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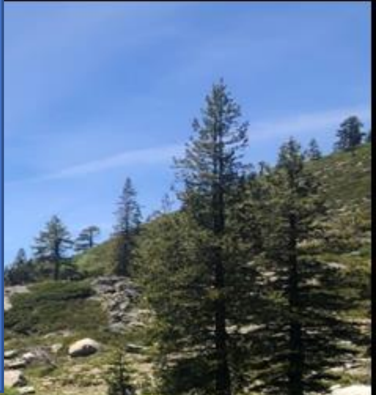
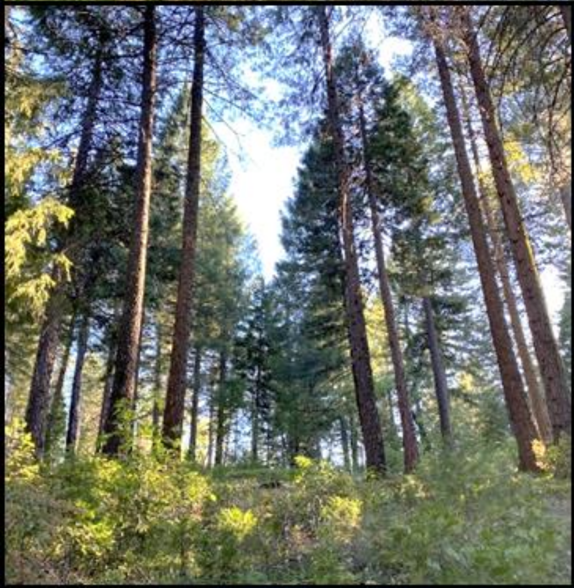
Adaptation Strategies and Approaches for California Forest Ecosystems



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Adaptation Strategies and Approaches for California Forest Ecosystems

Christopher W. Swanston, Leslie A. Brandt, Patricia R. Butler-Leopold, Kimberly R. Hall, Stephen D. Handler, Maria K. Janowiak, Kyle Merriam, Marc Meyer, Nicole Molinari, Kristen Schmitt, P. Danielle Shannon, Jennifer B. Smith, Amarina Wuenschel, and Steven M. Ostoja

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Cover photos, clockwise from top: Sierra Mixed Conifer Forest at Long Lake, Plumas National Forest, CA; Sierra Mixed Conifer Forest at Flemming Meadow, El Dorado National Forest, CA; Coastal Redwood Forest at Little River State Beach, Humboldt Co., CA; Emerald Bay, Lake Tahoe, CA; Aspen fall colors at Humboldt-Toiyabe National Forest, Alpine Co., CA.

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Introduction

Forest health has never been a more urgent concern in California. A variety of forest ecosystem types have experienced extraordinary combinations of stressors and disturbances over the past century, which have resulted in significant changes to forest conditions. Current conditions are a product of multiple interacting factors, including fire exclusion, historic logging practices, increased wildland-urban-interface expansion and, more recently, the effects associated with climate change. The intersection of the factors has led to high severity fire, drought linked mortality, and pest infestation and disease in the affected forests. It's increasingly clear that the expected effects of climate change will further impact California forest ecosystems, potentially compelling and, in some cases, forcing the application of targeted adaptation strategies and approaches in the years and decades to come.

One of the major challenges of adapting ecosystems to climate change is translating broad and sometimes amorphous concepts into the specific and tangible actions that land managers require. The scientific literature contains numerous conceptual frameworks (e.g., Millar et al. 2007, Peterson et al. 2011, Sample et al. 2014, Chornesky et al. 2015), compiled adaptation strategies (e.g., Heinz Center 2008, Ogden and Innes 2008, Heller and Zavaleta 2009, Hagerman and Pelai 2018), and tools to support management decisions (e.g., Cross et al. 2012, Morelli et al. 2012, Stein et al. 2014, Steel et al. 2020), but resolution for natural resources managers to identify specific actions suitable for their particular landscape has been insufficient. A flexible approach, as opposed to specific guidelines or recommendations, can help accommodate diverse management goals, geographic settings, local site conditions, and other resource interests.

Adaptation: Adjustments in human and natural systems, in response to actual or expected climate stimuli or their effects, which moderate harm or exploit beneficial opportunities (IPCC 2001). Various types of adaptation can be distinguished, including anticipatory and reactive adaptation, private and public adaptation, and autonomous and planned adaptation.

This California forest ecosystems menu of adaptation strategies and approaches provides options leading to adaptation actions to support integrating climate change considerations into management and conservation activities. The strategies and approaches are derived from a wide range of contemporary reports and peer-reviewed publications on climate change adaptation or resource management and serve as intermediate "stepping stones" for translating broad and sometimes amorphous concepts into targeted and prescriptive tactics for implementing adaptation. This menu *does not* provide recommendations or guidance. Like any menu, it presents options to the decision-maker but some options will appear more palatable and appropriate than others. In this respect, the menu can be useful for brainstorming and generating productive discussion about actions and values.

Although the menu has value as a synthesis of adaptation literature relevant to California forest management, it was specifically designed to be used in a practical manner with the Adaptation Workbook (Swanston et al. 2016). The Adaptation Workbook provides a structured, adaptive approach for integrating climate change considerations into planning, decision-making, and implementation (Figure 1, step 4). Thus,

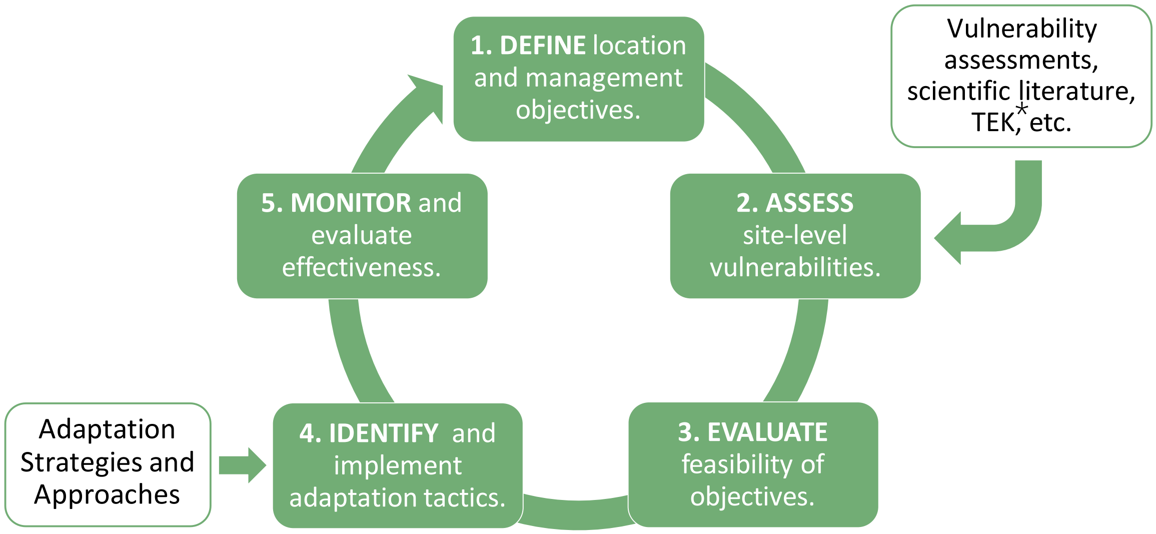


Figure 1. The Adaptation Workbook is a structured process designed to be used in conjunction with vulnerability assessments and adaptation strategies menus to generate site-specific adaptation actions that meet explicit management and conservation objectives under a range of potential future climates. This document is intended to be used with the Adaptation Workbook found in Forest Adaptation Resources: Climate Change Tools and Approaches for land managers, 2nd edition (www.nrs.fs.fed.us/pubs/52760, Swanston et al. 2016) and the corresponding online interactive tool (adaptationworkbook.org). A brief version is in Appendix 1 of this document.
TEK – Traditional Ecological Knowledge

the menu and Adaptation Workbook can be used together to help people link their specific actions to the broader adaptation strategies that align with their goals and objectives, generally define success, and explicitly identify intent. Complementary menus address resource areas such as forest carbon management (Ontl et al. 2019), recreation (O'Toole et al. 2019), forested watersheds (Shannon et al. 2019), open wetlands (Staffen et al. 2019), and culturally relevant tribal perspectives (Tribal Adaptation Menu Team 2019).

The Adaptation Workbook and growing suite of menus have been used together in hundreds of real-world natural resources management projects, many of which are described online as adaptation demonstrations at https://forestadaptation.org/adapt/demonstration-projects. Each menu, regardless of the resource or focal areas, are intended to be used with the Adaptation Workbook referenced herein.

Forest Ecosystems Menu – California Edition

This menu may be considered a "California edition" of the original Forest Ecosystems Menu of Adaptation Strategies and Approaches, which was published in the Forest Adaptation Resources: Climate Tools and Approaches for Land Managers (Swanston and Janowiak 2012, Swanston et al. 2016). The original forest ecosystems menu incorporates broad forest ecology and management concepts, and was generally designed to be used across the United States. It was synthesized from a comprehensive literature review of adaptation actions at numerous scales and locations. Input and feedback from experts, including ecologists and managers, was used to refine the adaptation strategies and approaches herein. This California edition refocuses the context of the original forest ecosystems menu to California forest and timberland ecosystems by adding new example tactics and adjusting the wording, context, and literature support of the approaches and strategies.

There are over 33 million acres of forest in California, spanning 10 degrees of latitude, 5 to 100 inches of rainfall, and from sea level to over 14,000 feet in elevation. These forests are managed by federal, state, tribal, municipal, conservation, and private entities who often manage for different values and have differing risk tolerances. This wide variation in forest types and management objectives across California is likely to engender a comparable variety in adaptation choices, just as it has in other diverse regions (Ontl et al. 2018). This California edition was crafted to support diversity and is, therefore, deliberately broad. This effort was led by the USDA California Climate Hub with critical expert input from the USDA Forest Service Ecology Program Region 5.

The menu of adaptation strategies and approaches were designed specifically to assist land managers; however, many adaptation actions will require or benefit greatly from planning, education and outreach, research, or changes in policy or infrastructure. A list of such considerations is provided at the end of this document. Many of these will be well outside the purview of the typical land manager, but it is important to acknowledge the intersection of these ideas and potential for collaboration.

The remainder of this document includes a brief introduction to a framework of climate adaptation, an overview of how to use the menu, and the detailed menu. A synopsis of the Adaptation Workbook is provided in Appendix 1.

Adaptation concepts: Resistance, Resilience, Transition

Adaptation strategies and approaches are part of a continuum of adaptation actions ranging from broad, conceptual application to practical implementation. This continuum builds upon the adaptation framework described by Millar and colleagues (2007). The concepts of resistance, resilience, and transition (Figure 2) serve as the fundamental options for managers to consider when responding to climate change (*excerpt from Swanston et al. 2016*):

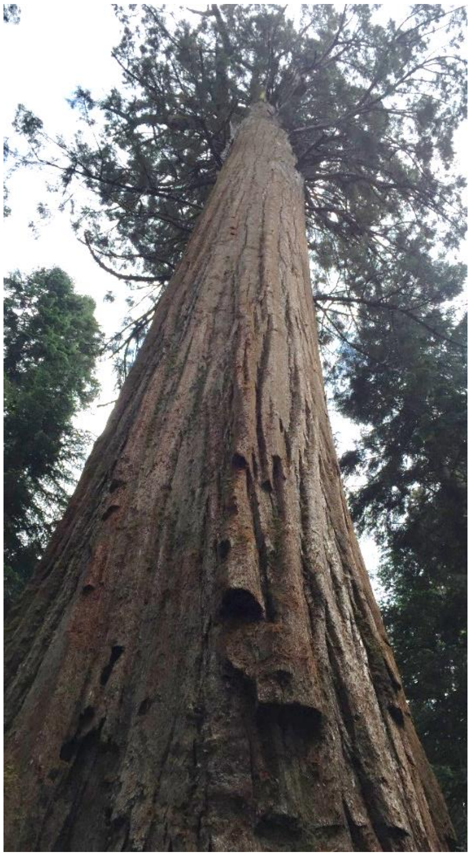
> Resistance actions improve the defenses of an ecosystem against anticipated changes or directly defend the ecosystem against disturbance in order to maintain relatively unchanged conditions. Although this option may be effective in the short term (mid-century or sooner), it is likely that supporting persistence of the existing ecosystem will require greater resources and effort over the long term as the climate shifts further from historical norms. This option may also be most effective in ecosystems (or portions of) with low vulnerability to climate change impacts. As an ecosystem persists into an unsuitable climate, the risk of the ecosystem undergoing irreversible change (such as through a severe disturbance) increases over time.
>
> Resilience actions enhance the ability of the system to bounce back from disturbance and tolerate changing environmental conditions, albeit with sometimes fluctuating populations (Holling 1973). Such actions may be most effective in systems that can already tolerate a wide range of environmental conditions and disturbance. Like the resistance option, this option may be most effective in the short term and

may be subject to increasing risk over time. Resilience is effective until the degree of change exceeds the ability of a system to cope, resulting in transition to another state.

Transition actions intentionally anticipate and accommodate change to help ecosystems adapt to changing and new conditions. Whereas resistance and resilience actions foster persistence of the current ecosystem, transition actions intentionally facilitate the transformation of the current ecosystem into a different ecosystem with clearly different characteristics. These actions may be considered appropriate in ecosystems assessed as highly vulnerable across a range of plausible future climates, such that the risk associated with resistance and resilience actions is judged to be too great. Transition actions are typically designed for long-term effectiveness. They are often phased into broader management plans that predominantly have a shorter-term focus on resilience actions.

These options of resistance, resilience, and transition serve as the broadest level in a continuum of adaptation responses to climate change (Janowiak et al. 2011, Swanston and Janowiak 2012, Swanston et al. 2016). Along this continuum, actions for adaptation become increasingly specific. Adaptation strategies are abundant in recent literature and illustrate ways that adaptation options could be employed (Figure 2). Strategies are however, still very broad and can be applied in many ways across many landscapes and ecosystems. The ten adaptation strategies for forested ecosystem management are generally arranged to start with ideas that focus on the "resistance" adaptation option, progressing to ideas that focus more on "transition," although this arrangement does not indicate preference or priority.

Photos: Creek Fire on the Sierra National Forest, Madera Co, CA.; Big Tree in McKinley Grove on the Sierra National Forest, Fresno Co., CA.



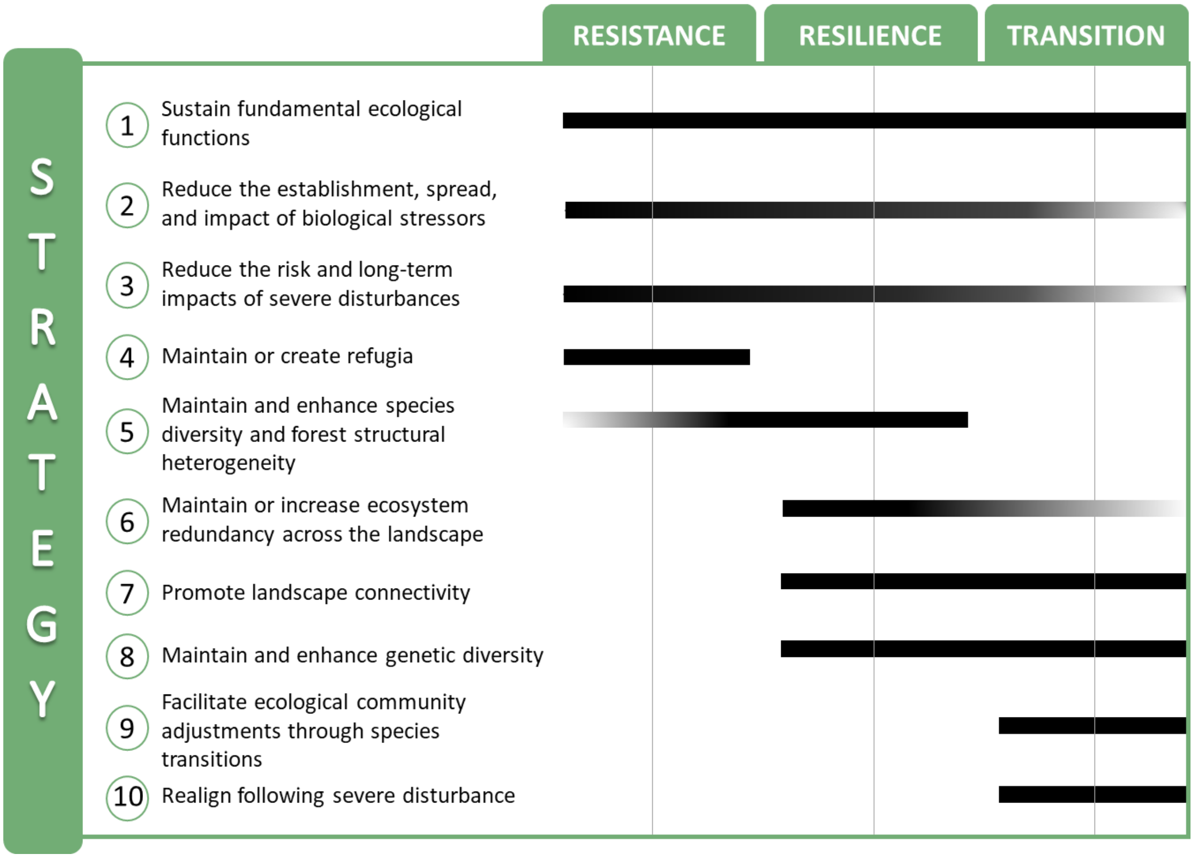


Figure 2. Climate change adaptation strategies work to achieve three broad adaptation options: resistance, resilience, and transition. Strategies may be used to achieve one or more options. A solid line indicates a strong relationship between an option and a strategy, whereas fading indicates that the strategy relates to that option under some circumstances. Although a strategy may work under multiple options, the implementation is likely to be achieved through very different approaches and tactics.

Using the Menu of Adaptation Strategies and Approaches

The menu of adaptation strategies and approaches can provide:

- A broad spectrum of possible adaptation actions that can help sustain healthy ecosystems and achieve management goals in the face of climate change.
- A framework of adaptation actions from which managers select actions best suited to their specific management goals and objectives.
- A platform for discussing climate change-related topics and adaptation methods.
- Examples of tactics that could potentially be used to implement an approach, recognizing that specific tactics will be designed by the land manager.

The menu of adaptation strategies and approaches does not:

- Make recommendations or set guidelines for management decisions. It is up to the manager to decide how this information is used.
- Express preference for any strategies or approaches within an ecosystem type, location, or situation. Location-specific factors and manager expertise are needed to inform the selection of any strategy or approach.
- Provide an exhaustive set of tactics. We encourage managers to consider additional actionable tactics appropriate for their projects. Further, some tactics have not been vetted through research and so should be employed with caution and followed-up with monitoring and adaptive management.

How to read this menu

Strategy is defined as a broad adaptation response that is applicable across a variety of resources and sites, hydrologic and ecological conditions, and overarching management goals.

Approach is defined as a more detailed adaptation response specific to a resource issue, site condition, and management objectives. Adaptation approaches describe in greater detail how strategies could be employed.

Tactics are defined as prescriptive actions designed for specific site conditions and management objectives. Tactics are the most specific adaptation response, providing prescriptive direction about what actions can be applied on the ground, and how, where, and when. Tactics can be developed specific to a species, the ecosystem type, site conditions, management objectives, and other factors. We have provided examples of tactics for each approach, but do not intend that they be implemented without due consideration of all relevant factors. The Adaptation Workbook also provides a method to explicitly consider the benefits and drawbacks of potential adaptation tactics.

Photo: Sierra Buttes, Plumas NF, CA

CONCEPT → ACTION

OPTIONS	STRATEGIES	APPROACHES	TACTICS
Foundational adaptation concepts *(after Millar et al. 2007)*	Broad adaptation responses that consider ecological conditions and overarching management goals	More detailed adaptation responses with consideration of site conditions and management objectives	Prescriptive actions designed for specific site conditions and management objectives
RESISTANCE Buffer or protect from change.	Maintain or create refugia.	Prioritize and maintain sensitive or at-risk species or communities.	Reroute roads or trails away from at-risk communities.
RESILIENCE Promote the return to normal conditions after a disturbance.	Reduce the risk and long-term impacts of severe disturbances.	Alter structure or composition to reduce risk or severity of fire.	Restore fire in oak forests to reduce surface fuel and promote fire- and heat-tolerant species.
TRANSITION Actively facilitate or accommodate change.	Facilitate community adjustments through species transitions.	Introduce species that are expected to be adapted to future conditions.	Consider oaks on lower-elevation, south-facing slopes formerly occupied by ponderosa pine.

Figure 3. A continuum of adaptation actions to address needs at appropriate scales and levels of management (top row) and examples of each level of action (lower rows).

Menu of Adaptation Strategies and Approaches

Box 1. Menu of Adaptation Strategies and Approaches

Strategy 1: Sustain fundamental ecological functions.

1.1. Reduce impacts to soils and nutrient cycling.
1.2. Maintain or restore hydrology.
1.3. Maintain or restore functional riparian systems.
1.4. Reduce vegetation competition for moisture, nutrients, and light.
1.5. Restore or maintain fire in fire adapted systems.

Strategy 2: Reduce the establishment, spread, and impact of biological stressors.

2.1. Maintain or improve the ability of forests to resist pathogens and insect pests.
2.2. Minimize the risk of the introduction and establishment of invasive plants and remove existing invasive species.
2.3. Manage herbivory to promote regeneration of desired species.

Strategy 3: Reduce the risk and long-term impacts of severe disturbances.

3.1. Alter forest structure and/or composition to reduce risk or severity of wildfire.
3.2. Establish and maintain fuelbreaks to minimize the risk of uncharacteristic, high-severity fire.
3.3. Alter forest structure to reduce severity or extent of extreme weather events.
3.4. Promptly revegetate after disturbance.

Strategy 4: Maintain or create refugia.

4.1. Prioritize and maintain unique sites.
4.2. Prioritize and maintain sensitive or at-risk species or communities.
4.3. Establish artificial reserves for at-risk and displaced species.

Strategy 5: Maintain and enhance species diversity and forest structural heterogeneity.

5.1. Promote forest age- and size-class diversity and spatial heterogeneity.
5.2. Maintain and restore diversity of native species.
5.3. Retain biological legacies.
5.4. Establish and protect reserves to maintain ecosystem diversity.

Strategy 6: Maintain or increase ecosystem redundancy across the landscape.

6.1. Manage habitats over a range of sites and conditions.
6.2. Expand the boundaries of reserves to increase diversity.

Strategy 7: Promote landscape connectivity.

7.1. Reduce landscape fragmentation.
7.2. Maintain and create landscape linkages through reforestation or restoration.

Strategy 8: Maintain and enhance genetic diversity.

8.1. Use seeds, germplasm, and other genetic material from across a greater geographic range.
8.2. Favor existing genotypes that are better adapted to future conditions.

Strategy 9: Facilitate ecological community adjustments through species transitions.

9.1. Favor or restore native species that are expected to be adapted to future conditions.
9.2. Establish or encourage new mixes of native species.
9.3. Guide changes in species composition at early stages of forest development.
9.4. Protect future-adapted seedlings and saplings.
9.5. Disfavor species that are distinctly maladapted.
9.6. Manage for species and genotypes with wide moisture and temperature tolerances.
9.7. Introduce species that are expected to be adapted to future conditions.
9.8. Move at-risk species to locations that are expected to provide sustainable habitat.

Strategy 10: Realign ecosystems after disturbance.

10.1. Promptly revegetate sites after disturbance.
10.2. Allow for areas of natural regeneration to test for future-adapted species.
10.3. Realign significantly disrupted ecosystems to meet expected future conditions.

Strategy 1: Sustain fundamental ecological functions.

Climate change will have substantial effects on a suite of ecosystem functions, such as carbon storage, nutrient cycling, wildlife habitat, hydroelectric generation and water provisioning. As a result, many management actions will need to work both directly and indirectly to maintain the integrity of ecosystems in the face of climate change. This strategy seeks to sustain fundamental ecological functions, especially those related to soil and hydrologic conditions.

Approach 1.1. Reduce impacts to soils and nutrient cycling.

Maintaining both soil quality and nutrient cycling are already common tenets of sustainable forest management (Oliver and Larson 1996, Burger et al. 2010) and can help improve the capacity of ecosystems to persist under new conditions. Physical and chemical changes can result from a variety of forest management and recreation activities, as well as from climate-related processes including fire, drought, and flooding (Johnstone et al. 2016, Schlesinger et al. 2016, Bradford et al. 2019). Examples of potentially damaging physical impacts to soil are compaction, mixing of soil layers, removal of organic layers, rutting, erosion, and land and mudslides; the latter can be especially damaging when heavy rains occur after a high severity fire (Cannon et al. 2008, Abney et al. 2017, Mayer et al. 2020). Complex interactions among climate, vegetation, and landforms can result in changes in nutrient cycling, including the leaching or fixation of nutrients and changes in soil biota (Mayer et al. 2020). Many existing guidelines and best management practices describe actions that can be used to reduce impacts to soil and water; many of these actions are also likely to be beneficial in the context of adaptation, either in their current form or with modifications to address potential climate change impacts.

Examples of adaptation tactics include:

- Altering the timing of forest management activities to reduce potential impacts on water, soils, and residual trees, especially in areas that rely on particular conditions for field operations that may be affected by a changing climate (e.g., saturated soil, or excessively dry conditions)
- Modifying field operations techniques and equipment (e.g., using pallets, debris mats, or float bridges) to minimize soil compaction, rutting, or other impacts on water, soils, and residual trees
- Retaining ecologically appropriate levels and distribution of coarse woody debris and fine soil organic matter to maintain soil moisture, quality, biota, and nutrient cycling
- Restricting recreational access in areas that show signs of excessive disturbance on soils and vegetation in order to allow for revegetation or soil stabilization.
- Restoring native herbaceous groundcover following management activities in order to retain soil moisture and reduce erosion.
- Promote and maintain native shrub cover (at appropriate patch sizes) to maintain soil quality and nutrient cycling.

Approach 1.2. Maintain or restore hydrology.

Projected changes in precipitation and temperature are expected to alter hydrologic regimes through changes in snowpack, streamflow, evapotranspiration rates, soil moisture, surface runoff, infiltration, flooding, and drought (Jones 2011, Bresehars et al. 2013, Allen et al. 2015, Diffenbaugh et al. 2015, Ficklin and Novick 2017, Bedsworth 2018, Gleason et al. 2019). Hydrologic changes could occur gradually or rapidly through extreme events. Some ecosystems are very susceptible to stress from drought, which is increasing in frequency, severity, duration, and geographical extent as a result of these changes in the hydrologic cycle and the effects of human water uses, such as irrigation (Van Loon et al. 2016, Crausbay et al. 2017). Other ecosystems are susceptible to flooding, ponding, or high-water tables as storm intensities increase. Maintaining sufficient water levels and flow patterns is critical to ecosystem function, and the survival of fish and other aquatic species (Roper et al. 2018). Hydrology can be altered by infrastructure (e.g., dams, roads, and other impervious surfaces), excessive groundwater extraction, soil compaction, stream channelization, and even invasive plants (Kondolf and Batalla 2005, Bales et al. 2006, Crausbay et al. 2017). Existing infrastructure that diverts water, or otherwise alters hydrology, may need to be reevaluated to compensate for changes in water levels or flows (Galatowitsch et al. 2009, Furniss et al. 2010, Brandt et al. 2012, Bedsworth et al. 2018). Infrastructure will also need to be designed to accommodate greater hydrologic extremes in the future. It is important to keep in mind that modifications to maintain hydrology at one site may have negative impacts on hydrology at another site. In places where hydrology has been altered by agricultural land uses, restoration actions can include managing the impacts of cattle and other grazers on streams, and using structures or berms to slow water flow and moderate the impacts of soil compaction and river channelization (Pollock et al. 2014, Silverman et al. 2019).

Examples of adaptation tactics include:

- Modifying aboveground forest structure to increase snow accumulation and or delay or extend melt off period, thereby promoting increased infiltration and soil moisture retention.
- Upgrading to appropriate culvert size and cleaning culverts regularly to accommodate changes in peak flow and thus reduce damage to infrastructure and the environment during heavy (e.g., atmospheric river) rain events.
- Reducing or eliminating agricultural drainage improvements near wetlands.
- Restoring and maintaining the hydrology of wetland ecosystems, including fens and wet meadows.
- Installing berms, dikes, or structures similar to beaver dams to divert surface water to a lowland area affected by decreased precipitation, or to restore permeability & seasonal flooding that was lost due to soil compaction or stream channelization.
- Removing or modifying dams, especially as they become defunct and if they have little hydroelectric or domestic interest value.
- Decommissioning or temporarily closing roads to reduce erosion and sedimentation and to restore permeability and soil hydrology. Restoration following decommissioning may include such techniques as re-contouring, revegetation, and passive restoration to enhance soil hydraulic connectivity and function.

Approach 1.3. Maintain or restore functional riparian systems.

Forests located within riparian areas serve important ecosystem functions, such as decreasing soil erosion, filtering water, and storing and recycling organic matter and nutrients (Barling and Moore 1994, Castelle et al. 1994, Caissie 2006, Brandt et al. 2012). Trees in riparian areas also provide shade, which moderates stream temperatures, and woody material, which provides various kinds of structures and nutrients essential to stream ecology (Dunham et al. 2007, Luce et al. 2016, Ebersole et al. 2020). Moreover, forested riparian areas serve as corridors for wildlife and plant species migrating across otherwise fragmented landscapes (Heller and Zavaleta 2009, Keeley et al. 2018, Krosby et al. 2018). Many of these functions and benefits may be degraded if riparian forests burn, or undergo decline or exacerbated stress from climatic shifts and extreme events. However, lack of forest disturbance can also lead to encroachment and loss of other important riparian ecosystems, or reduced water availability in streams and rivers (Robles et al. 2017, Boisramé et al. 2017 & 2019). The use of protective guidelines, such as best management practices and riparian management zones, can be used to minimize damage or additional stress to riparian areas during management activities.

Examples of adaptation tactics include:

- Restoring or promoting a diversity of tree, shrub, and herbaceous species to increase stream shading, provide a source of woody debris, stabilize the soil, and provide habitat and connectivity for wildlife.
- Utilizing fabric, wire, or natural materials to stabilize eroding stream banks.
- Restoring or reforesting riparian areas adjacent to agricultural areas in order to reduce erosion and nutrient loading into adjacent water bodies.
- Managing water levels to supply proper soil moisture to vegetation adjacent to the stream during critical time periods, either by manipulation of existing dams and water control structures or restoration of natural dynamic water fluctuations.
- Reconnecting floodplains to rivers and restoring natural floodplain conditions and associated native habitats (e.g., wetlands, meadows, fens, and grasslands) in order to restore fluvial processes, including flooding.
- Managing livestock grazing regimes to minimize stream bank erosion and maintain riparian vegetation.
- Promoting and maintaining disturbance regimes with appropriate severity and frequency, such as fire, in order to: (1) prevent forests from encroaching into adjacent meadow and grassland ecosystems, (2) maintain forest densities at levels required to sustain surface and ground water sources in adjacent wetlands, and (3) reduce fuel loading in riparian corridors.

Approach 1.4. Reduce vegetation competition for moisture, nutrients, and light.

Competition for resources between plants is established as one of the main mechanisms in plant succession and evolution (Weiner 1990). Competition occurs aboveground as plants compete for light, and belowground as they compete for water and mineral nutrients (Casper and Jackson 1997). Climate change is expected to affect many of the competitive relationships in California's forest and shrubland ecosystems, suggesting that management and reforestation practices may need adjustment (Hessburg et al. 2016, Hagerman and Pelai 2018, North et al. 2019). Productivity may increase in some species because of the positive effects of carbon dioxide (CO_2) fertilization and longer growing seasons, but other species will not be able to take equal advantage of these positive effects (Evans and Perschel 2009). On the other hand, increased temperatures, a contracted wet season, lower rates of precipitation, or reduced snowpack will increase competition for water, and increase the susceptibility of trees to many pests and pathogens. Reducing competition for resources can enhance the persistence of remaining individuals of desired species and increase the ability of ecosystems to cope with the direct effects (drought stress, temperature increases) and indirect effects (increased damage from pests and disease) of climate change (Evans and Perschel 2009, Dwyer et al. 2010, Hessburg et al. 2016, Wang et al. 2019, North et al. 2019). The effectiveness of reducing competition in terms of improving forest condition will vary based on many factors, such as species sensitivities, site condition, and degree of climate exposure; moreover, even if competition is reduced, there may not be a change in factors like vegetation or soil moisture (e.g., Stevens et al. 2020), and despite management actions, climate change may still push species past critical ecological thresholds (Crausbay et al. 2017).

Examples of adaptation tactics include:

- Using prescribed fire, managed wildfire, pyrosilviculture, or mechanical thinning to increase light and moisture availability and stimulate growth, recruitment, and regeneration in aspen (*Populus tremuloides*), cottonwood (*Populus trichocarpa*), alder (*Alnus rubra*), and other broadleaved or coniferous shade-intolerant trees.
- Mechanical or herbicidal removal of encroaching woody competitors and invasive species in post-disturbance environments to enhance the survivorship and growth of natural or planted regeneration of desired species.
- Mechanical thinning of forest stands (i.e., reduce tree density) in order to decrease competition for light, nutrients, and water and increase the survivorship and health of larger and older trees.
- Using prescribed fire in forests to maintain or increase growing space for fire-tolerant species, promote regeneration of shade-intolerant species, enhance soil moisture availability, or increase nutrient turnover.
- Applying variable density thinning treatments to enhance structural heterogeneity and reduce inter-tree competition while balancing other management objectives (e.g., maintaining wildlife habitat, fuel reduction).

Approach 1.5. Restore or maintain fire in fire adapted systems.

Long-term fire exclusion leads to shifts in ecosystem structure and composition, which may disproportionately favor certain species and reduce biodiversity and resilience (Nowacki and Abrams 2008, Hessburg et al. 2016, North et al. 2019, Stephens et al. 2020). Restoring fire regimes that attempt to mimic the spatial and temporal patterns of natural disturbance in fire-adapted systems can enhance regeneration and encourage stronger competition by fire-dependent and fire-tolerant species (Abrams 1992, Stephens et al. 2010, Churchill et al. 2013). These actions can simultaneously foster more complex ecosystem structure and reduce the risk of severe wildfire. Projecting the effects of climate change on California's fire regimes in forest ecosystems is an area of active research (e.g., Stevens et al. 2017, Hurteau et al. 2019, Syphard and Keeley 2020). The wildfire season is expected to lengthen in much of the western United States, and wildfires may occur at frequencies and severities outside of the natural range of variation for many forested ecosystems (Westerling et al. 2016, Crockett and Westerling 2017, Stephens et al. 2020). Many tactics within this approach focus on enabling fire-adapted ecosystems to adjust to these anticipated changes, which ideally reduces long-term risk to the ecosystem.

Examples of adaptation tactics include:

- Using prescribed fire to reduce surface and ladder fuels, increase understory diversity, create discontinuity in fuels across the landscape, and increase stand structural heterogeneity.
- Promoting fire- and drought-adapted species and ecosystems in areas that are expected to have increased fire risk as a result of climate change.
- Using prescribed fire to restore the open spatial arrangement of oak woodlands, meadows, and other inherently sun-exposed habitats.
- Managing wildland fire (i.e., prescribed fire, wildfire) within the natural range of variation to increase seral class diversity, benefit fire-dependent wildlife species, and enhance watershed function.
- Managing wildfires where feasible for resource objectives during cooler months and following wetter winters to maximize benefits of wildland fire in forest types adapted to low severity fire regimes.
- Implementing a strategic system of fuel treatments (e.g., mechanical or prescribed fire fuel breaks) in strategic locations to establish a network of low fuel "anchors" that could be used to facilitate the future management of wildfire for resource objectives.
- Developing burn plans that include some high intensity fire at appropriate return intervals for the management of serotinous conifers, such as *Pinus attenuata* (knobcone pine) and *Pinus muricata* (Bishop pine), when present.
- Assigning prescribed burn seasons to align with appropriate weather conditions, thereby reducing the risk of unintended and uncontrollable wildfire.
- Identifying "demonstration firesheds" within and across large, uninhabited landscapes where wildfires can be predominantly managed for resource objectives over the long-term, and the resultant fire effects can be studied and monitored for management effectiveness. Work across jurisdictional lines to lead a policy shift from fire suppression to using fire as a tool.
- Developing ecoregional fire management strategies to facilitate cross-jurisdictional fire management operations, effective communication, and positive fire effects at a landscape scale.

Strategy 2: Reduce the establishment, spread, and impact of biological stressors.

Biological stressors such as insects, pathogens, invasive species, and herbivores can act individually and in concert to amplify the effects of climate change on ecosystems (Fettig et al. 2019). Forest managers already work to maintain the ability of forests to resist and recover from stressors; as an adaptation strategy, these efforts include an emphasis on anticipating and preventing increased stress before it occurs. Climate change has the potential to add to or intensify the impact of many biological stressors, including forest insects and disease and invasive plant species (Millar and Stephenson 2015), which heightens the importance of responding to these issues (Larvie et al. 2019). Dealing with these existing stressors is a relatively high-benefit, low-risk strategy for climate change adaptation, in part because of the existing body of knowledge about their impacts and the existing collection of solutions (Bedsworth et al. 2018).

Approach 2.1. Maintain or improve the ability of forests to resist pathogens and insect pests.

Even modest changes in climate may cause substantial increases in the distribution and abundance of many insects and pathogens, including mostly native species, potentially leading to reduced forest productivity or increased tree stress and mortality (Ayres and Lombardero 2000, Dukes et al. 2009, Seidl et al. 2017). Impacts may be exacerbated where site conditions, climate, other stressors, and interactions among these factors increase the vulnerability of forests to these agents (Spittlehouse and Stewart 2003, Cartwright 2018, Comer et al. 2019). Actions to manipulate the density, structure, or species composition of a forest may reduce susceptibility to some insect pests and pathogens (Spies et al. 2010, Hessburg et al. 2016). Assessments that compare topographic features and site conditions can help identify forest stands with higher and lower vulnerabilities, especially for insects and pathogens favored by drought (Cartwright 2018, Krawchuk et al. 2020).

Examples of adaptation tactics include:

- Thinning to reduce the density of an insect's host species in order to discourage infestation, based on the knowledge that species are especially susceptible to insects and pathogens at particular stocking levels (these levels may decrease with warming climate, drought, and other stressors, necessitating lower densities to reduce host susceptibility).
- Adjusting rotation length in production forestry operations to decrease the period of time that a stand is vulnerable to insect pests and pathogens, based on the knowledge that species are especially susceptible to insects and pathogens at particular ages.
- Creating a diverse mix of forest or community types, age classes, and stand structures to reduce the availability of vulnerable individuals of host species for insects and pathogens.
- Thinning trees to promote wide and irregular spacing and selecting the healthiest trees that include a combination of both vigorous (i.e., fast-growing) and slower-growing trees to reduce the likelihood of insect attack and high stand mortality under outbreak conditions.
- Using insecticides, including the use of anti-aggregate semiochemicals (e.g., use of verbenone for mitigating impacts of mountain pine beetle), as a preventive treatment to protect high-value individual trees from attack in areas of increasing bark beetle activity and/or during protracted drought periods. However, semiochemical treatments are not effective on successfully attacked trees and not as effective in severe outbreak conditions where beetle pressure is high. Note: verbenone does not work for western pine beetle.
- Red turpentine beetle impacts can be reduced by limiting the amount of basal burn injury during prescribed fire and by duff raking around high value pines.

- Promptly treating potentially infested green material ("green slash") from healthy stands by chipping, burning, burying, or removing from the site to a safe location.
- Restricting harvest and transportation of logs near stands already heavily infested with known insects or pathogens.
- Using impact models and monitoring data to anticipate the arrival and spread of insects and pathogens (e.g., goldspotted oak borer, sudden oak death) and prioritize management actions to help limit their spread.

Approach 2.2. Minimize the risk of the introduction and establishment of invasive plants and remove existing invasive species.

Over 1,000 nonnative invasive plant species are currently present in California (Bossard et al. 2000, Natural Resources Conservation Service 2012). Climate change is expected to change habitat conditions and increase opportunities for establishment for many of these species, which may be able to outcompete native species (Chornesky et al. 2005, Bossard et al. 2000, Millar et al. 2007, Dey et al. 2018). Current methods for controlling nonnative invasive species emphasize early detection and rapid response to new infestations (Hellmann et al. 2008 and see www.cal-ipc.org/). Management of highly mobile nonnative invasive species may require increased coordination across property boundaries and over larger geographic areas and is likely to require a larger budget for eradication and control efforts. As a resistance or resilience strategy, this approach may work temporarily. Over the long term, limitations in available resources may require managers to make difficult choices to prioritize species for eradication efforts.

Examples of adaptation tactics include:

- Increasing monitoring for known or potential invasive species to ensure early detection, especially at disturbed sites such as trailheads, along roads, in forest treatment areas, including recently burned areas, and along other pathways known for infestation.
- Eradicating existing populations or seed sources of invasive plants, particularly and importantly when first detected, through physical or chemical treatments.
- Cleaning equipment prior to forest and fire management operations in order to prevent or minimize the opportunity for the spread of invasive plants during site preparation, harvesting, fire suppression operations, or other activities.
- Promoting an abundant and diverse native species understory (i.e., herbaceous plants, shrubs, and tree regeneration) that may limit the potential for invasive species' spread.
- Educating staff and volunteers on identification and eradication of current and potential invasive species, including the use of citizen science in monitoring and removal of invasive species within targeted areas. Create a list, with photos to illustrate and describe each plant species, of the most aggressive and problematic invasive species. For example, CalWeedMapper allows the user to create maps and reports of invasive plant distribution and identify management options.

Approach 2.3. Manage herbivory to promote regeneration of desired species.

Climate change has the potential to exacerbate many forest stressors and alter regeneration patterns. Additionally, climate change will probably have direct and indirect effects on populations of native forest herbivores such as mule deer (generally expected to increase) and Roosevelt elk (future change uncertain). Herbivores preferentially browse or graze on particular species, making it increasingly important to protect regeneration of desired species (e.g., oak (*Quercus*) species) from deer and other herbivores, including domestic livestock (i.e., cattle, sheep). Much of the available information on forest herbivores in California focuses on mule deer, which may alter stand dynamics, especially in oak and mixed oak-conifer woodlands of California (Long et al. 2016). Managing herbivory alone may not promote desired species. Thus, this approach may be combined with other approaches that release advance regeneration or stimulate new regeneration of desired species (Kie et al. 2003).

Examples of adaptation tactics include:

- Applying repellant or installing fences, bud caps, and other physical barriers to prevent herbivory, especially in areas where management treatments facilitate new tree regeneration (e.g., prescribed burned aspen stand).
- Promoting abundant regeneration of multiple species in order to supply more browse than herbivores are expected to consume.
- Partnering with state wildlife agencies to monitor native herbivore populations or develop management plans that maintain populations at appropriate levels.
- Applying diversionary and or supplemental forage to reduce herbivory pressure on desired regenerating species.
- Ensure range management plans support desired vegetation trajectories.

Strategy 3: Reduce the risk and long-term impacts of severe disturbances.

Climate change is projected to continue to increase the potential for severe disturbance events, such as uncharacteristically large and severe wildfires, floods, severe and extended drought, and insect outbreaks (Uriarte and Papaik 2007, Moritz et al. 2012, Millar and Stephenson 2015, Vose et al. 2016, Fettig et al. 2019, Halofsky et al. 2020, Stephens et al. 2020). These disturbances have the ability to alter community composition and structure, potentially for many decades or longer, over large landscapes (Coop et al. 2020). Disturbances can also interact with other stressors (Papaik and Canham 2006, Vose et al. 2016). For example, extreme drought can cause tree damage and mortality, which increase the risk of insect outbreaks and potentially influence wildfire behavior (Gandhi et al. 2007, Woodall and Nagel 2007, Stephens et al. 2018, Fettig et al. 2019). Even as trends continue to emerge, management will need to adjust appropriately to the changes in natural disturbance dynamics.

Approach 3.1. Alter forest structure and or composition to reduce risk or severity of wildfire.

Forest structure and composition in many locations (e.g., dense, second growth stands with accumulations of surface and ladder fuels) may interact with longer and drier fire seasons to increase the risk, rate of spread, intensity of wildfire. Mortality from climate-related disturbances can lead to further increases in fuel loading, which can increase the risk or severity of fire (Stephens et al. 2018). Although many forest types in California are tolerant of or dependent on fire (North et al. 2019), extremely hot fires can destroy seed banks, sterilize soils, induce hydrophobic soil conditions, or cause extensive tree mortality (Noss 2001, Nitschke and Innes 2008, Smith et al. 2017). These large, high-severity fires can create long-term challenges for regeneration of prior forest or shrubland conditions (Millar and Stephenson 2015, Coop et al. 2020). Management actions to alter species composition or ecosystem structure in mixed conifer forests may reduce susceptibility to these threats (Spittlehouse and Stewart 2003, Hulme 2005, North et al. 2009, Stephens et al. 2010, Hessburg et al. 2016, Lydersen et al. 2019, North et al. 2019).

Examples of adaptation tactics include:

- Using prescribed fire to reduce surface fuels, and mechanical thinning to remove ladder fuels, increase height to live crown, decrease crown closure, and create a more open forest structure that is expected to be less vulnerable to drought and severe wildfire.
- Enhancing forest structural heterogeneity by emphasizing variable inter-tree distances, varying densities based on topography, and creating a combination of individual trees, tree clusters, and canopy openings (known as the "ICO pattern"; Larson and Churchill 2012, North et al. 2019) that reduces wildfire spread and provides other ecosystem benefits (e.g., wildlife habitat).
- In areas of steeply rising topography, using prescribed fire to maintain open conditions in ecosystems at lower elevations as a means of reducing fuels and the risk of high severity wildfire in ecosystems at higher elevations. Also using mechanical thinning where feasible (i.e. slopes that are not too steep).
- Promoting growth of large, fire-resistant species, such as hardwoods and yellow pines (such as ponderosa pine (*Pinus ponderosa)* and Jeffrey pine (*Pinus jeffreyi)*), in buffer zones between more flammable conifers (such as white fir (*Abies concolor)* and incense cedar (*Calocedrus decurrens)*) to slow the movement of wildfires.
- Physically removing dead or dying trees (although retain key wildlife trees such as broken topped or trees with cavities) or other vegetation to reduce surface and ladder fuels, while minimizing exposure to invasive plants, pests, or pathogens.

Approach 3.2. Establish and maintain fuelbreaks to minimize the risk of uncharacteristic, high-severity fire.

Continued escalations in fire occurrence will increase demand on fire-fighting resources and may force prioritization of fire suppression efforts to targeted areas (Westerling 2016, Halofsky et al. 2020). Managers may seek to reduce the spread or intensity of fire by using a (1) non-vegetated fuelbreak, which is a physical barrier such as a road, bulldozer line, water body; or (2) vegetated fuelbreak, where surface, ladder, and canopy fuel loads have been heavily reduced, resulting in minimal fuel continuity. Establishing fuelbreaks can be complementary with actions to reduce the fuel load of the vegetation across the forest (Approach 3.1; Agee et al. 2000). Fuelbreaks can lessen fire spread and intensity in specific areas of ecological interest or high-risk areas such as the wildland-urban interface. They can also enhance the opportunity for fast, effective, and safe tactical response during wildfire suppression operations. However, fuelbreaks also have the potential for greater habitat fragmentation and increased invasive species spread. Thoughtful site selection and careful methods for creating fuelbreaks (e.g., take advantage of natural fuelbreaks as much as possible) will help minimize negative impacts of fuelbreaks.

Examples of adaptation tactics include:

- Using prescribed fire and mechanical thinning to lower the volume of dense vegetation and reduce flammability within a buffer zone of appropriate size for the landscape.
- Establishing fuelbreaks along roads, power lines, and other existing infrastructural features in order to minimize habitat disruption and reduce the spread of wildfire while minimizing additional fragmentation.
- Utilizing natural fuelbreaks across the landscape, such as exposed rock outcrops and sparsely vegetation ridgetops, when considering the strategic management of future wildfires (e.g., potential operational delineations).
- Reducing canopy bulk density immediately adjacent to human communities (i.e., wildland-urban interface) to reduce the probability of crown fire spread. Focus more on horizontal heterogeneity across the matrix of the forest to create natural openings and break up the fuelbed.
- Replacing vegetation with nonflammable materials (e.g., local rocks) around homes and other valuable structures.
- Creating fuelbreaks around fire-sensitive areas of high natural resource value, such as specific Experimental Forests, Research Natural Areas, Botanical Areas, where altered fire regimes would negatively impact target species of the protected area in the near future (e.g., forest ecosystem type burning too frequently).

Approach 3.3. Alter forest structure to reduce severity or extent of extreme weather events.

Climate change is expected to increase the occurrence, frequency and severity of extreme weather events, including drought, extreme precitipataion, heat waves, and wind disturbances (Uriarte and Papaik 2007, Moritz et al. 2012, Millar and Stephenson 2015, Vose et al. 2016, Bedsworth et al. 2018, Fettig et al. 2019, Halofsky et al. 2020, Stephens et al. 2020). Though such events are fundamental processes in many forest ecosystems, increases in frequency and severity can overstress and burden these systems. Periods of moderate to intense drought impact the magnitude of climatic water deficits and plant stress, and risk of fire; trees weakened by water limitation may be more susceptible to pathogens, disease, and pests (Gandhi et al. 2007, Woodall and Nagel 2007, Mann and Gleick 2015, Vose et al. 2016, Fettig et al. 2019). Heat waves driving abnormally high temperatures can further stress plants and contribute to transitions of forest plant species composition. Extreme precipitation events, such as atmospheric rivers and late season snowstorms, can disturb and burden aboveground plant structures, creating vulnerabilities, particularly in recently burned forests, to flooding, erosion, and the ensuing negative impacts on water quality (Cannon et al. 2008, Abney et al. 2017). Increasing intensity and frequency of windstorms may negatively impact the ability of stands to endure these disturbances. Moreover, high-intensity wind events may interact with intermittent features such as heavy canopy snow to increase blowdown (Gordon 1973), which can increase the risk of damaging electrical equipment and sparking fire. Management actions to alter forest composition and structure for reduced stress, increased resistance to blowdown or ice damage, or to avoid sudden exposure of retained trees to wind, may minimize the impact of extreme weather events (Everham & Brokaw 1996, Fettig et al. 2007, Burton et al. 2008, Mitchell 2012, Kolb et al. 2016).

Examples of adaptation tactics include:

- Applying variable density thinning treatments to enhance structural heterogeneity and reduce inter-tree competition.
- Retaining trees at the edge of a clearcut or surrounding desirable residual trees to help protect trees that have not been previously exposed to severe weather.
- Conducting forest harvest over multiple entries in order to gradually increase the resistance of residual trees to extreme weather events.
- Using directional felling, cut-to-length logging, and other harvest techniques that minimize damage to residual trees.
- Creating canopy gaps that have an orientation and shape informed by the prevailing winds in order to reduce the risk of windthrow.

Approach 3.4. Promptly revegetate after disturbance.

Changes in the frequency, intensity, and extent of large and severe disturbances may disrupt regeneration and result in loss of desirable vegetation cover, productivity, or function in the long term. Prompt revegetation of ecologically appropriate and climatically adapted native species at sites following disturbance is often necessary to reestablish lost forest canopy, reestablish wildlife habitat, reduce soil loss and erosion, maintain hydrologic function, and discourage invasive species in the newly exposed areas. These efforts can also provide an opportunity to promote natural regeneration or foster species that may be better adapted to future climate conditions (North et al. 2019). Provenance test studies can provide powerful insights that help guide the selection of suitable reforestation seed sources (e.g., Mahoney et al. 2020).

Examples of adaptation tactics include:

- Planting native species and genotypes (e.g., nearby seed zones) expected to be adapted to future conditions (e.g. future climatic conditions or altered disturbance regimes) and resistant to insect pests or present pathogens.
- Creating suitable physical conditions for regeneration through site preparation, for example herbicide application or mechanical removal to promote post-fire seedling establishment.
- Planting tree seedlings in variable densities according to topographic and site conditions, with relatively lower densities in drier sites (e.g., south-facing slopes, ridgetops, and less productive

soils) and higher densities in wetter sites (e.g., north-facing slopes, canyon bottoms, and more productive soils).

- Incorporating existing natural regeneration in reforestation efforts, such as creating gaps around artificial regeneration where naturally-regenerating tree seedlings (conifers and hardwoods) enhance future structural heterogeneity and contribute to current stocking levels.
- Planting tree seedling densities in spatially-variable local arrangements, including the use of cluster plantings and uneven seedling spacing.
- Reforestation that use plating arrays with a combination of scattered individuals, clusters and open spaces (i.e., ICO) may promote landscape heterogeneity.
- Monitoring areas of natural regeneration on a more frequent basis, and prioritizing planting or seeding where natural regeneration is slow to succeed.
- Planting larger individuals (saplings versus seedlings, or containerized versus bare-root stock) to help increase survival in sites where dry conditions are expected.
- Reducing competing vegetation around planted or naturally regenerated desired species by physical, prescribed fire, or chemical means.

Strategy 4: Maintain or create refugia.

Refugia are areas that have resisted ecological changes occurring elsewhere, often providing suitable habitat for relict populations of species that were previously more widespread (Millar et al. 2007, Keppel et al. 2012). Climate refugia are often formed by topography (e.g., north sides of slopes, or sheltered ravines), proximity to large water bodies, or connection to groundwater (Ashcroft 2010, Dobrowski 2011, Morelli et al. 2016, Cartwright 2018, Krosby et al. 2018, Krawchuk et al. 2020, Ebersole et al. 2020, Ackerly et al. 2020). An excellent example of this are the 75 or so giant sequoia (*Sequoiadendron giganteum*) groves scattered across the Sierra Nevada mountain range that have persisted in sites that are relatively more mesic and have reliable summer moisture (Holland and Keil 1995). Springs and other sites with strong connections to groundwater can provide cool water refugia (Cartwright et al. 2020), and are critical habitat for a variety of California's threatened and endangered species (Rohde et al. 2019). During previous periods of rapid climate change, at-risk populations persisted in refugia that avoided extreme impacts (Noss 2001, Millar et al. 2007, Keppel et al. 2012, Nydick et al. 2018). These populations allowed species to persist until more favorable climatic conditions returned and species were able to expand into newly available habitats. This strategy seeks to identify and maintain habitats that: (1) are on sites that may be better buffered against climate change and short-term disturbances, and or (2) contain communities and species that are at risk across the greater landscape (Noss 2001, Millar et al. 2007).

Approach 4.1. Prioritize and maintain unique sites.

Some sites host a higher diversity of species than adjacent sites, have many endemic species, or have retained species through past periods of climate change (Loarie et al. 2008, Keppel et al. 2012, Comer et al. 2019). These locations of high ecological value can be identified at multiple scales and may occur as a result of many factors, including geophysical factors such as complex topography, variation in geology and soils, variation in microclimates due to vegetation differences, or variation in hydrology, including access to cold groundwater or climatic buffering from large surface waters (Beier and Brost 2010, Anderson and Ferree 2010, Klausmeyer et al. 2011, Lawler et al. 2015, Comer et al. 2019, Cartwright et al. 2020, Morelli et al. 2020). When these factors moderate exposure to climate change, they are often referred to as climate refugia. Species at these sites are not necessarily sensitive or at-risk, although they may face increased stress under future climate on some landscape positions. Committing additional resources may be necessary to ensure that the characteristic site conditions are not degraded by invasive species, herbivory, altered fire regimes, or other disturbances.

Examples of adaptation tactics include:

- Identifying and managing cooler and wetter locations (i.e., locations with a relatively lower future climate exposure) that are expected to buffer native plant communities from rising temperatures and/or decreases in soil moisture.
- Identifying forested slopes (i.e., north facing) that retain snowpack later into the spring/summer than other sites, and manage actions on these sites with the goal of retaining the benefits they provide to freshwater habitats and flows
- Limiting harvest or management-related disturbance in areas that may be buffered from climate change (e.g., spring-fed stands or groundwater dependent ecosystems sheltered in swales or valleys).
- Identifying and protecting a network of sheltered mountain slopes, valleys, or forests with continuous shading canopy (such as along canyon bottoms or riparian corridors).
- Identifying areas with unique geology, landform, soils (e.g., serpentine parent material soils) or vegetation (e.g., endemic species) for increased protection or conservation.
- Protecting areas that have been generally undisturbed by humans, such as those within old forests, old-growth chaparral, subalpine stands, or prairie, in order to preserve a reference condition or legacy while allowing for natural processes (e.g., fire) to operate within their natural range of variation.

Approach 4.2. Prioritize and maintain sensitive or at-risk species or communities.

Many species are projected to decline as the changing climate causes physiological stress and habitat shifts (Kueppers et al. 2005, Loarie et al. 2008, Asner et al. 2016). For example, some subalpine species in the Sierra are likely to experience a reduction in suitable habitat as temperatures increase, even as other species become more competitive (Kueppers et al. 2017, Thorne et al. 2017, Ackerly et al. 2020). Likewise, coastal species dependent on a narrow range of site conditions, such as regular, heavy fog, may be more vulnerable as precipitation changes in form and pattern (Dawson 1998). Identifying and maintaining sensitive or at-risk species as long as possible may help them persist until new long-term sites can be accessed and/or populated.

Examples of adaptation tactics include:

- Using vulnerability assessments or climate exposure models and monitoring data to identify and prioritize management of species expected to decline under future conditions.

- Retaining individuals of a priority species across many diverse sites representing various environmental conditions or within differing forest types.
- Rerouting roads, trails or recreational activities away from particularly vulnerable at-risk communities to reduce damage from traffic or reduce the risk of introducing invasive species.
- Minimizing harvest and other disturbances to species with dispersal or migration barriers, such as high-elevation or lowland conifer species, in order to protect viable populations where they currently occur.
- Prioritizing forest density reduction treatments in strategic locations near at-risk and sensitive communities to buffer these areas from the future impacts of large and severe wildfires and other disturbances.
- Prioritizing at-risk landscapes for larger-scale forest management treatments to increase the resilience of these landscape to future stressors, while minimizing short-term impacts of treatments in specific locations that may contain at-risk species or communities.
- Monitoring regeneration across broad environmental gradients to detect migration of plant populations or communities to adjacent areas.

Approach 4.3. Establish artificial reserves for at-risk and displaced species.

Species already exist outside their natural habitats in nurseries, arboretums, greenhouses, botanical gardens, and urban environments around the world. These highly controlled environments may be used to support individuals or genetic lineages that are no longer able to survive in their former location, or to serve as interim refugia for rare and endangered plant species that have specialized environmental requirements and low genetic diversity (Millar 1991, Fiedler and Laven 1996, Havens et al. 2006, Vitt et al. 2010). These man-made reserves may in some cases maintain species until they can be moved to new suitable habitat. Although creating and maintaining a controlled environment would probably require substantial resources, this approach may be critical for at-risk species (Coates and Dixon 2007).

Examples of adaptation tactics include:

- Using existing artificial reserves to cultivate species after suitable habitat has shifted and when target species will face considerable lag time before new habitat may become available.
- Collecting seeds and other genetic material of at-risk species to contribute to a genetic repository.
- Planting individuals in a protected location expected to provide suitable habitat in a natural setting, such as an arboretum (e.g., UC Davis arboretum oak collection) or a stand on a partner's property.
- Planting individuals in a controlled setting, such as a climate-controlled arboretum or botanical garden.

Strategy 5: Maintain and enhance species diversity and forest structural heterogeneity.

Land managers' objectives already include increased structural and species diversity in many cases, and as an adaptation strategy this general goal merits added effort and focus (Mooney et al. 2009, North et al. 2009, Groves et al. 2012, Schmitz et al. 2015, Hessburg et al. 2016, Halofsky et al. 2018, North et al. 2019). Structural diversity, typically characterized by horizontal and vertical heterogeneity, combined with species diversity may buffer a community against the susceptibility of its individual components to climate change (Peterson et al. 1998, North et al. 2009, Anderegg et al. 2018, North et al. 2019). A community may still experience stress as individual components fare poorly, but the redundancy of roles and variability among all species' responses or tolerances contribute to the resilience of the community (Elmqvist et al. 2003). Although an ecosystem is often defined by its dominant or most abundant species, even rare species can provide valuable function, such as contributing to the suppression of invasive exotic plants (Mooney et al. 2009).

Approach 5.1. Promote forest age- and size-class diversity and spatial heterogeneity.

Any given species will have unique vulnerabilities to different stressors which may differ at different stages in their life cycle. Even-aged forested stands are often more vulnerable to insects and diseases, many of which are likely to increase in range and severity as a result of climate change. In uneven-aged systems, more typical of most forests in California, a smaller proportion of the population may be exposed to a particular threat at any one time, which can increase the resistance or resilience of a stand to a wider range of disturbances (O'Hara and Ramage 2013). Forest stands with a combination of widely scattered individuals, clusters of mixed age trees, and open spaces may increase forest resilience (North et al. 2019). Maintaining a mix of species, ages, sizes, or canopy positions will help buffer vulnerability to stressors of any single age class, as well as increase structural diversity within stands or across a landscape (Noss 2001).

Examples of adaptation tactics include:

- Emulating aspects of disturbances through forest management techniques such as variable-density treatments or irregular return intervals in order to encourage the development of multiple age cohorts.
- Focusing salvage operations on creating desired residual stand structures following disturbance.
- Using site scarification, chaining, planting, or other techniques to support adequate regeneration.
- Maintaining a variety of stand structural or seral classes of a given forest type across a larger landscape, especially in approximate proportion to the natural range of variation.
- Managing competing vegetation in areas of older regeneration (typically 10 to 20 years post-fire) with prescribed burning and using a prescription that creates an appropriate mixture of tree and shrub survivorship and cover patchiness (e.g., spring burning prior to bud break).
- Silvicultural or reforestation designs that emphasize arrays with a combination of scattered individual, clusters of trees and patches of open spaces.

Approach 5.2. Maintain and restore diversity of native species.

Diverse communities may be less vulnerable to climate change impacts and disturbances because different species have unique susceptibility to stress or disturbance; thus a diverse community allows the risk to be dispersed among multiple species, reducing the likelihood that the entire system will decline even if one or more species suffer adverse effects (Heller and Zavaleta 2009, Anderegg et al. 2018, Comer et al. 2019). This may be especially important in communities with inherently low diversity; even small increases in diversity may increase resilience without greatly altering species composition (Anderson and Chmura 2009, Cadotte et al. 2012, Wilkerson and Sartoris 2013). Forests with higher levels of species diversity are also expected to be less vulnerable to declines in productivity due to climate change (Duveneck et al. 2014, Creutzburg et al. 2016).

Examples of adaptation tactics include:

- Using silvicultural treatments to promote and enhance a mixture of diverse native species, including through regeneration.
- Transitioning plantations to more complex systems by underplanting or promoting natural regeneration of a variety of native species (conifers and hardwoods) expected to do well under future conditions.
- Planting select desired native species within an area that is otherwise expected to regenerate naturally in order to add diversity.
- Restoring native vegetation in areas that have been severely altered by anthropogenic activities, such as abandoned deforested or urban sites, logging landings, or surface mine sites.
- Planting species with diverse timing of phenological events (e.g., flowering, fruiting, leaf out, leaf drop) to provide necessary resources over a longer timeframe to forest-dependent wildlife species.
- Using prescribed fire, managed wildfire, pyrosilviculture, and/or mechanical thinning to increase light and moisture availability and stimulate growth, recruitment, and regeneration in aspen, cottonwood, alder, and other broadleaved or coniferous shade-intolerant trees.
- Prioritize and restore areas of high cultural or socioecological value in partnership with local tribes and communities; these may include meadows and riparian forests that can produce valued foods and uses such as elderberries, California mint, Yarrow, black oak acorns, and pinyon pine nuts.
- Develop early detection monitoring and environmental analysis for nonnative species eradication.

Approach 5.3. Retain biological legacies.

Biological legacies are organisms, structures, or patterns inherited from a previous ecosystem and often include mature trees, snags, and down logs remaining after natural disturbance or harvesting (Society of American Foresters 2008). In California, a few notable examples of biological legacies include giant sequoia, coastal redwood (*Sequoia sempervirens*) and the bristlecone pine (*Pinus longaeva*) forests, stands and groves. Biological legacies are often critical components of habitat for many species of wildlife, such as large trees with structures suitable for nesting, denning, roosting, or resting sites. Consequently, biological legacies can enhance species and structural diversity, serve as a seed source, or provide nurse logs for seed germination (Gunn et al. 2009, Hessburg et al. 2016). Additionally, mature trees can often survive through periods of unfavorable climate, even while conditions become unsuitable for seedling establishment (Brubaker 1986). In a changing climate, biological legacies may play a critical role in a species' persistence or colonization of new habitat (Gunn et al. 2009). These unique ecological legacies also have important historical and cultural significance.

Examples of adaptation tactics include:

- Retaining the oldest and largest trees with good vigor during forest management activities.
- Retaining wildlife trees and logs for habitat purposes, including living trees with decay or broken tops, trees with brooms, hollow trees (cavities) and standing dead (snags).
- Retaining survivors of insect or disease outbreaks, droughts, wind throw events, or other disturbances during salvage or sanitation operations.
- Retaining individual trees of a variety of uncommon species to maintain their presence on the landscape.

Approach 5.4. Establish and protect reserves to maintain ecosystem diversity.

Some areas with exemplary combinations of soil, hydrologic, and climatic variation support a correspondingly high degree of species diversity. Such ecosystems may be protected through the establishment of reserves in order to sustain the ecological elements contained therein. Reserves are traditionally defined as natural areas with little to no harvest activity, but do not exclude fires burning within the natural range of variation or other natural disturbance processes (Halpin 1997). However, the use and definition of reserves may need to be evaluated within the context of changing climate and forest response. It may be valuable to retain explicit flexibility in management practices, so long as management directly supports the justifications and goals for establishing the reserve. This approach may also be used as a "control" for monitoring adaptation actions implemented in other forest stands.

Examples of adaptation tactics include:

- Identifying areas with high diversity, unique vegetation types, or other desirable attributes that can be set aside as a reserve on an existing ownership.
- Setting a minimum requirement for percentage of land in reserve.
- Prioritizing areas where riparian corridors connect core areas to other reserves and habitats.
- Providing a large reserve based on a species' known optimum conditions in order to preserve a species.

Strategy 6: Maintain or increase ecosystem redundancy across the landscape.

Some losses of species or communities are inevitable, whether due to catastrophic events or unforeseen interactions of management, climate change, and forest response. Increasing ecosystem redundancy attempts to lower the overall risk of losing a species or community by increasing the extent, number of occurrences across the landscape, and diversity of regeneration stages (Akçakaya et al. 2007). This strategy may benefit greatly from developing partnerships across land base jurisdictions, with other land management organizations and coordinating landscape-scale conservation practices.

Approach 6.1. Manage habitats over a range of sites and conditions.

The suitable site conditions for a community or species may shift on the landscape as the climate changes, resulting in new combinations of locations and species assemblages. Therefore, managing habitats in multiple sites and conditions may increase opportunities for successful regeneration and the likelihood of persistence of a species or community (Millar et al. 2007, Joyce et al. 2009, Groves et al. 2012). Similarly, exposure and sensitivity to widespread disturbances such as drought and fire can show strong spatial variation as a result of differences in site exposure, and local adaptations (Brodick et al. 2019, Buotte et al. 2019). Species currently covering a large extent may provide many options for retaining redundancy across the landscape.

Examples of adaptation tactics include:

- Restoring or increasing a community type on a variety of appropriate soil types and across a range of topographic positions.
- Implementing a variety of forest management activities or silvicultural prescriptions across multiple stands or areas with similar starting conditions in order to diversify forest conditions and evaluate different management approaches.
- Coordinating with partners to manage at-risk species or communities existing on a variety of suitable sites.

Approach 6.2. Expand the boundaries of reserves to increase diversity.

Approaches 4.1 and 5.4 describe protecting and maintaining climate refugia and reserves to maintain ecosystem diversity and legacy. Expanding existing reserve boundaries may buffer and replicate the diversity within the core of the reserve, but more importantly, may also increase the overall species diversity within the expanded reserve (Akçakaya et al. 2007). This approach may be more effective over the long term if focused on reserves that also encompass climate refugia.

Examples of adaptation tactics include:

- Restoring or conserving land directly adjacent to established reserves.
- Developing a network of reserves across adjacent management units or with adjacent landowners with shared or complementary management or conservation goals.
- Designating buffer zones of low-intensity management around core reserve areas and between different land uses.

Strategy 7: Promote landscape connectivity.

Species movement and landscape permeability are critical factors for enabling species persistence and in the maintenance of ecosystem function in a changing climate; fragmentation of landscapes and loss of habitat may restrict species movement and gene flow, and disrupt ecological processes (Davis and Shaw 2001, Iverson et al. 2004, Krosby et al. 2010, Haddad et al. 2017, Dickson et al. 2017, Hilty et al. 2019). Managing the landscape to provide for multiple avenues of connectivity may allow for easier species movements and seasonal migrations, reduce lags in range shifts in response to climate change, and supports the flow of genetic material that enhances adaptive capacity at local, regional, and continental scales. The current rate of climate change coupled with contemporary land use and development, however, creates unique challenges to movement. Many species are not expected to be able to shift location at a rate sufficient to keep up with changes on the landscape resulting from climate change (Davis and Shaw 2001, Iverson et al. 2004, Aitken et al. 2008, Loarie et al. 2009, Dobrowski et al. 2013). Identifying options for protecting or restoring connectivity that incorporate climatic constraints or benefits is a rapidly growing area within the climate adaptation literature, especially in the western US (e.g., Keeley et al. 2018). It may be beneficial to combine the approaches under this strategy with efforts to create refugia or relocate species (i.e., assisted migration) for species with low movement potential, or those that have reached the coolest available microsites (e.g. Ackerley et al. 2020). Connectivity may not only enable extensive migration of native species, but also facilitate increased movement of invasive species and insects, thereby increasing the need to prevent introduction of these species.

Approach 7.1. Reduce landscape fragmentation.

The fragmentation of contiguous habitats is a primary driver of biodiversity loss and reduced productivity through exposure to uncharacteristic disturbance, obstruction of migration pathways, and overall lowered resilience (Fischer and Lindenmayer 2007, CA Dept. Fish and Wildlife 2015, Haddad et al. 2017). In many parts of California, the state's forests and other ecosystems have been compromised due to increased urban development and expansion of the wildland-urban-interface, which constrains adaptation potential (Radeloff et al. 2005, Klausmeyer and Shaw 2009, Radeloff et al. 2018). Protecting large areas from development and fragmentation will require a concerted effort to create partnerships, agreements, and other mechanisms for land protection and management across property boundaries. Strategic acquisition of high-priority conservation areas, conservation easements, certification programs, restoration projects, and other efforts to increase the size and connectivity of ecosystems will foster a landscape-level response to counter the widespread effects of climate change (Spittlehouse and Stewart 2003, Millar et al. 2007). This approach may be complemented by approach 5.4, which focuses on establishing new reserves.

Examples of adaptation tactics include:

- Establishing or expanding reserves adjacent to other habitat cores to form a connected network of a few large reserves, many small reserves along a climatic gradient, or a combination of large and small reserves close to each other.
- Promoting or participating in conservation easement programs (e.g., Cal Fire CFIP) that retain vegetation cover and achieve landscape-scale connectivity.
- Restoring native vegetation and vegetation structure in degraded areas within the ecosystem matrix, especially in key linkage areas that join fragmented population cores.
- Establishing partnerships and coordinating acquisition of crucial lands to achieve common management goals.

- Using geospatial information to identify new and existing migration corridors.
- Work with partner agencies (e.g., Cal Trans, NPS, USFS) to develop effective road-crossing structures that facilitate wildlife dispersal and minimize impacts from vehicle collisions, particularly in key habitat corridors.
- Review system roads periodically and eliminate unneeded ones. Eliminate or restore user-created non-system roads, as appropriate.

Approach 7.2. Maintain and create landscape linkages through reforestation or restoration.

The presence of both small and large corridors on the landscape may help species to migrate without expensive and challenging human-aided assistance (Heller and Zavaleta 2009, Hilty et al. 2019). Corridors oriented in any direction may be useful to facilitate genetic mixing, but corridors arranged along climatic or elevational gradients may be more useful if the goal is to allow for species movements along the gradient (Keeley et al. 2018). Reforestation or restoration of stream and river corridors will bolster conservation of riparian species while also providing a movement corridor for other species; these habitats may also be somewhat buffered from high temperatures and drought (Keeley et al. 2018, Krosby et al. 2018).

Examples of adaptation tactics include:

- Establishing or restoring forest cover (especially hardwoods where appropriate) along rivers, canyon bottoms, or drainages to build on natural linear features that connect larger forests.
- Establishing a connected network of conservation easements.
- Eradicating invasive species within a corridor to minimize competition with desired species.
- Working with partners to identify high-priority sites to protect for landscape-scale corridors or habitat.

Strategy 8: Maintain and enhance genetic diversity.

Greater genetic diversity in adaptive traits will enable species to adapt to new conditions or sites by increasing the likelihood that some individuals within a species will be able to withstand climate-induced stressors (Westfall and Millar 2004, Sork et al. 2013). Current guidelines for management of tree seed zones, developed originally for California in 1946 and updated most recently in 1970 (an addition update is currently underway), generally promote the conservation of local gene pools, restrict transfer of germplasm, and define small seed zones to minimize contamination between pools (Buck et al. 1970, Millar et al. 2007, J. Wright pers. Comm. 2019). A changing climate, in concert with large fire events, has promoted a new investment in guidelines that accommodate shifting seed zones and promote more options for maintaining or enhancing genetic diversity (Heller and Zavaleta 2009, Aitken and Bemmels 2016). Actions to use genetic diversity in restoration could be timed to occur after large-scale disturbances to take advantage of regeneration and establishment phases. Approaches under this strategy are best implemented with great caution, considering the uncertainties inherent in climate change, the sparse record of previous examples, the ecological and social suitability of particular locations, and continued uncertainties of forest response. Collaborating with researchers and engaging in adaptive management or experimental approaches to implementation may help site managers and the broader community learn from novel actions.

Approach 8.1. Use seeds, germplasm, and other genetic material from across a greater geographic range.

Planted seedlings typically have greater survival when they originate from local seed sources, but local seed sources may no longer produce the best adapted seedlings if the governing environmental factors change (Vitt et al. 2010). Using seed zones that change over time and are based on regional analyses of climate change data may provide better seed sources than static seed zones (Spittlehouse and Stewart 2003, Erickson and Navarrete-Tindall 2004, Millar et al. 2007, Aitken and Bemmels 2016). This may entail importing genetic stock from locations ranging from nearby to substantially distant in order to introduce plants that are expected to be better adapted to current or future climatological conditions. Though there are many uncertainties, research on potential risks, benefits, and trade-offs of "assisted gene flow" are rapidly increasing for forest tree species (Aitken and Bemmels 2016). At the same time, ecoregional and political boundaries may continue to restrict the distance from which genotypes (or species) may be imported (McKenney et al. 2009, Pedlar et al. 2012). This strategy may require communicating with policy-makers to reevaluate seed zone sizes and rules governing the movement of seed stocks. It is important to note that although many environmental factors may match seedlings to geographic areas, limitations such as cold tolerance may remain (Millar et al. 2007). It is also important to take the necessary precautions to avoid introducing a new invasive species (Vitt et al. 2010).

Examples of adaptation tactics include:

- Using mapping programs to match seeds collected from a known origin to planting sites based on climatic information.
- Identifying and communicating needs for new or different genetic material to seed suppliers or nurseries.
- Planting seedlings germinated from seeds collected from various locations throughout a species' native range.
- Monitoring and research of survivorship and fitness to identify preferred genetic sources.
- Considering the findings of provenance studies (i.e. botanical studies that examine, for a given location, fitness of individuals derived from different geographic areas) conducted at numerous locations around the western United States.
- Development of a seed collection and cultivation infrastructure for high elevation white pine species susceptible to the effects of white pine blister rust and climate change, including *Pinus albicaulis* (whitebark pine), *P. balfouriana* (foxtail pine), *P. flexilis* (limber pine), and bristlecone pine.

Approach 8.2. Favor existing genotypes that are better adapted to future conditions.

As populations experience cumulative changes in climate, or short-term extremes in climate, new selective pressures on populations may result in changes in phenotypic expression and genotypic evolution responses Westfall and Millar 2004, Aitken et al. 2008, Reed et al. 2011, Sork et al. 2013, Aitken and Bemmels 2016). Some genotypes may be better adapted to future conditions or changing conditions because of insect resistance, broad physiological tolerances, short regeneration times, or other characteristics (Spittlehouse and Stewart 2003, Millar et al. 2007). Identifying and managing these future-adapted genotypes during various life stages may allow a population to persist where it may otherwise fail. However, the use of this approach may be currently limited by the uncertainty about precise future conditions and which genotypes are best suited to these conditions (Breed et al. 2013). It is also possible that genotypes from other sites could interfere with the adaptation of local populations, if the imported resources are not adapted to withstand local pressures (e.g., frost tolerance or pathogen resistance). Availability of source material may also limit the use of this approach.

Examples of adaptation tactics include:

- Planting stock from seeds collected from local species that exhibit drought tolerance, pest resistance, or other desirable qualities.
- Planting stock from seeds collected from healthy individuals in warmer or drier locations in the region.
- Retaining some survivors of a die-back event, such as drought-induced mortality or pathogenic blight, rather than salvage harvesting all trees in an affected area.
- Detecting and monitoring areas of natural regeneration in order to identify and promote well-adapted phenotypes.
- Collecting, cultivating, and planting white pine blister rust-resistant sugar pine (*Pinus lambertiana)* and other white pines (e.g., whitebark pine) in order to maintain these important species on the landscape.
- Permitting forest managers and enabling private forest landowner to experiment with various lines of plant material types that might prove more climate adapted where experimental data are sparse.

Strategy 9: Facilitate ecological community adjustments through species transitions.

Species composition in many forest ecosystems is expected to change as species adapt to a new climate and transition into new communities (Thorne et al. 2017, Comer et al. 2019). The "facilitate adjustments" strategy seeks to maintain overall ecosystem function and health by gradually enabling and assisting adaptive transitions of species and communities in suitable locations. This strategy concedes that change in community composition and structure is inevitable and thus attempts to facilitate transition of ecosystems from current to new conditions (Handler et al. 2018). This may result in slightly different species assemblages than those present in the current community, or an altogether different community assemblage in future decades (Schwartz et al. 2012). Assertive actions are taken to promote forest community change rather than an unchanging community or species mix. Many of the approaches in this strategy attempt to mimic natural processes but may currently be considered unconventional management responses. In particular, some approaches incorporate assisted migration or gene flow, which remains a challenging and contentious issue (McLachlan et al. 2007, Ricciardi and Simberloff 2009, North et al. 2019). It is not suggested that managers attempt to introduce new species without thoroughly investigating potential consequences to the native ecosystem (Ricciardi and Simberloff 2009). approaches in this strategy are best implemented with great caution for the same reasons outlined in Strategy 8 (e.g., the inherent uncertainties of climate change and lack of examples to predict response). Outcomes from early efforts to transition communities can be evaluated to provide both information on future opportunities and issues of concern as well as specific information related to methods and timing.

Approach 9.1. Favor or restore native species that are expected to be adapted to future conditions.

There are many cases where native species may be well-adapted to the future range of climatic and site conditions (Landscape Change Research Group 2014, Bouchard et al. 2019). Using management to favor native species in a community or forest type that are expected to fare better under future climate change can facilitate a gradual shift in the forest composition. Establishing or emphasizing future-adapted species now may create opportunities to fill the niche left by species that decline. Where communities are dominated by one or a few species, this approach will probably lead to conversion to a different community type, albeit with native species (Figure 2).

Examples of adaptation tactics include:

- Underplanting a variety of native species on a site to increase overall species richness and provide more options for future management.
- Favoring or establishing oak, pine, and other more drought- and heat-tolerant species on sites that are expected to become warmer and drier, such as narrow ridge tops or south-facing slopes with shallow soils.
- Establish trials that vary the spacing and species mixtures to explore alternatives that might reduce water competition under future climates.
- Seeding or planting drought-resistant genotypes of commercial species (e.g., ponderosa pine) where increased drought stress is expected.
- Seeding or planting species found suitable to a location but that would likely not be able to naturally disperse there (i.e., assisted range expansion).


Photo: Lodgepole pines at Mud Lake in Plumas NF, CA.

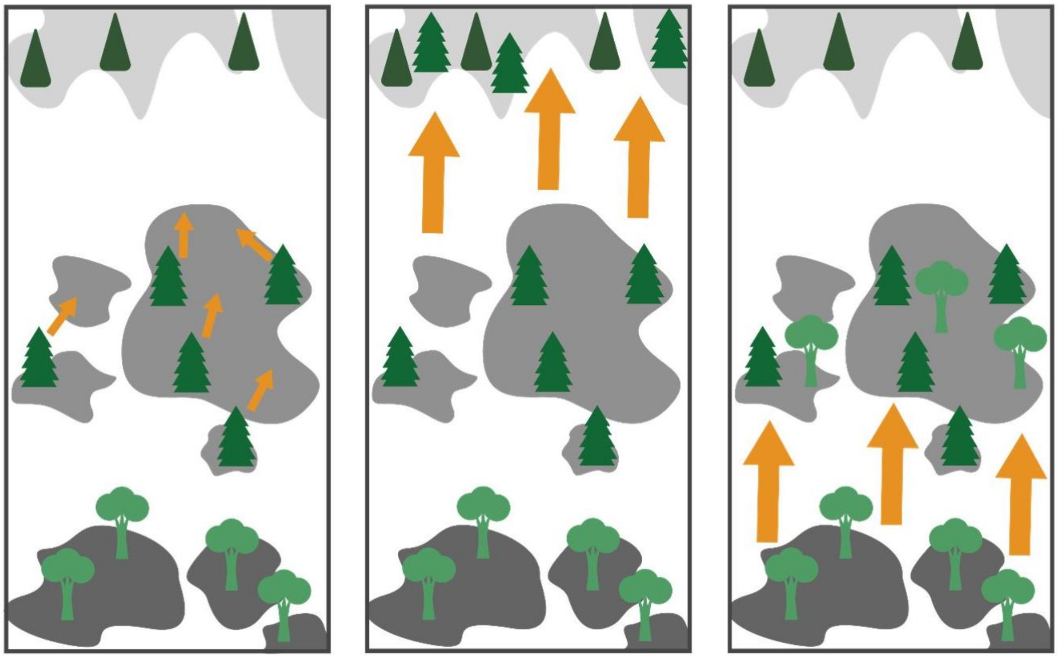


Figure 4. This graphical depiction (from Handler et al. 2018) illustrates three possible tactical applications related to this strategy 9 (Facilitate ecological community adjustments through species transitions). Assisted population migration occurs when moving seed sources or populations to new locations within the historic range of the species (see approach 9.3). Assisted range expansion occurs when seed source or populations are moved from their current range to potentially suitable areas nearby, but beyond the historic range of the species – thereby facilitating or mimicking natural dispersal (see approach 9.1, 9.8). And finally, assisted species migration occurs when seed sources or populations are moved to a location far outside the historical species range – beyond locations accessible by natural dispersal (see approach 9.7, 9.8).

Approach 9.2. Establish or encourage new mixes of native species.

Repeated periods of warming and cooling over the last 15,000 years have resulted in large shifts in species composition (Davis 1983, Jacobson et al. 1987, Shuman et al. 2002, Crausbay et al. 2017). Novel combinations of climatic and site conditions are expected to continue to affect individual species in different ways. Although some species may not occur in a forest or other community type as currently defined, they may have been together previously. Novel mixing of native species may lead to the dissolution of traditional community relationships and result in conversion to a newly defined or redefined forest or other community type (Root et al. 2003, Davis et al. 2005, Williams and Jackson 2007, Comer et al. 2019).

Examples of adaptation tactics include:

- Planting or seeding a mixture of native species currently found in the area that are not typically grown together but may be a suitable combination under future conditions.

- Underplanting with shade tolerant species (which tend to have wide ecological tolerance) to diversify the conifer component of a stand.
- Allowing a species native to the region or elevational zone to establish where it was not historically present, if it is already encroaching and likely to do well there under future climate conditions.

Approach 9.3. Guide changes in species composition at early stages of forest development.

Long-term ecosystem function may be jeopardized if existing and newly migrated species fail to regenerate and establish. Active management of understory regeneration may help transition forests to new and better-adapted compositions more quickly by promoting desired species and reducing competition from shrubs or from undesirable, poorly adapted, or invasive species. Natural disturbances often initiate increased seedling development and genetic mixing and can be used to facilitate adaptation (Joyce et al. 2009). Silvicultural prescriptions can mimic natural disturbance to promote regeneration in the absence of natural disturbance. Under drier conditions and increased stress, promoting regeneration and discouraging competitors may require more intensive site preparation, including prescribed fire, soil disturbance, and herbicide use. When forests are dominated by one or a few species, this approach may lead to conversion to a different forest type.

Examples of adaptation tactics include:

- Preventing and removing undesired species, including invasive nonnative, aggressive native species, or shade tolerant species where they have become overly abundant due to fire suppression tactics, in order to reduce competition for moisture, nutrients, and light.
- Planting or seeding sufficient stocks of desired species before undesirable species have the chance to establish or compete.
- Planting in heterogeneous patches to mimic historic stand structures to favor future diverse understory species.
- Thinning stands to favor and promote the growth of desirable species (e.g., shade-intolerant pines and oaks).

Approach 9.4. Protect future-adapted seedlings and saplings.

As climate change increases both direct and indirect stressors on forest ecosystems, it becomes increasingly important to ensure the adequate regeneration of tree species in order to maintain forest or woodland conditions (Bouchard et al. 2019, Shannon et al. 2019) Some genotypes may be fostered or introduced that are better adapted to future or changing conditions because of pest resistance, broad physiological tolerances, short regeneration times, or other characteristics (Spittlehouse & Stewart 2003, Millar et al. 2007). Seedlings and saplings are generally more sensitive than older growth stages to changes in moisture and temperature, physical disturbance, herbivory, and other stressors (Dobrowski et al. 2015). For this reason, protecting seedlings or saplings of existing or newly migrated species can strongly influence how communities adapt. Further, tending regeneration by protecting it from herbivory, removing competition, or otherwise reducing damage to seedlings and saplings helps to promote the transition to desired future conditions and functions.

Examples of adaptation tactics include:

- Using repellent sprays, fencing, or physical protection such as Vexar tubing, netting, and bud caps to prevent browsing on species that are expected to be well-adapted to future conditions.
- Using tree tops from forest harvest or plantings of non-palatable tree species as locations for "hiding" desirable species from herbivores to reduce browse pressure.
- Preventing and removing undesired species, including invasive nonnative, aggressive native species, or shade tolerant species where they are overly abundant in order to reduce competition for moisture, nutrients, and light.
- Restricting recreation or management activities that could damage regeneration.

Approach 9.5. Disfavor species that are distinctly maladapted.

A species is considered maladapted when its environment changes at a rate beyond the species' ability to adapt and accommodate those changes (Johnston 2009). Species at the southern or highest elevational extent of their geographic range are especially vulnerable to habitat loss, and some of these species are expected to decline rapidly as conditions change (Iverson and Prasad 1998, Iverson 2002, Ackerly et al. 2020). Maladapted species can also be identified through monitoring or inventory data, which may show evidence of decline at a particular site for some species, although their decline may not be attributed to a single cause, but to a combination of causes that may include varying degrees of interaction with climate change. Additionally, models that incorporate climate change and species' life history characteristics may identify other species that are likely to decline (Landscape Change Research Group 2014, Wang et al. 2014, Thorne et al. 2017). Species declines may require rapid and aggressive management responses to maintain forest cover and ecosystem function during periods of transition. In ecosystems where the dominant species are likely to decline dramatically or disappear, this may mean dramatically altering the species assemblage through active or passive means, potentially including transitions to non-forested systems on marginal sites (Hessburg et al. 2016).

Examples of adaptation tactics include:

- Removing unhealthy individuals of a declining species in order to promote other species expected to fare better. This does not imply that all individuals should be removed, and healthy individuals of declining species can be retained as legacies.
- Anticipating and managing rapid decline of species with negative prognoses in both the short and long term (e.g., sugar pine) by having adequate seed stock of a desired replacement species that are expected to do well under future climate conditions.
- Protecting healthy legacy trees that fail to regenerate while deemphasizing their importance in the mix of species being promoted for regeneration.

Approach 9.6. Manage for species and genotypes with wide moisture and temperature tolerances.

Inherent scientific uncertainty surrounds climate projections at finer spatial scales (Schiermeier 2010), making it necessary to base decisions upon a wide range of predictions of future climate. Managing for a variety of species and genotypes with a wide range of moisture and temperature tolerance may better distribute risk than attempting to select species with a narrow range of tolerances that are best adapted to specific set of future climate conditions (Millar et al. 2007, Young et al. 2020).

Examples of adaptation tactics include:

- Identifying and favoring species that are currently present and can persist under a wide variety of climate and site conditions.
- Planting or otherwise promoting species that have a large geographic range, occupy a diversity of site conditions, and are projected to have relatively stable or increased suitability in habitat and productivity.
- Promoting long-lived conifers with wide ecological tolerances, such as Douglas-fir (*Pseudotsuga menziesii*).
- Identifying and promoting species that currently occupy a variety of site conditions and landscape positions.

Approach 9.7. Introduce species that are expected to be adapted to future conditions.

Maintaining ecosystem function or transitioning to a better-adapted system may involve the active introduction of species or genotypes to areas that they have not historically occupied, often described as assisted migration, assisted colonization, or managed relocation (Figure 4. Hunter 2007, McLachlan et al. 2007, Hoegh-Guldberg et al. 2008, Ricciardi and Simberloff 2009). One type of assisted migration, sometimes called forestry assisted migration, focuses on moving species to new locations in order to maintain forest productivity and health under climate change (Seddon 2010, Pedlar et al. 2012, Young et al. 2020). Given the uncertainty about specific climate conditions in the future, the likelihood of success may be increased by relocating species with a broad range of tolerances (e.g., temperature, moisture) from across a wide range of provenances (von Holle et al. 2020). This approach is generally considered less risky than species rescue assisted migration (described in the next section) because it moves species to new habitats within their current range or over relatively short distances outside their current range, and focuses on widespread species for which much is known about their life history traits (Pedlar et al. 2012). However, there are still risks associated with moving any species, such as introducing new pests or diseases, the potential for hybridization with other closely related species, and genetic bottlenecks if the introduced seed source is not adequately diverse (Aubin et al. 2011).

Examples of adaptation tactics include:

- Planting oaks, pines, and other drought-tolerant species on sites within the current range that are expected to become drier and that have not been historically occupied by those species.
- Planting lower elevation species, such as ponderosa pine, higher than its current range on suitable sites based upon its projected range expansion.
- Planting disease-resistant cultivars of species such as sugar pine where they are likely to have suitable habitat.
- Planting closed-cone, stand replacing species such as knobcone or Coulter pine (*Pinus coulteri)* that will likely be more resilient in future higher severity fire regimes.

- Increasing species identity or genetic diversity of planting mix.

Approach 9.8. Move at-risk species to locations that are expected to provide sustainable habitat.

The climate may be changing more rapidly than some species can migrate, and the movement of species may be restricted by land use or other impediments between areas of suitable habitat (Davis and Shaw 2001, Iverson et al. 2004, Ackerly et al. 2020). This can be particularly challenging for species that are already rare or threatened. Another subset of assisted migration, sometimes called species rescue assisted migration, focuses on avoiding extinction of species threatened by climate change (Pedlar et al. 2012). If current habitat occupied by those species is expected to become (or already is) unsuitable, assisted migration to potential new suitable habitat may be the best option to ensure survival of the species (Vitt et al. 2010). Because some species are extremely rare, this type of assisted migration can also potentially cause declines in the donor populations through removal of seeds or individuals (Aubin et al. 2011). This approach is best implemented with great caution, incorporating due consideration of the uncertainties inherent in climate change, the sparse record of previous examples, and continued uncertainties of forest response (Ricciardi and Simberloff 2009).

A note on moving species and genotypes

Practitioners may choose to consider expanding the provenance (geographic source location) of seeds for plantings, ideally with thoughtful and informed development of provenancing guidelines (Breed et al. 2018). The risks of non-local seed provenancing include outbreeding recession (diminishment or loss of local adaptations when local and non-local genotypes hybridize), maladaptation (failure of a non-local genotype to thrive in a new setting), and introduction of a non-local genotype that behaves aggressively in a new setting. The challenge lies in identifying expanded seed provenances that promote genetic diversity and population fitness while avoiding the risks noted above (Breed et al. 2018). Practitioners are additionally encouraged to filter broad-scale provenancing guidelines with their local knowledge of species populations and microsites when selecting species.

Examples of adaptation tactics include:

- Planting or seeding a rare, threatened, or endemic plant species that is at risk for extinction in its current habitat to a newly suitable habitat outside its current range (i.e., assisted species migration).
- Assisting the migration of wildlife around barriers (e.g. across large tracts of unsuitable habitat or from low elevations to higher elevations) by trapping and releasing in newly suitable locations.
- Moving plants or animals from a mountaintop to another mountaintop north of their current range (i.e., assisted range expansion).

Strategy 10: Realign ecosystems after disturbance.

Ecosystems may face significant impacts as a result of climate change-related alterations in disturbances, including wildfire, drought, invasive species, and severe weather events (Dale et al. 2001, Williams and Jackson 2007, Millar and Stephenson 2015, Crausbay et al. 2017). Disturbances are primary drivers of many ecosystems, but changes in the frequency, intensity, and duration of disturbance events may result in pushing ecosystems outside their bounds of resiliency. Recent work by Davis et al. (2019) suggest low elevation conifers (ponderosa pine and Douglas-fir) in the west may already be crossing critical regeneration thresholds. This potential outcome will make it difficult for ecosystems to recover, creating significant management challenges (Lawler 2009, Millar and Stephenson 2015). Although it is often not possible to predict a disturbance event, it is possible to increase overall preparedness for uncharacteristically large and severe disturbances and prioritize rapid response. Many of the best opportunities for addressing disturbance-related impacts may occur immediately after the disturbance event. Having a suite of pre-planned options in place may facilitate an earlier and more flexible response and prevent maladaptive responses. In the future there are likely to be more frequent situations where a disturbance exceeds the resilience of an ecosystem, such that even intensive management may be insufficient to return the ecosystem to a prior condition. In these cases, it may be necessary to reevaluate and adjust management goals, which can involve realigning the ecosystem to better match new climate and environmental conditions (Millar et al. 2007). This strategy involves consideration of the full range of potential impacts and planning to respond to severe ecosystem disturbance and disruption.

Approach 10.1. Promptly revegetate sites after disturbance.

Changing conditions are expected to threaten regeneration processes for some species and may result in failure of natural regeneration of desired species. The state is already experiencing an increase in the frequency, intensity, and extent of uncharacteristically large and severe disturbances may disrupt regeneration and result in loss of forest cover, productivity, or function in the long term. Prompt revegetation of sites following disturbance can help reduce soil loss and erosion, maintain water quality, and discourage invasive species or even prevent vegetation type change in the newly exposed areas. These efforts can also provide an intervention point for promoting species and systems as well as promoting landscape structural heterogeneity that may be better adapted to future conditions (North et al. 2019).

Examples of adaptation tactics include:

- Planting a variety of future-adapted species during revegetation efforts to ensure diverse regeneration and provide options for future management.
- Reforesting disturbed sites, like those affected by fire or tree mortality, in planting arrays with a combination of scattered individuals, clusters of trees and non-planted open spaces (i.e., ICO plant design) to help facilitate forest compositional heterogeneity.
- Creating suitable physical conditions for natural regeneration through site preparation (e.g., chaining after burning to promote seed establishment).
- Monitoring areas of natural regeneration on a more frequent basis, and prioritizing planting or seeding where natural regeneration is slow or unlikely to succeed.

- Coordinating with the public and other organizations to avoid conflicting or misguided responses.

Approach 10.2. Allow for areas of natural regeneration to test for future-adapted species.

Although many areas may be replanted after severe disturbance, some areas can be set aside to allow for natural regeneration as a means to identify the well-adapted species and populations (Joyce et al. 2009). The use and monitoring of test or "control" areas of natural revegetation following disturbance may help managers identify (1) species that are well-adapted to the changing climate and environmental conditions and (2) potential threats in the form of invasives or poor regeneration of desirable species. This approach may be most effective if the implementation and monitoring are designed in collaboration with researchers.

Examples of adaptation tactics include:

- Using remote sensing to evaluate the likelihood remaining trees will provide for natural regeneration, thus anticipating the need for augmentation through planting.
- Using modeling and remote sensing to identify areas most likely to regenerate naturally.
- Monitoring naturally revegetated areas for changes in species composition, productivity, and other factors.
- Controlling competition from invasive species to enhance regeneration of desired tree species.
- Removing selected small-diameter residual trees to reduce competition, increase sunlight, and improve seed germination potential.
- Creating conditions that will be favorable for regeneration of desired species, for example by removing the duff layer to allow germination and sprouting of pine species.

Approach 10.3. Realign significantly disrupted ecosystems to meet expected future conditions.

California, like many western states, is expected to experience increases in uncharacteristically large disturbance events, such as wildfire, or stress, such as prolonged and severe drought. Some ecosystems may experience such significant disruptions that desired conditions or forest management objectives appear to be no longer feasible. This situation may be linked to "mega-disturbances" such as massive wildfires or extended severe drought (Millar and Stephenson 2015, Crausbay et al 2020) in places where most species in the ecosystem are projected to decline as climate changes. Such a forecast will likely produce conditions for invasive species to quickly colonize and establish. Management of systems experiencing this level of change may require adjustment to create necessary changes in species composition and structure to better adapt forests to current and anticipated environments, rather than to historical pre-disturbance conditions (Spittlehouse and Stewart 2003, Millar et al. 2007). Developing clear plans that establish processes for realigning significantly altered ecosystems before engaging in active management will allow for more thoughtful discussion and better coordination with other adaptation responses.

Examples of adaptation tactics include:

- Allowing a transition in forest type by planting future-adapted species within a stand that is already declining or is expected to decline (see figure 4 above).
- Planting species expected to be better adapted to future conditions, especially where natural regeneration in forests affected by disturbance is widely failing.
- Creating novel communities "from scratch" in areas that have been severely affected by natural or human disturbance as part of intensive remediation efforts.
- Reevaluating altered ecosystems to manage for critical ecosystem services, such as soil or water quality, rather than managing for specific species or communities.

Photo: Lakes Basin region, Plumas NF, CA.

Adaptation Strategies for Planning and Policy

The Adaptation Strategies and Approaches for land managers have been designed for natural resource managers to use in planning on-the-ground management activities. However, many adaptation actions will require or benefit greatly from planning, education and outreach, research, or changes in policy or infrastructure. These additional actions will involve many other people beyond the core land management staffs traditionally charged with executing treatments on the ground. It will be vital to engage these different disciplines to optimize effective climate change adaptation across large scales, but the steps involved in working with these other groups are beyond the scope of this document. Some examples of these actions include:

Planning

- Including risk management in forest plans and developing enhanced capacity for risk management (Kellomäki et al. 2005, Ohlson et al. 2005, Johnston et al. 2006, Eyvindson and Kangas 2018).
- Working with collaboratives to manage expectations and obtain social license for executing innovative land management strategies (Cerveny et al. 2018).
- Documenting clear plans for how to respond to more frequent or severe disturbances in advance to allow for a faster, more thoughtful, better-coordinated response (Joyce et al. 2009).
- Using landscape-level planning and partnerships to identify and acquire high-priority areas for conservation or to share resources, expertise, and actions across jurisdictional boundaries (D'Antonio et al. 2004, Mawdsley et al. 2009, Anderson et al. 2012, Keenan 2015).
- Incorporating predicted climate change impacts into species and land management plans, programs, and activities (Mawdsley et al. 2009, Peterson et al. 2011, Swanston and Janowiak 2012).
- Increasing flexibility of planning goals and objectives to address dynamic processes, unexpected occurrences, and uncertainty (Ogden and Innes 2007, Millar et al 2007, Spies et al. 2010, Messier et al. 2016).
- Realigning management of significantly altered ecosystems to meet expected future environmental conditions (Spittlehouse 2005, Millar et al. 2007, Groves et al. 2012, Morelli et al. 2012).
- Linking adaptation planning to larger regional and national guidance documents that outline emerging principles for ecosystem-based adaptation (Peterson et al. 2011, The National Wildlife Federation and Manomet Center for Conservation Sciences 2013).

Adaptation Strategies for Planning and Policy (continued)

Policy

- Reviewing and amending laws, regulations, or policies to improve their ability to support adaptation actions (Spittlehouse 2005, Johnston et al. 2006, Mawdsley et al. 2009, Morelli et al. 2012, Peterson et al. 2011, Cross et al. 2012).
- Streamline permitting processes to support landowners' ability to enact adaptive actions (CA Forest Management Task Force 2020).
- Managing populations of native herbivores (e.g., deer), grazers (e.g., cattle), or invasive animals (e.g., feral hogs) by using landscape-level and cross-disciplinary planning (Creamer et al. 2019, Lesser et al. 2019).
- Reevaluating seed zone sizes maps and policy and rules guidance governing the movement of seed stocks (Spittlehouse and Stewart 2003, Millar et al. 2007, Stein et al. 2013, Doherty et al. 2017).

Infrastructure and Institutional Capacity

- Improving infrastructure and resources for species regeneration propagation (e.g., nurseries) that focuses on providing a diversity of genetic material (Millar et al. 2007).
- Encouraging and helping to enable increases in wood processing facilities distributed around the state to help facilitate treatments across the landscape (Crandall et al. 2017).
- Developing a gene management program to maintain diverse gene pools (Halofsky et al. 2011).
- Evaluating and diversifying the forest economy (e.g., timber sales and forest products) in response to changes in the market (Ogden and Innes 2008).
- Evaluating and improving road construction standards and stream crossings to minimize negative impacts on forest communities (Groves et al. 2012, Nolan et al. 2015, Warrington et al. 2017).

Research

- Engaging manager prior to developing research questions and ensuring results are applicable to decision making (Carter et al. 2020).
- Developing decision-support tools that incorporate climate change information into management plans (National Fish Wildlife and Plants Climate Adaptation Partnership 2012, Swanston and Janowiak 2012, Stein et al. 2013).
- Bridging the gap between academic research and implementation by identifying current science and research needs (Swanston and Janowiak 2012).
- Creating climate change vulnerability assessments for a wide range of ecosystems and geographies (Swanston and Janowiak 2012, Thorne et al. 2018).

Adaptation Strategies for Planning and Policy (continued)

- Developing decision-support tools that incorporate climate change information into management plans (National Fish Wildlife and Plants Climate Adaptation Partnership 2012, Swanston and Janowiak 2012, Stein et al. 2013, Steel et al. 2020).
- Staging management activities as experiments to measure the effects or success of adaptation actions (Hemery 2008, Nagel et al. 2017).
- Capturing genetic variability in trees for adaptation to climate change (Wright 2014)
- Supporting and coordinating monitoring programs to track impacts of climate change and adaptation actions on ecosystems (Brandt et al. 2012, Cross et al. 2012, Morelli et al. 2012, National Fish Wildlife and Plants Climate Adaptation Partnership 2012, Swanston and Janowiak 2012).
- Including climate variables in growth-yield models (Kellomäki et al. 2005, Trasobares et al. 2016).

Education and Outreach

- Increasing the knowledge and experience of natural resource professionals, including decision makers and planners, so that they can better integrate climate change considerations into their projects and work plans (Groves et al. 2012, Morelli et al. 2012, National Fish Wildlife and Plants Climate Adaptation Partnership 2012, Swanston and Janowiak 2012, Stein et al. 2013).
- Creating training opportunities and communities of practice (National Fish Wildlife and Plants Climate Adaptation Partnership 2012, Swanston and Janowiak 2012).
- Preparing the public for adaptation principles through outreach (Groves et al. 2012, National Fish Wildlife and Plants Climate Adaptation Partnership 2012, St-Laurent et al. 2019).
- Developing a science-management or citizen science partnerships to assist in the collection, cultivation, research, or monitoring of at-risk plant species grown outside their natural habitats, such as within urban environments or novel ecosystems (National Fish Wildlife and Plants Climate Adaptation Partnership 2012, Swanston and Janowiak 2012, Stein et al. 2013).

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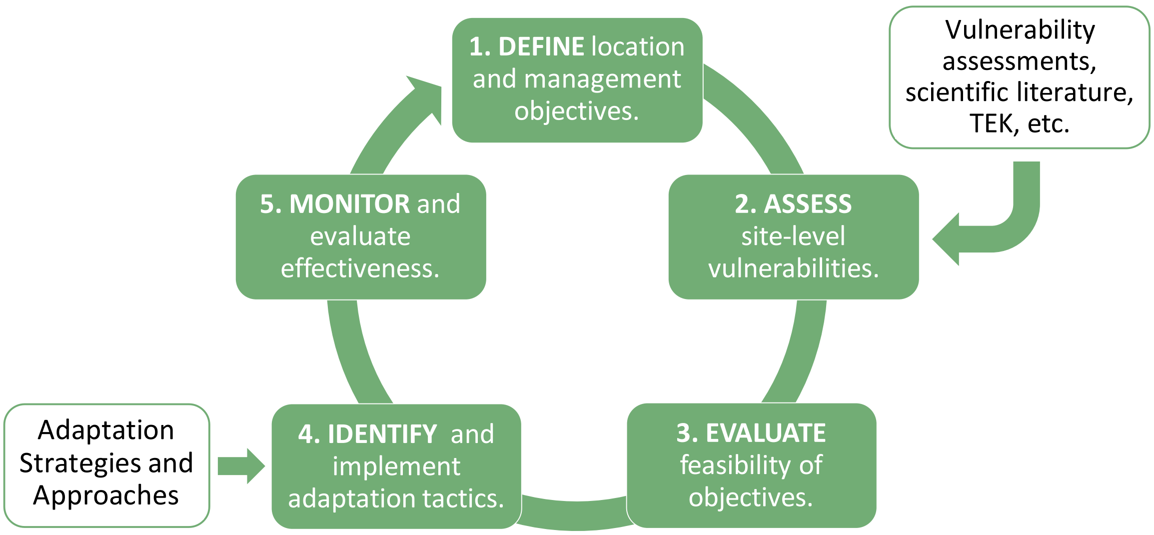
Appendix 1

Adaptation Workbook Steps in Brief

This is a brief outline of the Adaptation Workbook process. Find the full process in the *Forest Adaptation Resources: Climate change tools and approaches for land managers, 2nd edition* (www.nrs.fs.fed.us/pubs/52760) and as an online tool at www.adaptationworkbook.org.



Step 1: DEFINE location, project, and time frames.

"What are your management goals and objectives for the project area?"

The first step is to describe the project area and your management objectives before considering the potential effects of climate change. This may include identifying:

- Any ecosystem types, stands, or other distinct areas that you want to consider individually
- Any short- or long-term milestones that can be used to evaluate progress

Step 2: ASSESS site-specific climate change impacts and vulnerabilities.

"What climate change impacts and vulnerabilities are most important to this particular site?"

Climate change will have a wide variety of effects on the landscape, and not all places will respond similarly. List site-specific factors may increase or reduce the effects of climate change in your project area, such as:

- Site conditions, such as topographic position, soils, or hydrology
- Past and current management
- Forest composition and structure
- Susceptibility to pests, diseases, or other stressors that may increase

Step 3: EVALUATE management objectives given projected impacts and vulnerabilities.

"What management challenges and opportunities may occur as a result of climate change?"

This step explores management challenges and opportunities that may arise under changing conditions. For each of your management objectives, consider:

- Management challenges and opportunities given the climate impacts you identified previously
- The feasibility of meeting each management objective under current management
- Other considerations (e.g., administrative, legal, or social considerations) beyond climate change that may affect your ability to meet your management objectives

Step 4: IDENTIFY adaptation approaches and tactics for implementation.

"What actions can enhance the ability of the ecosystem to adapt to anticipated changes and meet management goals?"

Generate a list of adaptation tactics —prescriptive actions specifically designed for your project area or property and your unique management objectives. Use the menu of Adaptation Strategies and Approaches from the following page as a starting point for identifying specific management tactics (e.g., what, how, when) that you can implement. As you develop tactics, consider the

- Benefits, drawbacks, and barriers associated with each tactic
- Effectiveness and feasibility of each tactic

Step 5: MONITOR and evaluate effectiveness of implemented actions.

"What information can be used to evaluate whether the selected actions were effective and inform future management?"

Monitoring metrics can help you determine whether you are making progress on your management goals and evaluate the effectiveness of those actions. When identifying monitoring items, work to identify monitoring items that:

- Can tell you whether achieved your management goals and objectives
- Can tell you whether the adaptation tactics had the intended effect
- Are realistic to implement

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