Chapter 6: Adapting Infrastructure and Recreation in the Sierra Nevada to Climate Change

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Introduction

Climate change is currently affecting ecosystems and natural resources in forest ecosystems across the Western United States (Dettinger et al. 2018, Halofsky and Peterson 2017, Wuebbles et al. 2017). To prepare for the effects of increasing temperatures and shifts in precipitation, resource managers working for the U.S. Department of Agriculture, Forest Service (USFS) are currently mandated to integrate climate change information into decisionmaking during land management planning (USDA FS 2012). Climate change adaptation, or taking actions to reduce risks from changing climatic conditions and prepare for the effects of future changes (Lempert et al. 2018), will be necessary to maintain resilient ecosystems and sustainable natural resources on National Forest System lands. Implementing effective climate-informed management actions across large landscapes will require increased coordination between federal and state agencies, nongovernmental organizations, industry partners, and private landowners.

This chapter describes adaptation options that were developed to support sustainable management for recreation and infrastructure resources on National Forest System lands across the Sierra Nevada. We provide background on key climate sensitivities and discuss adaptation options identified during each of the workshops. Although the adaptation strategies and tactics presented here are not an exhaustive list, they represent diverse high-priority climate sensitivities and actions that are relevant for the Sierra Nevada, and, in many cases, other regions of the Western United States.

Adaptation strategies and tactics were developed over the course of three, 1-day workshops held at locations in the northern, central, and southern Sierra Nevada. During each workshop, climate change sensitivities and stressors were reviewed for infrastructure (chapter 4) and recreation (chapter 5). These workshops were designed to build the capacity of resource managers to adapt to climate change by having a focused dialogue on regional climatic patterns and projections, projected climate change effects, and potential adaptive responses. Workshops were attended by resource managers from national forests, national parks, and state agencies, as well as representatives from conservation organizations, utility and water providers, and industry. The three workshops were attended by a total of 75 participants.

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Following the review of climate change effects, breakout groups for each resource area identified a series of high-priority climate sensitivities and supporting adaptation strategies and tactics through facilitated discussion and worksheet exercises adapted from Swanston et al. (2016). Adaptation options for each resource area were then presented to the rest of the workshop group, and steps toward implementing them in future planning efforts and project designs were

Table 6.1—Adaptation options for infrastructure in the Sierra Nevada

Sensitivity to climate change	Adaptation strategy	Adaptation tactic
Increasing wildfires will pose a greater risk to infrastructure and communities in the wildland-urban interface (WUI).	Increase awareness of fire ecology and fuels management to reduce risk.	• Expand fuel reduction programs and increase fire-resilient communities and structures. • Increase public communication, education, outreach, and real-time alerts on fire safety. • Increase postfire hazard mitigation and education. • Collaborate with local communities to develop improved zoning, land use planning, safety zones, and evacuation routes in WUI areas.
	Manage vegetation to reduce fuel loads and increase defensible space around facilities, WUI communities, and other vulnerable sites.	• Use prescribed burns and thinning to reduce fuel loading and increase forest resilience to fire. • Restore natural forest processes and conditions (e.g., regeneration, disturbance, landscape heterogeneity) where ecosystem characteristics fall outside the range of desired conditions.
Warming temperatures, extreme weather events, and disturbances will alter public access into vulnerable areas with limited infrastructure.	Establish or improve egress, evacuation routes, and safety zones.	• Identify evacuation routes and safety zones in vulnerable locations. • Identify alternate routes (e.g., when closures are in place) to avoid high-risk areas. • Improve public communication to increase awareness of risks and emergency response protocols. • Plan on increased stabilization of needed alternate routes.
Reduced snowpack and earlier peak streamflows can lead to water shortages in late summer.	Increase watershed resilience to increased or more variable runoff events.	• Increase offstream water storage capacity (water outside river channels, water transported via irrigation canal networks). • Increase groundwater recharge in headwater/upper elevation watersheds. • Conserve and manage water storage for prolonged drought conditions.
	Increase management flexibility and reduce risk exposure when considering infrastructure use, construction, and maintenance.	• Control access and timing of use on vulnerable infrastructure. • Develop additional and more flexible maintenance options. • Relocate and improve access points and plan for increased access in the future (e.g., higher elevation sites where snowpacks are reduced). • Increase forecasting and monitoring programs to improve predictions of runoff volume and timing.

discussed. The adaptation strategies and tactics presented in this chapter reflect the responses from the three adaptation workshops (tables 6.1 and 6.2). As a result, certain adaptation approaches may be emphasized relative to others. For a more comprehensive overview of additional adaptation options, readers should refer to chapters 4 (infrastructure) and 5 (recreation).

Sensitivity to climate change	Adaptation strategy	Adaptation tactic
Climate change effects will occur across management boundaries, straining already limited resources for site and infrastructure maintenance.	Increase awareness of the need for an "all lands" approach to climate change adaptation.	• Increase public education and outreach around shared stewardship and collaborative land management. • Use the incident command structure to create rapid-response teams to respond to disturbances or extreme events. • Identify and prioritize high-value assets/ investments at risk of climate change effects.
Increasing tree mortality leads to more hazard trees.	Reduce safety risks associated with hazard trees.	• Limit access to high tree-mortality areas until hazard trees are removed. • Remove hazard trees near critical infrastructure and facilities, ingress/egress points, and transportation/utility corridors. • Preserve quality of developed recreation sites (e.g., build shade structures) by changing design features and managing user expectations.
Increased flooding from extreme precipitation events or increasing rain on snow events can damage infrastructure.	Incorporate future conditions into project design.	• Adjust infrastructure design to account for shifts in runoff and precipitation type (e.g., upsize culverts, change construction material). • Reassess recurrence intervals and risk levels for established infrastructure design, and define uncertainties in terms of climate change projections. • Stabilize and reinforce soils along streambanks and near crossings where higher streamflows can damage roads, bridges, and culverts. • Relocate vulnerable roads and infrastructure away from channels.
Shifting streamflows and increased winter rainfall will lead to increased debris movement (e.g., sediment and logs) in streams and channels.	Design infrastructure to withstand larger streamflow events and debris loading.	• Increase vegetation cover to slow water flow and decrease erosion. • Improve drainage structures to prevent concentration and displacement of water. • Install trash racks, do channel maintenance, and armor eroding streambanks. • At problematic culverts, consider a ford. • Restrict or control access to high-risk areas (via road and trail closures) to improve vegetation establishment and improve public safety.

Table 6.2—Adaptation options for recreation in the Sierra Nevada

Sensitivity to climate change	Adaptation strategy	Adaptation tactic
Increased tree mortality from fire, drought, insects increases hazard, damages infrastructure, and reduces landscape aesthetics and quality of visitor experiences.	Increase resilience of social recreation infrastructure to increasing disturbances.	• Mitigate risks (e.g., remove hazard trees). • Expand communication of current conditions, user expectations, and alternative sites. • Create and maintain climate-adaptive infrastructure (e.g., install shade structures). • Establish fast-growing tree species after disturbance to provide shade on recreation sites.
	Improve hazard response protocols.	• Communicate risks associated with climate change and potential responses to hazards. • Collaborate with first responders to increase visitor safety and response protocols. • Actively manage recreation resources to reduce risk exposure.
Warming temperatures and decreasing snowpack will lead to shifting recreational seasons and patterns of use.	Adjust staffing and management during variable shoulder seasons to accommodate changes in seasonal access and recreation locations.	• Leverage local partnerships to help manage recreation facilities. • Pursue additional funding and partnerships to increase staffing and maintenance capacity. • Provide or increase housing and other resources for seasonal employees.
	Adjust visitor management policies and practices to increase management flexibility and facilitate transitions to meet user demands and expectations.	• Integrate projected recreation shifts into resource planning efforts. • Develop infrastructure design and maintenance plans to sustainably accommodate increasing visitor demands. • Identify potential carrying capacity thresholds and incorporate them into management plans and projects.
Climate change may increase the closure of recreation sites due to staffing shortages, disturbances, extreme weather events, safety issues, and higher maintenance costs.	Increase resilience of recreation sites to changing conditions and/or increased demand to continue providing recreation opportunities.	• Identify substitute locations to manage use and user overflow; improve reservation flexibility and transfer protocols. • Develop a communication plan (internal, external) with respect to contingencies and protocols for openings/closures in order to manage expectations. • Rotate use of recreation sites to minimize degradation.
Warming temperatures and decreasing snowpack will alter the elevation and timing of recreation use.	Increase capacity to anticipate and respond to shifting seasonal recreation patterns.	• Increase staffing capacity in areas where visitation increases. • Increase cross-boundary collaboration to improve access to recreation sites. • Monitor use and mitigate over-use. • Provide transportation alternatives to reduce congestion.

Sensitivity to climate change	Adaptation strategy	Adaptation tactic
Changing habitat conditions and decreased connectivity can lead to increased wildlife-human interactions.	Reduce human-related pressures and increase wildlife habitat connectivity.	• Improve wildlife habitat by reducing nonnative and invasive plants. • Increase habitat connectivity by restoring degraded sites in key areas. • Use wildlife-deterrent systems near facilities and infrastructure to minimize encounters with humans. • Increase public education and outreach about wildlife, habitat connectivity, and climate change.
Climate change can result in increased wildfire and smoke problems that reduce recreation opportunities and create health issues.	Increase management flexibility and anticipate fire-related effects at a regional scale.	• Create contingency plans for unexpected shifts in recreational use and timing. • Support research on alternative activity selection by recreationists. • Establish thresholds and protocols for site closure due to air quality or health concerns.
	Standardize and unify cross-agency communications.	• Increase communication across agencies to support consistent messaging. • Develop better public communication tools for real-time updates on disturbances, site conditions, and recommended responses to mitigate risks. • Work with interagency and non-governmental partners to increase outreach to clients and specific users.
Increasing tree mortality creates more hazard trees.	Reduce safety risks associated with hazard trees.	• Limit access to high tree-mortality areas until hazard trees are removed. • Remove hazard trees near critical infrastructure and facilities, ingress/egress points, and transportation/utility corridors. • Preserve quality of developed recreation sites by changing design features (e.g., build shade structures in areas that may experience extreme heat or tree mortality).
Climate change stressors reduce resilience of iconic places and recreational opportunities.	Manage iconic places for resilience using an interdisciplinary approach to provide recreation opportunities.	• Increase resilience of iconic sites by reducing human impacts (e.g., reduced visitation, installing boardwalks). • Communicate and collaborate across management boundaries and land ownerships, and improve communication about recreation alternatives that provide similar recreational or cultural experiences. • Increase education and outreach about other recreation options, changing conditions, and collaborative stewardship.

Climate Change Adaptation on National Forest Lands

Climate change adaptation consists of four general steps: (Peterson et al. 2011):

- Synthesize and review current climate change science and integrate this information with local management and social conditions and contextual factors (review).
- Evaluate climate change sensitivities, future climate exposure, and adaptive capacities for key ecosystems or natural resource areas (evaluate).
- Develop and implement adaptation options (resolve).
- Monitor the effectiveness of adaptation actions (observe) and adjust as needed.

Information from each of these steps is often integrated into climate change vulnerability assessments that describe the exposure, sensitivity, and adaptive capacity of natural resources.

Vulnerability assessments are often synthesized as reports, decisionmaking tools, or peer-reviewed publications designed to support science-based resource management and decisionmaking (Timberlake and Schultz 2019). Adaptation options developed during the assessment process describe specific actions that can be taken in response to climate change stressors to increase the resiliency of natural resources, ecosystems, and natural processes to changing climatic conditions (Peterson et al. 2011). Adaptation options vary in their scope and specificity, whereas **adaptation strategies** are first identified in response to a climate change vulnerability for a specific resource or ecosystem. These strategies typically have a broader focus conceptually and geographically and are often associated with management planning efforts.

To support adaptation strategies, managers identify **adaptation tactics**. Tactics are more targeted and prescriptive actions implemented to improve resilience to climate change at a particular location. Tactics are typically associated with efforts taking place at the project level. Climate change adaptation actions developed as strategies and tactics can range from small adjustments to significantly revised management practices (e.g., upsizing a new culvert on a flood-prone stream) to extensive, long-term projects (e.g., development of new recreation infrastructure to support year-round recreation).

Previous vulnerability assessments conducted across the Western United States (Halofsky et al. 2018a, 2018b), and in the Sierra Nevada specifically (Kershner 2014), have primarily focused on a variety of resource areas including forest vegetation, aquatic ecosystems, water resources, and ecosystem services. There is growing awareness that public lands and the built infrastructure on them are critical for recreational opportunities (Hand et al. 2018). Climate change is interacting with infrastructure networks and growing recreational demands to create management challenges that deserve specific attention.

The Sierra Nevada provides an opportunity to concurrently assess the effects of climate change on recreation and infrastructure. With continued warming, significant shifts in hydrologic processes and snow-water resources are projected across the Sierra Nevada (chapter 3). These climate change effects will occur as populations grow and recreation increases (chapter 5). The vulnerability of key recreation and infrastructure resources was assessed in the previous chapters to help inform resource managers as they prepare for both climatic and socioecological changes across the region (chapters 4 and 5).

This climate change vulnerability assessment is unique in its focus on recreation and infrastructure. By assessing the vulnerabilities of two interconnected resource areas, the assessment team was able to increase the focus of the overall assessment to synthesize the most relevant climate change information, so that specific adaptation options could be developed in response to climate change stressors. The vulnerability assessment was initiated and developed through a science-management partnership with recreation managers and engineers across the Sierra Nevada. Through these partnerships, the assessment team (1) synthesized the best available regionally focused climate change science, (2) assessed regional and forest-level climate change vulnerabilities, (3) collaboratively developed locally relevant climate change adaptation options with managers and stakeholders, and (4) integrated those adaptation options into a spatially explicit and peer-reviewed assessment for the entire Sierra Nevada region (chapter 1), (fig. 1.1).

Overview of Climate Change Effects in the Sierra Nevada

The Sierra Nevada has a Mediterranean climate, with approximately 80 percent of annual precipitation falling during the winter months, with total incoming precipitation exhibiting high interannual variability across the region (chapter 2). Because the precipitation regimes of this region are winter dominated, precipitation predominantly falls as snow at higher elevations where temperatures are cooler. Water resources used by a large proportion of the state are generated from mountain snowpacks accumulated on national forest lands (Belmecheri et al. 2015, Dettinger et al. 2018).

Owing to the strong seasonality of incoming precipitation, current transportation infrastructure, hydroelectric networks, and recreational resources across the Sierra Nevada are coupled with hydrologic processes and fluctuations (chapters 3, 4, and 5). Roads and other infrastructure on national forests provide access to recreational opportunities across all seasons. Recreational demand and outdoor recreation economies are increasing with growing populations in California (chapter 5).

With projected warming temperatures and more intense precipitation events, higher demand for public access in national forests may coincide with increasing occurrence of floods, landslides, and fire hazards (chapters 3 and 4).

Shifting hydrologic conditions driven by warming temperatures will have complex effects on the function of Sierra Nevada forest ecosystems (chapter 3). However, shifts in precipitation type or phase (i.e., rain or snow) will be one of the most direct and widespread effects of warming temperatures on regional hydrologic regimes. Shifts in precipitation regimes from snow-dominated to rain-dominated will significantly reduce snowpack storage capacities, alter the timing and magnitude of streamflow, and alter the timing of soil moisture inputs and availability later in the summer (chapter 3). Overall, the amount of water stored in snowpacks across the Sierra Nevada is projected to decrease by 60 percent by the end of the 21st century (Dettinger et al. 2018), with middle elevations experiencing the biggest losses.

As precipitation regimes become increasingly rain-dominated, there will be subsequent changes in the timing and amount of streamflow (Regonda et al. 2005, Schwartz et al. 2017) (chapter 3). Large advances in the timing of spring streamflows are projected to follow earlier snowmelt, with peak flows occurring as much as 1 to 2 months earlier in streams across the Sierra Nevada by the end of the 21st century (chapter 3). With rainfall events occurring more frequently during the winter, the number of large winter streamflow events will also increase (Das et al. 2011). Earlier and larger spring streamflows will potentially lead to prolonged and lower summer low flows for many streams that deliver water resources and support aquatic ecosystems.

Shifts in hydrologic regimes can also affect disturbance regimes in forest ecosystems. Drier atmospheric conditions resulting from increased air temperatures can accelerate soil moisture use and increase drought stress in water-limited ecosystems. Trees have physiological limits to the amount and duration of drought stress they can tolerate, with some drought-intolerant species experiencing mortality in response to more severe drought, insects, and subsequent disturbance events like wildfire (Allen et al. 2010, Anderegg et al. 2015, Westerling et al. 2006).

Climate Change Effects on Infrastructure

Infrastructure on national forests provides access to a variety of natural resources and supports the use of many ecosystem services and recreational opportunities. The 10 national forests in the Sierra Nevada contain a combined 26,500 mi of roads, 9,300 mi of trails, 684 bridges, 169 dams, over 4,100 buildings and administrative sites, and over 50 campgrounds. Total infrastructure investments for facilities alone have an estimated value of $750 million (chapter 4). Many of the current transportation, water resource, and facility infrastructure networks are a legacy of a century of natural resource extraction, recreation, and human settlement. The primary use of infrastructure resources has shifted in recent decades toward increasing recreational use (chapter 5). However, the combined effects of increasing use, aging infrastructure design, and changing climatic and hydrologic conditions are increasing the vulnerability of infrastructure and increasing risk for users.

The vulnerability of transportation and water allocation infrastructure to climate change and extreme events is a concern for forest, recreation, and water resource managers in the Sierra Nevada (chapters 3, 4, and 5). Infrastructure can be affected by direct climate change effects, increased climatic variability (e.g., precipitation timing, extreme temperatures, drought severity and duration) and indirect climate change effects such as increased fire and insect outbreaks. Infrastructure networks are interrelated with other resource management programs, and the vulnerability of infrastructure to climate change can influence access to and quality of other natural resources and ecosystem services (e.g., recreation). For example, many of the extensive road networks in the Sierra Nevada have been constructed in complex terrain where the risk of disturbance and natural hazards is high, and maintenance and repairs are difficult and costly. Some transportation infrastructure may become nonfunctional or unsustainable, given its age, outdated design, increasing usage for recreation, and vulnerability to hydrologic changes (Black et al. 2012, Luce and Black 1999).

Water resource infrastructure, including dams and reservoirs, stores water, reduces flooding, and provides recreational opportunities (chapter 5). Future changes in timing, type (rain vs. snow), and amount of precipitation will create challenges when storing and allocating water for irrigation, flood prevention, and energy production (chapter 3). Innovative adaptation solutions will be needed to address climate change stressors, including an expanded spatial scale of management actions (especially in highly vulnerable landscapes) and coordination among resource management programs.

Climate change will affect infrastructure over short and long time scales. Extreme events occurring over the course of several hours to several weeks often cause the most significant damage or are the most disruptive to operations. For example, roads, bridges, and culverts are susceptible to increased runoff during storm events and failures resulting from washouts, plugging, overtopping, stream diversion, and scour (chapter 4). However, long-term climatic patterns that affect infrastructure over the course of multiple decades—altered freeze-thaw cycle, timing and length of suitable construction weather, and snowmelt and stream hydrology—can also affect the sustainability of transportation, recreation, and water resource infrastructure. Population growth and changes in infrastructure use and demand will also affect the sustainability of built infrastructure in the Sierra Nevada.

Climate Change Effects on Recreation

The Sierra Nevada supports the largest outdoor recreation economy in California owing to its extensive recreation opportunities and proximity to nearby population centers (chapter 5). Recreation opportunities are available every season of the year across the region and are enjoyed by users who travel from throughout the United States and beyond. With increasing recreation demands over the past several decades, smaller rural communities in the Sierra Nevada have grown seasonal economies that depend on recreation visitation and expenditures.

Altered temperature, precipitation, water resources, and seasonality of weather conditions will affect evolving recreation patterns in the Sierra Nevada over the course of the 21st century (chapter 5). Higher temperatures are expected to be a primary driver, because most recreational activities are seasonal and vulnerable to changing seasonal conditions and extreme events. Climate change will likely affect the availability, quality, and timing of recreation opportunities, creating additional challenges when managing recreation sites and infrastructure (Hand and Lawson 2017) (chapter 5). These include snow-dependent activities like skiing, snowboarding, and snowmobiling, and warm-weather activities like hiking and camping. As temperatures continue to increase, the economic effects of climate change are expected to occur earlier in communities near national forests, particularly those that have developed economies that depend on outdoor recreation (Wear et al. 2012) (chapter 5).

Adapting to Climate Change in the Sierra Nevada

Adapting Infrastructure to Climate Change

Adapting infrastructure to changing hydrologic regimes—

Warming temperatures will likely have direct effects on hydrologic regimes and water resources (chapter 3), potentially increasing the vulnerability of infrastructure built along rivers and streams, and of facilities located in floodplains. Shifts in precipitation regimes from snow dominated to rain dominated can lead to increased peak flows that accelerate scouring, erosion, and sedimentation. Reduced snowpack and increased rain-on-snow events can also lead to increased and more variable streamflows (chapter 3), potentially increasing erosion and leading to flows that exceed the design parameters of culverts, bridges, and flood prevention infrastructure. To prepare for these extreme events, financial resources and maintenance plans can be improved by risk assessments that identify and prioritize vulnerable roads and infrastructure (Strauch et al. 2015).

At vulnerable or flood-prone sites, resilience near stream crossings and in floodplains can be enhanced by designing future infrastructure to withstand more frequent and severe flood events, and by upsizing or upgrading existing infrastructure to withstand future flooding and erosion. In the most vulnerable locations, roads and other infrastructure can be decommissioned or moved to mitigate risks (table 6.1). For example, engineers can adapt design standards to account for altered streamflow in locations where future rain-on-snow events or shifts to rain-dominated precipitation regimes are expected (Halofsky et al. 2011). Future maintenance and repair operations should occur during periods when weather conditions are optimum and risks to worker safety and site integrity are low. However, altered seasonal conditions may result in closures or restricted public access until conditions are suitable for maintenance and repairs.

Although extreme events like flooding are projected to increase in frequency (chapter 3), they remain difficult to project at the watershed scale. To improve forecasting and response times, managers can expand monitoring efforts to increase their capacity to respond to uncertain and rapidly changing streamflow, snowpack, and weather conditions. Fortunately, expanding monitoring networks can inform decisionmaking processes for multiple resource management programs (e.g., recreation, transportation, reservoirs), and the benefits are frequently shared by neighboring federal and state partners and local communities.

Altered precipitation regimes will also create challenges for dam and water resource managers who allocate water resources to support flood control, energy production, and irrigation demands that fluctuate throughout the year. Adjusting management operations of water control and allocation infrastructure may be necessary as precipitation regimes become more rain dominated (chapters 3 and 4). For example, as streamflows become increasingly variable, shifting the timing and amount of water releases during spring and summer dam operations is an option for maintaining reservoir levels to minimize flood risk in the spring while maximizing water storage for longer periods across the year (Wood and Lettenmaier 2006). To supplement reservoir storage, managers can consider using offstream water delivery infrastructure (canals, ditches, holding ponds) to increase water storage or divert excess streamflows (table 6.1).

Information on the current state of snowpack has typically been more beneficial than climate or weather forecasts for predicting runoff in basins with substantial snowmelt contributions (Wood et al. 2015). However, as precipitation regimes continue to shift with warming, responding to changing hydrologic conditions may require investment in monitoring upstream snowpack, soil, and weather. In areas where snowpack may no longer be a reliable predictor of streamflow timing in a warmer climate, alternative monitoring techniques or protocols may be needed (Harrison and Bales 2016). Improving streamflow forecasting and expanding streamflow and snowpack monitoring networks will help managers respond to extreme events by ensuring water allocation for downstream municipalities, irrigation, riparian areas, and recreation opportunities (Broad et al. 2007) (table 6.1).

Adapting infrastructure to disturbance—
Nearly all infrastructure in the Sierra Nevada is vulnerable to wildfires, particularly outdoor recreation and administrative facilities (chapters 4 and 5). To prevent damage before and during wildfires, vegetation can be managed to reduce fuel loads and increase defensible space around vulnerable facilities and transportation corridors located in the wildland-urban interface (Halofsky and Peterson 2016, Spies et al. 2010) (table 6.1). In addition to the direct effects of wildfire, infrastructure in recently burned areas where vegetation cover has been reduced is often vulnerable to unstable soils and intense precipitation events following fire that can cause erosion, landslides, and debris flows (Guardiola-Claramonte et al. 2011). Following wildfires, managers can prioritize slope stabilization projects around infrastructure near unstable slopes and riverbanks, increase monitoring of soil and slope conditions, and restrict public access to sites where unstable soils create safety hazards (table 6.1).

Concurrently, improving the resilience of ecosystems, infrastructure, and ecosystem services to changing disturbance regimes will help maintain the functionality of ecological processes such as regeneration, productivity, and nutrient cycling. However, with warming temperatures and increasing drought, disturbances like fire will continue to affect large landscapes managed by a mix of federal, state, tribal, and private entities.

Collaborative adaptation efforts and an “all lands” approach are essential for effective responses to increasing disturbances. Expanding existing partnerships among federal, state, and local agencies will increase the capacity of national forests and other organizations to maintain functional ecosystems, water resources, and recreation and transportation infrastructure. Public awareness of the connections among infrastructure, forest ecosystems, and disturbance can be promoted through outreach and education programs with local communities and stakeholders. This will also allow national forests to obtain feedback from the public, which can in turn help identify and prioritize vulnerable infrastructure and collaboratively develop climate-smart actions (table 6.1)

Adapting Recreation to Climate Change

Managing public lands to provide access to sustainable recreational opportunities is a growing priority for land management agencies. Specifically, the USFS framework for sustainable recreation (USDA FS 2010) describes the importance of restoring and adapting recreation settings; implementing "green" operations; enhancing communities; investing in special places; forging strategic partnerships; promoting citizen stewardship; knowing visitors, community stakeholders, and other recreation providers; providing the right information; building a solid financial foundation; and developing the workforce (chapter 5). As forest ecosystems become more vulnerable to climate change, there will be increasing risks to human safety, as well as strained staffing and financial resources. Increasing efforts to make vulnerable infrastructure and recreation resources more resilient to climate change will be necessary under increasingly uncertain conditions.

Adapting winter recreation management—

Higher average and more extreme temperatures will drive changes in the timing and patterns of seasonal outdoor recreation, with some of the most direct effects occurring at elevations where precipitation regimes will shift from snow dominated to rain dominated (chapter 3). Decreasing snowpack and shifts in the availability of snow-dependent recreation opportunities are a concern for managers throughout the Sierra Nevada, where ski resorts and widespread access to winter recreation sites on national forests generate economic revenue (chapter 5). Reduced snowpack can have significant effects on winter recreation, with the most notable being a decrease in the season length for snow-dependent recreation (e.g., skiing and snowmobiling).

As snowpack and snow residence times continue to decrease with warming temperatures, recreationists will likely respond in a variety of ways, including changing the location of recreation (e.g., moving to higher, snow-dominated sites), reducing the duration of their recreation use, or choosing to not participate in snow-dependent recreation by either staying home or choosing an alternative form of recreation at a different location (O'Toole et al. 2019, Scott and McBoyle 2007) (chapter 5).

To adapt to changes in the patterns and timing of winter recreation, managers can increase staffing and provide transportation alternatives at higher elevation sites that will continue to retain snow and may experience increased use with warming temperatures and increased access (table 6.1). However, recreation facilities and infrastructure in newly accessible areas may be unable to support increased use. Managers can minimize site degradation by developing preemptive strategies to control visitation rates (e.g., altered permitting or site closures) or upgrading infrastructure and facilities at sites that will likely experience increased use in the future.

Adapting warm-weather recreation management—

Reduced snowpack and snow residence times will simultaneously affect warm-weather- dependent recreation, as warming temperatures will lead to increased warm-weather recreational opportunities at elevations where snowpack historically limited access during the spring and fall shoulder seasons (e.g., hiking, camping, and driving for pleasure) (Mendelsohn and Markowski 2004). As warm-weather opportunities increase in some locations, prolonged or increased use throughout the year may lead to accelerated degradation and congestion at popular high-use sites (chapter 5). At low- and mid-elevation sites where warm-weather recreation use will occur across longer seasons, identifying site-specific user capacities, planning for increased use, and updating facilities to accommodate increased recreation demand and pressure will increase site resilience and support increasingly variable recreation patterns (table 6.2).

Iconic ecosystems and natural areas (e.g., giant sequoia [*Sequoiadendron giganteum* {Lindl.} J. Buchholz] groves) will also experience the combined stressors of increasing drought severity along with increased visitation rates and human pressures. To increase the resilience of vulnerable sites to changing climate, managers can consider taking actions that reduce human-related impacts. There are many tactics that can support this strategy. For example, managers can limit visitation through site closures, rotate the timing of access to sites, implement permitting or lottery programs, increase onsite education and awareness about human impacts, and work with conservation organizations to monitor site conditions and communicate about alternative sites (table 6.2). However, implementing many of these tactics may be controversial at popular sites. Working closely with local partners and recreation groups to develop plans, communicate goals and objectives, and implement tactics will be critical (chapter 5).

Adapting recreation management to extreme weather events and disturbance— Climate change will likely lead to an increase in the frequency of extreme precipitation and rain-on-snow events, which can exacerbate natural hazards such as flooding and landslides (Ren et al. 2014) (chapters 3 and 5). As population and recreation demands grow, extreme events can increase risk exposure to recreationists and damage recreational infrastructure on which users depend to access recreation destinations (e.g., roads, trails, bridges, and facilities). Decreasing snowpack and increasing rain intensity will also alter streamflow timing and magnitude (chapter 3), leading to increased safety risk to water-based recreation users and travelers near streams and river crossings.

To prepare for these hazards and mitigate risk, managers can develop adaptation strategies that increase flexibility during resource planning efforts and management operations (table 6.2). Tactics to support these strategies include improving or updating rapid communication and response protocols following extreme events, increasing planning and coordination with other agencies and nongovernmental recreation partners, and identifying alternative sites and contingency plans to continue providing recreation opportunities when there are site closures in response to extreme events (table 6.2).

Increasing drought severity and intensity can also lead to more frequent disturbance events like wildfire. Although these disturbances are natural processes and play a critical role in the function of Sierra Nevada forests, the increasing extent and severity of recent events has affected ecosystem services in recent years, including both short- and long-term effects on recreation and infrastructure. During wildfires and in their immediate aftermath, the availability and quality of recreational opportunities can be reduced (chapter 5). For example, smoke emissions can degrade air quality to levels that are hazardous to human health, affecting large regions downwind of a fire and the quality of recreation opportunities that require physical exertion such as hiking, trail running, and mountain biking. The availability of outdoor recreation opportunities is reduced under these conditions, and communities with recreation-dependent economies may experience financial losses as fire seasons increase in length and wildfires become more frequent.

To prepare recreation resources for changing disturbance regimes and increase social resilience to the effects of wildfire, managers can mitigate fire risk at popular sites and in high-use travel corridors, increase the resilience of recreational facilities to fire risk, and improve rapid-response protocols to facilitate efficient closures owing to health or safety concerns (table 6.2). Even in the absence of climate change, managers have limited capacity to control or prevent these disturbances. Regardless of management intervention, disturbances like wildfire will continue to influence forest ecosystems in the Sierra Nevada. Increasing public understanding of the role disturbance plays in forest ecosystems will be important as disturbance regimes continue to change (chapter 5). Managers can work with local partners to increase public awareness about the ecological role of fire by increasing communication and outreach efforts to help manage user expectations of landscape aesthetics and recreation following wildfires.

With shifting climatic regimes and increasing recreation demand, extreme events, and disturbance frequency, current approaches to maintaining or repairing seasonal recreational sites may be insufficient to ensure economically feasible or sustainable recreation opportunities. Responding to altered seasonal conditions and recreation patterns with limited staffing and financial resources will be challenging (chapter 5). Recreation managers can identify ways to increase staffing presence, particularly during the spring and fall shoulder seasons and at high-use sites where existing facilities may be overwhelmed by greater use (table 6.2). Identifying and prioritizing the most vulnerable locations based on climate change projections will inform management plans and improve how staff and resources are deployed.

Increasing management flexibility in order to rapidly respond to changing conditions is another strategy that can increase the efficiency and effectiveness of management responses (table 6.2). This strategy can be facilitated by developing or updating protocols for enforcing rapid closures or access restrictions; for example, site access can be rotated to minimize human pressures and ecological degradation. Implementation of these tactics can be expanded across management boundaries by increasing staffing capacity through partnerships with local conservation and recreation groups that have volunteers available. Leveraging these partnerships will be a critical component of adapting to disturbances and changing ecosystem conditions in national forests (chapter 5).

Connections Between Infrastructure and Recreation

Management of recreation and infrastructure resources needs to be considered concurrently, because the ability of the public to access outdoor recreational opportunities depends on sustainable infrastructure. Although climate change effects on recreation and infrastructure are typically managed as separate programs on national forests, areas of overlap exist in how climate change will affect the two resource areas (chapter 5). In addition, although water resource infrastructure like reservoirs are critical for flood control and water allocations (chapter 4), they also provide opportunities for water-based recreation and generate significant income for nearby communities.

Recreation Use and Infrastructure Degradation

Some of the social and economic benefits associated with outdoor recreation can come at the cost of strained infrastructure and degraded natural areas. As demand for recreation and access to public lands increases, conflicts about development, congestion, and degradation of overused or sensitive sites can be expected in some locations (chapter 5). The extensive transportation networks in the Sierra Nevada create access to many recreation opportunities, but ease of access can also create risks to users and natural resources. For example, increasing or concentrated use can exceed current infrastructure design tolerances, overwhelm site capacity, strain maintenance resources, and potentially reduce the quality of recreation experiences. To maintain the resilience of these areas, managers can consider limiting travel on vulnerable roads and trails and restricting access to high-use sites (tables 6.1 and 6.2).

Climate change, recreation, and infrastructure are linked relative to water resources such as alpine snowpack, rivers, and lakes. These resources are focal points for recreation but also support diverse ecosystems and provide storage and release of water.

Climate change, recreation, and infrastructure are linked relative to water resources such as alpine snowpack, rivers, and lakes. These resources are focal points for recreation but also support diverse ecosystems and provide storage and release of water. Altered hydrologic regimes are a primary concern for infrastructure and recreation management. Roads, bridges, trails, and facilities are often located in proximity to streams or in floodplains. Increasing maximum temperatures, precipitation intensity, disturbance frequency, and peak streamflows, as well as altered timing and amount of recreation can reduce the resilience of infrastructure and recreation resources (chapter 4).

Disturbance, Extreme Events, and Hazards

Warming temperatures and increasing precipitation intensity will likely increase the frequency of disturbances such as debris flows, landslides, and avalanches, creating challenges when providing access to recreation sites, maintaining transportation and recreation infrastructure, and minimizing risk to travelers and staff (Lazar and Williams 2008, Strauch et al. 2015). To increase coordination across resource programs and agencies, managers can consider developing rapid response plans with neighboring landowners, first responders, and recreation groups (table 6.2). At locations where infrastructure is damaged by natural hazards or other extreme events, there may be considerable losses or shifts in recreation opportunities (chapter 5). These effects can have socioeconomic effects that extend beyond a single site, and surrounding communities may incur loss of critical infrastructure, as well as recreation and tourism revenue.

Drought-driven forest disturbances such as fire and insect outbreaks (chapter 2) can rapidly alter recreation and infrastructure resources across large landscapes, with effects that can last for decades. During wildfires, fire and smoke can lead to dangerous conditions and health hazards that put recreationists at risk and limit access to recreation opportunities. Following wildfires, landslides and debris flows can damage roads and facilities and reduce recreational opportunities by damaging infrastructure or increasing sedimentation and debris that can obstruct roads and trails. To prepare for these events, managers can upsize culverts, upgrade stream crossing designs, stabilize slopes near high traffic routes, minimize human and infrastructure exposure in high-risk areas, and increase communication about alternative travel routes and recreation opportunities during and after disturbance events (tables 6.1 and 6.2) (chapter 4).

Other long-term effects following fire and insect outbreaks include reduced scenic values, decreased site capacity to support sustainable infrastructure and recreation, and large numbers of dead and dying trees. Hazard trees are a major concern in the assessment area, particularly in the southern Sierra Nevada where forest mortality has been particularly high since 2010. Hazard trees present risks to human safety that can last for decades. Removal of hazard trees to prevent damage to facilities and provide access to recreation sites increases maintenance and road clearing costs.

Hazard-tree management typically focuses on removal near high-use facilities, roads, and trails (tables 6.1 and 6.2). However, responding to a large number of hazard trees may not be timely and may have financial limitations. Recreation and infrastructure managers can consider working together to increase education and communication about the risks of hazard trees and to inform the public about traveling and recreating safely in disturbance-affected landscapes (tables 6.1 and 6.2). Given the size and severity of recent fires and insect outbreaks, managing public expectations about recreation opportunities and access following disturbances is an important communication issue (table 6.2).

Because of the complex nature of climate change effects on infrastructure and recreation and the limited time and resources available to managers, collaboration will be a necessity when increasing the scale and flexibility of management actions.

Coordinating efforts and resources with local communities, partners, and other agencies to better manage recreational resources and infrastructure was a key theme that emerged during the Sierra Nevada adaptation workshops. Because of the complex nature of climate change effects on infrastructure and recreation and the limited time and resources available to managers, collaboration will be a necessity when increasing the scale and flexibility of management actions. Coordination with adjacent landowners will be particularly critical when adapting infrastructure to climate change effects because many roads pass through multiple ownerships (table 6.1) (chapter 4). Changes in the amount and quality of recreational opportunities on national forest lands can also affect recreation on lands adjacent to national forests. Coordination with recreation managers from other agencies and local recreation groups will be important, because recreation opportunities span management boundaries, and users frequently travel across those boundaries (chapter 5). Based on the results of the Sierra Nevada adaptation workshops, leveraging partnerships to increase the scale of adaptation projects will be a critical first step when adapting recreation and infrastructure in the Sierra Nevada to climate change stressors.

Conclusions

Climate change adaptation is a four-step process:

- Synthesize and review climate change science in the context of local management and socioecological issues.
- Evaluate climate change exposure, sensitivities, and adaptive capacities for natural resources and ecosystems of interest.
- Identify and develop adaptation options that guide climate-smart resource management.
- Implement adaptation actions, monitor their effectiveness, and modify management approaches as needed.

The Sierra Nevada adaptation partnership for infrastructure and recreation produced climate change adaptation options that address climate change vulnerabilities across the 10 national forest units in the Sierra Nevada. Adaptation strategies developed from the collaborative science-management partnership focused primarily on increasing resilience of existing recreation and infrastructure resources, as well as leveraging partnerships to expand the scale of future adaptation actions. Integrating resilience-focused adaptation strategies into management, planning, and project design for infrastructure and recreation will have multiple benefits to forest ecosystems and communities that rely on natural resources and ecosystem services.

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