological resources, and education about environmental hazards to protect user safety (table 7.2). Workshop participants also suggested that research on use patterns would help adaptation planning, as this information is needed to evaluate potential adaptation options (table 7.2).

Higher temperatures and altered precipitation patterns are projected to reduce snowpack and snow residence time (chapter 3); workshop participants were particularly concerned about an increase in erratic snow events and snow-based recreation by novice users inexperienced in assessing safe conditions (table 7.2). Maintaining snow-based recreation activities (skiing, tubing, sledding) where possible was considered a high priority (table 7.2). Adaptation tactics to ensure the provision of these activities include providing shuttles and transportation to reduce traffic and increase user access in areas where snow is persistent (table 7.2). Although providing alternate transportation may reduce traffic to the destination site, potential tradeoffs include traffic at the transit site and overuse at the destination site (Lawson et al. 2011, Spornbauer et al. 2022). To increase safety for novice users, adaptation options include providing education related to safe driving in winter conditions and identifying cold-weather hazards, such as hypothermia and frostbite (table 7.2).

Adapting Recreation to Extreme Events

Wildfires, extreme precipitation events, and heatwaves are likely to increase across much of the assessment area (chapter 2), leading to closures that affect recreation. For example, both fires and floods may require closures along California State Highway 1, which can influence access to recreation areas (chapter 5). Recreation areas, such as campgrounds, may also be closed before and after extreme events to ensure user safety and to assess and repair damage (chapter 5). Adaptation options to mitigate effects from closures focus on maintaining resilience of recreation opportunities (table 7.2). Removing hazards (e.g., hazard trees) quickly after events allows maintenance crews to access the area to conduct assessments and repairs (table 7.2). Alternate recreation opportunities, such as other parks or virtual tours, can also be offered to visitors during times of closure (table 7.2). Virtual tours may be sufficient to entice users to recreate once the

affected area reopens (tom Dieck et al. 2018). Offering alternative recreation opportunities during closures may help maintain user satisfaction and create resilience in recreational offerings.

Extreme events are also a threat to user safety. Adaptation workshop participants identified user safety during heatwaves as an important vulnerability. Indeed, high-heat days already pose a threat to recreationists in southern California (chapter 5), and the number of extreme-heat days is expected to increase throughout the SOCAAP assessment area (chapter 2). Closures during high-heat days is an adaptation tactic that can be used to promote user safety (chapter 5). In addition, workshop attendees suggested that increasing user resilience is an important adaptation tactic. For example, providing users with adequate water sources and natural or built shade structures can allow for safer recreation during high-heat days (table 7.2). Providing visitor education related to safe recreation is another adaptation tactic (table 7.2). User safety may also be threatened when extreme heat damages infrastructure such as roads (table 7.1, chapter 4), so modifying existing structures to withstand high heat will benefit both infrastructure and recreation.

Adaptation Options for Ecosystem Services

Ecosystem services in southern California encompass a range of provisions that include water quality and quantity, soil regulation, and biodiversity. During the workshops, participants identified vulnerabilities of these services to extreme climatic events. Changing climate baselines (i.e., average temperature and precipitation) were also identified as a major vulnerability for biodiversity. Here, we summarize and add context to the adaptation options that were considered for mitigating climate change effects on ecosystem services.

Adapting Ecosystem Services to Extreme Events

Extreme climatic events can disrupt the provisioning of ecosystem services. In the SOCAAP assessment area, projected increases in extreme precipitation events will likely increase soil erosion. This effect can be mitigated through the implementation of flood- and erosion-control methods. For example, American beaver-dam analogs have gained popularity for stream restoration in the

Western United States and can be used to reduce soil erosion along streambanks by reducing the rate of water flow (Pearce et al. 2021). Reducing cattle grazing in riparian areas (Fleischner 1994) and rerouting unpaved roads out of floodplain areas may also help reduce soil erosion (table 7.3). Restoring and maintaining the hydrologic function of springs, and maintaining water availability during drought events, can also benefit biodiversity (table 7.3). If roads and trails cannot be rerouted, they can be modified to disperse increased water flow while maintaining soil integrity (table 7.3). Because high rates of soil erosion can reduce water quality, mitigating climate change effects on soil erosion can help maintain the integrity of both soil and water resources.

Postfire vegetation loss and vegetation conversion can also lead to increased soil erosion and subsequent degradation of water quality. Adaptation options to resist high-severity fire may be implemented to mitigate these effects. For example, fire prevention programs implemented in major recreation areas and nearby communities may reduce fire ignitions (table 7.3). Fire suppression is also a viable adaptation tactic that can be used to resist ecosystem change. Managing for fire-resilient landscapes can include fuels management activities, such

as livestock grazing, prescribed fire, and mechanical removal of hazardous fuels (table 7.3). Adapting landscapes to be more resilient and resistant to vegetation conversion, particularly to invasive grasses following fire events, has the added benefit of promoting biodiversity (chapter 2) (table 7.3). Targeting these approaches in areas of high biodiversity or in municipal watersheds provides value-added adaptation options.

Adapting Biodiversity Conservation to Changing Climate Baselines

Biodiversity in southern California is vulnerable to changing temperature and precipitation baselines. One adaptation option for maintaining biodiversity is to increase resilience to climate stressors (table 7.3). For example, increasing resilience to water stress could include restoring hydrologic regimes and restricting use of water from aquifers so that water is more consistently available (table 7.3). Restoring native vegetation can have multiple benefits, including reducing the risk of high-severity wildfire, encouraging plant and pollinator biodiversity (Potts et al. 2010), and reducing existing stressors, such as invasive species. Restoration projects may include species reintroductions from populations

Table 7.3—Adaptation options for ecosystem services in the Southern California Adaptation Partnership assessment area

Sensitivity to climate change	Adaptation strategy	Adaptation tactics
Heavy precipitation from atmospheric river events can increase soil erosion.	Increase resilience through erosion control and managing water flows.	Restore meadows by raising groundwater level or installing flood-control features, such as beaver dam analogs. Restore floodplains to increase efficacy of sediment management. Stormproof roads and trails by engineering them to disperse water. Armor roads where concentrating water is unavoidable.
Increased wildfire occurrence can reduce water quality and quantity.	Support resistance and resilience to severe wildfires.	Encourage effective fuels management through mechanical treatments, prescribed fire, and grazing treatments. Prevent fires by educating users. Suppress fire starts in areas and under conditions where severe fire events may occur.
Temperature increases and extreme events can affect biodiversity and vulnerable species.	Increase resilience of current populations to stressors.	Restore duration of water availability through meadow and floodplain restoration. Restore and maintain the hydrologic function of springs. Increase native vegetation to improve pollinator habitat. Remove barriers to wildlife passage and increase habitat connectivity. Control invasive species. Reintroduce species of interest for conservation.

already adapted to new climate baselines (Havens et al. 2015, Prober et al. 2015).

Identifying and protecting existing movement corridors, or creating new movement corridors, may enhance overall habitat connectivity and provide species an opportunity to shift their ranges to track a changing climate (table 7.3). However, it is important to consider effects on local ecosystems when providing opportunities for these movements (Wallingford et al. 2020). For example, species that are abundant or have a large influence on ecological processes in their native ecosystems might have outsized or unanticipated effects in recipient ecosystems if corridors encourage movement.

Adaptation Options Across Resource Areas

Just as the three resource areas are connected and share climate change vulnerabilities, adaptation options will often help mitigate climate change effects across resource areas. For example, providing shuttles to accommodate increased user traffic may reduce the burden on associated infrastructure. Restoring hydrologic regimes to enhance the provisioning of water resources may benefit visitors by providing drinking water and water resources for recreation and wildlife. Closing recreation areas after extreme weather events to protect user safety may facilitate more efficient infrastructure repairs. In some cases, adaptation options for one resource area may negatively affect other resource areas. For example, building new infrastructure (e.g., a road) may create a barrier to movement along an existing corridor. Effective adaptation planning will consider both positive and negative interactions associated with adaptation options across resource areas.

Although we discuss adaptation options separately in this chapter, coordinating efforts across resource management disciplines will benefit adaptation implementation. Indeed, workshop participants often attended workshops associated with more than one resource area, underscoring the importance of an integrated approach for effective management. This type of collaboration across resource areas will also help efficiently use limited financial and human resources. Working with partners outside the Forest Service and U.S. Department of the Interior,

National Park Service systems will likely help resource managers create more holistic climate change solutions, as most resources do not end at the management area boundary. The workshops included participants from adjacent lands and various agencies, underscoring the need for climate change planning, and illustrating enthusiasm for cooperation in the region.

Conclusions

This SOCAAP climate change vulnerability assessment and the adaptation partnership for infrastructure, recreation, and ecosystem services produced adaptation options that address vulnerabilities across four national forests and one national recreation area. During the associated workshop series, adaptation strategies were developed as part of a collaborative science-management partnership. These strategies include many resistance options that would help priority natural and built areas avoid or withstand extreme events. The strategies also incorporate resilience options that would allow areas to return to use after a perturbation.

Because infrastructure, recreation, and ecosystem services are inherently connected, they share many of the same vulnerabilities. This interconnectedness also means they can benefit from many of the same climate change adaptation options. Working together across resource areas and boundaries can help resource managers in southern California create robust strategies to reduce the negative effects of climate change and help transition natural resources and organizations to sustainable conditions in a warmer climate.

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Chapter 8: Conclusions

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The Southern California Adaptation Partnership (SOCAAP) contributes to our understanding of climate change vulnerabilities and responses to potential climate change effects on federal lands in southern California that compose Angeles, Cleveland, Los Padres, and San Bernardino National Forests and Santa Monica Mountains National Recreation Area. This effort synthesized the best available scientific information to (1) assess climate change vulnerability for key resources of concern (infrastructure, recreation, ecosystem services), (2) develop recommendations for adaptation options, and (3) catalyze a collaboration of land management agencies and stakeholders seeking to address climate change issues. Furthermore, the vulnerability assessment and corresponding adaptation options provided information to support the national forests in implementing climate change objectives that the U.S. Department of Agriculture, Forest Service originally described in *National Roadmap for Responding to Climate Change* (USDA FS 2011) (chapter 1).

Relevance to Forest Service Climate Change Response Strategies

The SOCAAP assessment process is directly relevant to the Forest Service's climate change adaptation plan (USDA FS 2022). Information presented in this report is also relevant for other land management entities and stakeholders in the SOCAAP assessment area. Any organization can replicate and implement this process, and the adaptation options are applicable beyond Forest Service lands. As in previous assessment and adaptation efforts (Halofsky and Peterson 2017; Halofsky et al. 2011, 2018a, 2018b, 2019, 2021, 2022a, 2022b, 2024; Hudec et al. 2019; Raymond et al. 2014), a science-management partnership was critical to the success of the SOCAAP assessment. Those interested in using this approach are likely to be more successful if they pursue

a partnership as the foundation for increasing climate change awareness, assessing vulnerability, and developing adaptation plans.

Communication, Education, and Organizational Capacity

Organizational capacity to address climate change, as outlined in the Forest Service's *Climate Change Performance Scorecard* (2011–2016) (USDA FS 2010) and its successor, the *Climate Action Tracker* (USDA FS 2022), requires building institutional capacity in management units through information exchange and training for employees. Information sharing and education were built into the SOCAAP process through a virtual workshop in which (1) scientists presented results of the vulnerability assessment (effects of climate change on hydrology and infrastructure, recreation, and ecosystem services), and (2) resource managers and stakeholders developed adaptation options in response to climate sensitivities identified in the assessment. This hands-on approach allowed resource managers to both participate in the process and contribute directly to information and outcomes, thus increasing organizational capacity to address climate change in the future.

Partnerships and Engagement

Relationships developed through the SOCAAP process were as important as the products that were developed because these relationships build the partnerships that are the cornerstone for successful agency responses to climate change. We fostered a partnership among the Forest Service; U.S. Department of the Interior, National Park Service; and other stakeholders. This partnership will remain relevant for future forest planning efforts and restoration conducted by the Forest Service in collaboration with other partners and stakeholders. Working with partners enhances capabilities to respond effectively to climate change.

Climate change response is a relatively new and evolving aspect of land management, and the SOCAAP provided an opportunity for participants to effectively communicate their professional experiences with respect to climate change and resource management in a collaborative and supportive environment. The workshop was

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especially valuable because it covered a broad range of topics, and multidisciplinary group discussions resulted in conceptual breakthroughs across disciplines.

Assessing Vulnerability and Adaptation

The *Sustainability Scorecard* required Forest Service units to identify the most vulnerable resources, assess the expected effects of climate change on vulnerable resources, and identify management strategies to improve the adaptive capacity of national forest lands. The Forest Service's *Climate Action Tracker* (USDA FS 2024) required Forest Service units to report accomplishments in understanding and adapting to climate change effects as milestones for implementing climate-informed management and planning. This SOCAAP vulnerability assessment describes the climate change sensitivity of multiple resources, and adaptation options developed for each resource area can be incorporated into resource-specific management plans. Adaptation options will also be added to the *Climate Change Adaptation Library for the Western United States* (Adaptation Partners 2019).

Dialog among groups of resource managers and scientists identified management practices that are useful for increasing resilience and reducing stressors to various ecosystem components. Although implementing all adaptation options developed in the SOCAAP process may not be feasible, resource managers can draw from the options as needed. Some adaptation options can be implemented now, whereas some may become appropriate as climate change effects become more apparent. Others may require changes in management plans or policies.

Science and Monitoring

This report has identified information gaps and uncertainties important to understanding climate change vulnerabilities and management influences on vulnerabilities. These information gaps can help determine where monitoring and research would reduce uncertainties inherent in management decisions. We also identified current monitoring programs that provide information for detecting climate change effects and additional monitoring needs for some resources in the vulnerability assessment.

Working across multiple jurisdictions and boundaries

will allow SOCAAP participants to potentially increase collaborative monitoring on climate change effects and effectiveness of adaptation actions. Scientific documentation in the assessment can also be incorporated into large landscape assessments, such as national forest land management plans, environmental analysis for National Environmental Policy Act (NEPA 1969) projects, and specific project design criteria and mitigations.

Implementation

Although challenging, implementation of adaptation options will gradually occur with time, often motivated by extreme weather and large disturbance events, and facilitated by changes in policies, programs, and land management plan revisions. It will be especially important for ongoing restoration programs to incorporate considerations for climate change adaptation to ensure effectiveness. A focus on thoroughly vetted strategies may increase ecosystem function and resilience, while minimizing implementation risk. Land management agencies, American Indian tribes, and private landowners working together can facilitate effective implementation, particularly across boundaries.

Toward a Landscape Approach

In many cases, similar adaptation options were identified for more than one resource sector, suggesting a need to integrate adaptation planning across multiple disciplines. Adaptation options that yield benefits to more than one resource are likely to have the greatest benefit (Halofsky and Peterson 2017; Halofsky et al. 2011, 2018a, 2018b, 2019, 2021, 2022a, 2022b, 2024; Hudec et al. 2019; Peterson et al. 2011; Raymond et al. 2014). However, some adaptation options involve tradeoffs and uncertainties that need further exploration. Assembling an interdisciplinary team to tackle this issue will be critical for assessing risks and developing risk management options. Scenario planning may be a useful next step.

Information in this assessment can be incorporated into everyday work through climate-informed thinking, as well as assist planning and influence management priorities, such as public safety. Climate change may exacerbate both flooding and wildfires, increasing the frequency and extent of hazards to federal employees and the public, while affecting infrastructure, recreation, and ecosystem services. Resource management can help

minimize these hazards by restoring hydrologic function, reducing fuels, and modifying forest structure. These management activities are commonplace, demonstrating that, in many cases, current resource management is already preparing for a warmer climate.

Integration Across Resources

Within this report, climate sensitivities are discussed in separate chapters for each resource. In practice, these resources interact with one another in terms of biophysical function and management applications. For example, hydrologic resources are relevant for infrastructure (e.g., potential damage from flooding), recreation (e.g., people recreate on lakes and streams), and ecosystem services (e.g., water supply for human use). Thinking about and managing resources in an integrated fashion will likely provide a more effective understanding of climate change effects, as well as more effective and comprehensive management approaches.

For the adaptation options in this report, some of the resource areas share common climate change sensitivities. For example, water, infrastructure, and recreation are sensitive to postfire soil saturation that can lead to erosion and landslides. Higher temperatures and earlier snowmelt clearly affect multiple resources. Lower summer streamflow, increased disturbances, and change in timing of events are also prominent effects. Recognizing shared goals across multiple resource areas on an interdisciplinary or planning team can enhance organizational capacity to coordinate adaptation efforts.

Operations

Insufficient human resources, insufficient funding, and conflicting priorities may limit implementation of adaptation actions. However, climate-influenced effects are already apparent for some resource areas, such as altered hydrologic regimes. Some adaptation options may be precluded and resources may be compromised if actions are not implemented soon. This creates an imperative for timely inclusion of climate change considerations as a component of resource management and agency operations.

The Forest Service, National Park Service, and other organizations can use the climate change vulnerability assessment and adaptation approach developed by the

SOCAAP in many ways. From the perspective of federal land management, this information can contribute to the following aspects of agency operations:

- **Landscape and resource assessments**—The vulnerability assessment provides information on departure from desired conditions and best available science on climate change effects to resources. The adaptation options describe desired conditions and management objectives for inclusion in planning documents.
- **Resource management strategies**—The vulnerability assessment and adaptation options can be used in forest resilience and restoration plans, conservation strategies, fire management plans, infrastructure planning, and state wildlife action plans.
- **NEPA project analysis**—The vulnerability assessment provides best available science for documentation of resource conditions, climate change effects analysis, and development of alternatives. Adaptation options provide mitigations and project design recommendations for specific locations.
- **Monitoring plans**—The vulnerability assessment can help identify knowledge gaps that can be addressed by monitoring.
- **National forest land management plan revision**—The vulnerability assessment provides a foundation for understanding key resource vulnerabilities caused by climate change for the assessment phase of forest plan revision. Information from vulnerability assessments can be applied in assessments required under the Forest Service's 2012 Planning Rule (USDA FS 2012), describe potential climatic conditions and effects on key resources, and identify and prioritize resource vulnerabilities to climate change in the future. Climate change vulnerabilities and adaptation strategies can inform forest plan components, such as desired conditions, objectives, standards, and guidelines.
- **Project design/implementation**—The vulnerability assessment and adaptation options provide recommendations for mitigation and project design at specific locations.

We are optimistic that climate change awareness,

climate-informed management and planning, and implementation of climate change adaptation options in the SOCAAP assessment area will continue to evolve. We anticipate that the following will be accomplished within a few years:

- Climate change will become an integral component of federal agency operations.
- The effects of climate change on natural and human systems will be continually assessed.
- Monitoring activities will include indicators to detect the effects of climate change on a broad range of resources.
- Agency planning processes will provide more opportunities to manage across boundaries.
- Restoration activities will be implemented in the context of the influence of a changing climate.
- Organizational capacity to manage for climate change will increase within federal agencies and with local stakeholders.
- Resource managers will implement climate-informed practices in long-term planning and management.

This assessment provides a foundation for understanding potential climate change effects and implementing adaptation options that help reduce the negative effects of climate change and transition resources to a warmer climate. We hope that by building on existing partnerships, this assessment will foster collaboration in climate change adaptation and resource management planning throughout the SOCAAP assessment area.

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Metric Equivalents

When you know:	Multiply by:	To find:
Inches	2.54	Centimeters
Feet	0.305	Meters
Miles	1.609	Kilometers
Acres	0.405	Hectares
Tons	0.907	Tonnes

U.S. Standard Equivalents

When you know:	Multiply by:	To find:
Millimeters	0.0394	Inches
Centimeters	0.394	Inches
Meters	3.28	Feet
Kilometers	0.621	Miles
Hectares	2.47	Acres
Square meters	10.76	Square feet
Kilograms	2.205	Pounds
Tonnes	1.102	Tons

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