PUBLIC POLICY INSTITUTE OF CALIFORNIA

SEPTEMBER 2017

Van Butsic,
Henry McCann,
Jodi Axelson,
Brian Gray,
Yufang Jin,
Jeffrey Mount,
Scott Stephens,
William Stewart

Supported with funding from the S. D. Bechtel, Jr. Foundation and the US Environmental Protection Agency

Improving the Health of California's Headwater Forests

Cover image: Ken Meinhart, USFWS Pacific Region

SUMMARY

CONTENTS

California's headwater forests are not thriving under current management practices, and changes are needed to make them more resilient to periodic drought and long-term climate change. More active management of these lands is needed to improve forest health, reduce the risk of major wildfires and pest infestations, and maintain the flow of benefits provided by this critical natural infrastructure.

Decades of fire suppression, an emphasis on short-term management priorities, weather extremes, and a warming climate have set the stage for the decline in forest resilience. Two-thirds of the state's surface water supply originates in these mountainous forests. California stands to lose timber production, wildlife habitat, recreational opportunities, and water supply if this vital natural infrastructure continues to decline. Management options exist—prescribed fire, managed wildfire, mechanical thinning, and forest pest treatments—that can help rebuild resilience in these forests and prepare them for a challenging future.

California needs to increase the pace and scale of efforts to improve forest health. The strategic removal of high-density smaller trees and fuels is essential to increasing long-term resilience of headwater forests. This will require management, regulatory, and legal reforms. We suggest changes in three areas:

- Make long-term forest health the top priority for guiding agency rules, policy, and management practices.
- Define forest treatment needs and make the most of available funds.
- Make greater use of tools that create opportunities for collaboration.

Within each of these broad themes, we suggest specific reforms and actions to implement them. Many of these actions can take place without major legislation or large increases in funding, relying instead on changes in rules or administrative decisions. Taken together, implementing these reforms will improve the health of California's headwaters and ensure the environmental, social, and economic benefits they provide.

Introduction

All Californians benefit from headwater forests. A crucial part of the state's natural infrastructure, they provide a range of benefits—abundant high-quality water, habitat for iconic plants and animals, timber, forage products, and areas for outdoor recreation. Yet there is no assurance that these benefits will continue. The combination of low precipitation and record-high temperatures during California's most recent drought (2012–16) resulted in sharply increased tree mortality and large, severe wildfires. These short-term stressors, combined with historical management decisions and a changing climate, have made California's headwater forests susceptible to dramatic change from future droughts, fires, and pest infestations. There is an urgent need to reform policy and management to ensure that Californians continue to benefit from these forests for generations to come.

Headwaters collect and convey water from higher elevations to lower elevations. California's most important headwater region—nearly 15 million acres of forest, woodland, and rangeland stretching from Siskiyou County in the north to Kern County in the south—drains into the major multiple-purpose dams on the western slopes of the Sierra Nevada and southern Cascade ranges (Figure 1). Runoff from these lands flows into more than 20 reservoirs of statewide importance, providing nearly two-thirds of California's surface water supply and 15 percent of its electricity from hydropower plants (Mount et al. 2016). Our research scope is the nearly 10 million acres of forest lands within this region.[1]

What is Forest Resilience?

Resilience is the ability of a forest to absorb and recover from disturbance (e.g., fire, drought, and insect outbreaks) and return to its original or similar condition (Gunderson 2000). Forests that lack resilience may undergo permanent dramatic change in response to disturbances. For example, repeated severe fires can shift conifer forests to shrublands (Coppoletta et al. 2016). Such changes can reduce streams of ecological, social, and economic benefits that now flow from forests. Climate change has already begun to place significant pressure on forests by intensifying stressors, and as a result many headwater ecosystems could experience changing conditions in the future.

While measuring resilience is difficult, one broad metric is annual tree mortality, since forests with consistently high mortality will eventually shift to other vegetation types. Efforts to increase resilience now will not prevent some forests from transitioning to shrublands as the climate continues to change. However, this can reduce the risk of transformative events such as catastrophic fires and pest and disease outbreaks. Improving resilience now may also increase the longevity of some headwater forests well into the future. This management approach supports the continuation of benefits provided by headwater forests and supports a more diverse mosaic of forest and shrub habitat. The short- and medium-term efforts to increase resilience described in this report may help ecosystems adjust to future climate trends (Schoennagel et al. 2017).

The decline in headwater forests can be traced to historic management practices that have resulted in an unusually high density of trees (both dead and alive) and a lack of large trees. Fortunately, management tools exist to selectively thin forests, which can reduce the risk of severe wildfires and pest infestations and improve adaptation to climate change. Prescribed fire and managed wildfire can build resilience by reducing the density of small diameter trees and surface fuels such as leaves, needles, downed wood, and shrubs, while leaving large trees that provide important ecosystem functions. Mechanical thinning, commonly referred to as "selection thinning" and

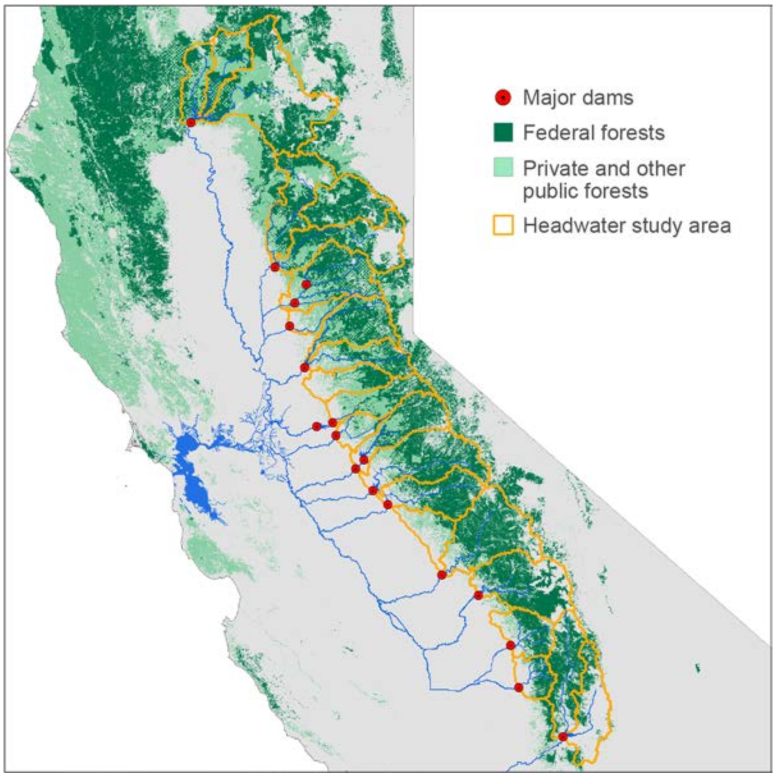
---

[1] California has about 24 million acres of land that can be classified as forest. The major headwater region—the study area for this report—encompass nearly 15 million acres, 10 million of which are defined as forests. The study area excludes headwater forests in the Klamath/North Coast, Central Coast, and South Coast hydrologic regions.

"vegetation treatment" when done on private lands, mimics some of the effects of fire and provides wood products for commercial uses. Commercial uses of wood products include the construction of housing in urban and suburban areas—which has the added benefit of sequestering carbon.[2] Reducing the density of forests using a mix of fire and mechanical thinning can make them less vulnerable to current and future stressors, particularly those associated with climate warming and increasing variability of precipitation. Yet these tools remain underutilized due to many political, social, historical, and budgetary reasons.

FIGURE 1

California's headwater forests are above major dams on western slopes of the Sierra Nevada and southern Cascades



SOURCES: California Spatial Information System for hydrologic features; USGS Small-scale Dataset—Major Dams of the United States for location of major dams; USDA Natural Resources Conservation Service GeoSpatialDataGateway for watershed boundaries; California Forests and Rangelands Assessment Statewide Land Use/ Land Cover Mosaic (2006) for forest vegetation boundaries; California Forests and Rangelands Assessment California Multi-Source Landownership (2009) for landownership boundaries.

NOTE: The study area boundaries delineate major watersheds based on hydrological unit maps (HUC8) as modified by the authors.

Finally, long-term resilience may require actions that can have short-term consequences—for example, allowing wildfire to spread in some areas, or harvesting trees to make forest management economically viable. Such management decisions may not be well-received by the public because of their local negative impacts, such as temporarily generating smoke, initially making landscapes less attractive, or modifying other ecosystem attributes. Potential policy and management solutions will have to acknowledge these short-term impacts while recognizing that the headwater forest ecosystem faces long-term existential threats in the absence of adequate management.

[2] Wood framing was used to construct more than 90 percent of residential housing units in the western US since 2009 (author estimate using US Census Bureau 2016). The use of wood as a construction material sequesters carbon more effectively than concrete or brick (Gustavsson et al. 2006).

Forest resilience can be improved by crafting policies that increase the pace and scale of the use of these tools by federal, state, and local agencies and stakeholders. We suggest changes that fall under three broad categories:

- Prioritize long-term forest health for guiding agency rules, policy, and management.
- Define forest treatment needs and make the most of available funding sources.
- Make greater use of tools that create opportunities for collaboration.

We believe that the portfolio of linked reforms detailed in this report can produce real change.

This report is organized as follows: We begin with an explanation of key players in California’s headwater forests. This is followed by background on how these forests have changed over the past century. Next is a summary of forestry management tools to build resilience. And finally, we offer a breakdown of specific reforms to help bring California’s headwater forests back to health and prepare them for a warming future.

This project has benefited from the input of numerous policymakers and stakeholders who provided insights through individual discussions and at a 2016 workshop on challenges and opportunities for building resilience in California’s forests.

Glossary

Biomass: In this context, the amount of living and dead trees and other plant material in a forest.

Disturbance regime: The pattern of stressors (e.g., fire, drought, pest infestation) experienced by forest ecosystems.

Forest: Any land containing conifer and/or hardwood trees with greater than 10 percent tree canopy cover.

Forest resilience: The ability of a forest to absorb and recover from disturbance (e.g., fire, drought, and insect outbreaks) and return to its original or similar condition.

Forest structure: A mix of variables such as the number of trees per acre, the age and size of living and dead trees within a forest, and other factors that influence forest resilience.

Headwater: The lands that collect and convey water from high to low elevations.

Inventoried roadless areas: Portions of US Forest Service lands where new roads and timber harvesting are prohibited—though some harvesting for fuel reduction is permitted.

Ladder fuels: Plant matter—dead or alive—that helps a fire to spread from the ground into the tree canopy.

Managed wildfire: Monitoring and managing wildfires to thin dense forests and improve forest structure.

Mechanical thinning: Using mechanized cutting and hauling equipment to selectively remove trees and shrubs from the forest.

Non-reserved lands: The portion of US Forest Service lands where timber harvesting is permitted.

Prescribed fire: Planning and intentional setting of fires.

Sawlog: The part of a harvested tree that is suitable for sawing into lumber.

Surface fuels: Vegetation and downed woody material near or on the ground through which fire will spread.

Wildfire suppression: The suite of tactics used to extinguish a wildfire.

Key Players in Forest Management

A wide variety of agencies and stakeholders own land and have management responsibilities in the state's major headwater region. Landownership is dominated by the federal government (which owns about two-thirds of the major headwater region), followed by family forest owners (25%) and industrial timber producers (10%). The following summarizes their primary roles in the management of these lands.

United States Forest Service (USFS): USFS Region 5 (covering California, Hawaii, and the Pacific Islands) owns and manages about 7.7 million acres of the state's major headwater region (53% of this report's study area). Just over half of all USFS Region 5 lands are "non-reserved," meaning that they are managed for activities such as timber production, livestock grazing, and energy and mineral production. The remaining 45 percent of Region 5 lands are referred to as "reserved lands," which have some restrictions on resource extraction activities. About half of the reserved lands have been designated by Congress as wilderness areas where timber harvesting, mining, grazing, and road construction are prohibited. The other half is defined as "inventoried roadless areas." These areas generally prohibit the construction of new roads and timber harvesting—though some harvesting for fuel reduction is permitted. USFS also conducts forestry research and provides management assistance to non-federal forest owners. It is also responsible for managing wildfires on most federal and some non-federal lands. USFS allocated $67 million for active forest management to USFS Region 5 in fiscal year 2016. USFS Region 5 spent an additional $321 million on wildfire suppression during the same period (USDA Forest Service 2017a; personal communication, Nicole Williams, USFS Region 5).

National Park Service (NPS): NPS manages about 1.6 million acres (11% of the state's major headwater region), including some of California's most cherished headwater ecosystems (e.g., Lassen, Yosemite, Kings Canyon, and Sequoia National Parks). NPS is tasked with conservation of natural and historic amenities while facilitating access for the public.

Bureau of Land Management (BLM): BLM is responsible for managing lands and resources on approximately 0.4 million acres (3% of the state's major headwater region). Management programs range from conservation and species protection to energy production. The BLM fire program conducts fire suppression, preparedness, fuels management, and community assistance and protection in the agency's areas of responsibility.

California Department of Forestry and Fire Protection (CAL FIRE): CAL FIRE is responsible for fire prevention and suppression on wildlands within the State Responsibility Area—comprising more than 31 million acres of mostly privately owned undeveloped forests, grasslands, and shrublands across the state. CAL FIRE does not have fire suppression responsibilities for dense population centers, agricultural lands, or lands administered by the federal government. CAL FIRE regulates forest management on private land in California through enforcement of the Forest Practice Act. The state of California owns just 90,000 acres of the major headwater region. CAL FIRE spent $1.9 billion in 2015–16, with the lion's share ($1.8 billion) dedicated to fire suppression (California Department of Finance 2017).

Family-owned forests: Family-owned forested parcels less than 5,000 acres in size account for almost 25 percent of California's major headwater region. Forest management and harvest is less likely to take place on these small properties, partly due to the high cost per acre of planning and permitting (Stewart et al. 2016). These landowners benefit in the short term from fire suppression, as wildfire can put their property and assets at direct risk of damage.

Industrial forests: Privately owned forested parcels greater than 5,000 acres account for around 10 percent of California's major headwater region. These forests are typically managed for high yields and fire-risk reduction, which are achieved through intensive management. Statewide, industrial forests produce more than 80 percent of California's harvested wood products (Stewart et al. 2016).

Non-governmental organizations (NGOs): Many NGOs work in the forests, directly impacting the landscape through restoration activities on their own lands or by agreement with other landowners. These organizations influence policy and practice by advocating for specific actions by public agencies and other landowners.

Local communities: The headwater forests are home to roughly 800,000 people (Sierra Nevada Conservancy 2011).[3] American Indians are just over 2 percent of the regional population and the headwaters are the ancestral home of many California tribes. The largest employment sectors in the region are now health, retail trade, and education (Sierra Nevada Conservancy 2011). Many land-use decisions related to forest management will have direct effects on nearby communities. Local communities can act as strong voices in conversations about the future direction of forest management.

Decades of Decline in Forest Resilience

Headwater forests have experienced significant change over the past 150 years. Logging, natural regeneration, and fire suppression have resulted in forests that are denser and have fewer large trees than in the past. This new forest structure, which is characterized by high densities of small trees and uncharacteristically high levels of "surface fuels" (highly combustible shrubs, grasses, downed wood, leaves, and needles), presents challenges for management. Poor forest conditions and the recent five-year drought generated an unprecedented pulse of tree mortality, with an estimated 15 million additional dead trees per year (Asner et al. 2016). The spatial extent, severity, and frequency of tree mortality from water stress, insects, and disease have surpassed anything recorded in recent human history (Millar and Stephenson 2015).

Fire, insects, and diseases have interacted to shape forests in California for millennia. In the past, California had a fire regime characterized by frequent low- to moderate-intensity fires that mostly spared large trees, with most areas burning every 8 to 20 years (Stephens et al. 2007). This fire regime reduced the build-up of surface fuels and small trees and shrubs, which promoted a forest structure favoring larger diameter and fire-tolerant species (Stephens et al. 2008). At the time, larger trees were being killed by beetles and other insects, which find them to be more abundant food resources. The combination of fire and loss of some larger trees opened the canopy and provided for species which use dead trees as habitat. The classic parklike landscapes of large trees with open understories that many Californians associate with the Sierra Nevada were driven by the combined disturbances of fire and insects.

The progressive introduction of logging, fire suppression, and environmental laws has changed the structure of California's forests. After the northwestern states experienced a series of devastating wildfires in the early 20th century, USFS made suppression of all fires a primary goal to improve safety and support economic development. This reduced the primary mechanism for maintaining low-density forests with large trees. As a result, logging became the dominant form of tree removal. Logging peaked in California in the 1950s, but new roads in the national forests kept statewide harvest levels high through the 1970s. Timber harvest throughout the 20th century removed most of the largest trees from the landscape. Planting programs and natural regrowth in logged forests—in the absence of regular fires—led to the proliferation of numerous small trees.

---

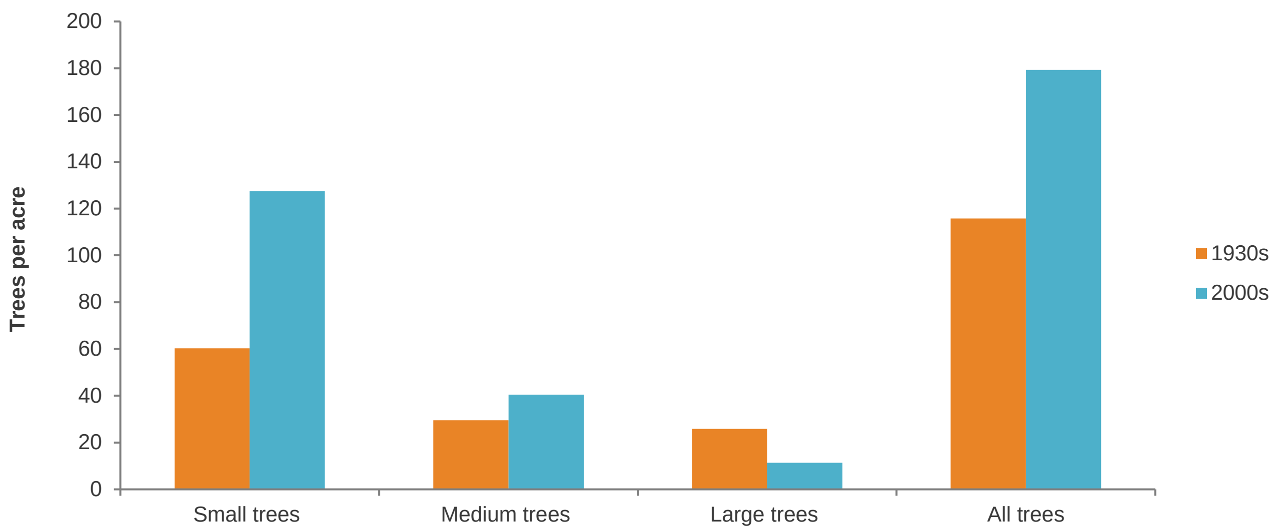
[3] Population characteristics described here were derived from a demographic study of communities located within the Sierra Nevada Conservancy (SNC) regional boundary. This boundary overlaps significantly, but not completely, with the major headwater region as defined in this report. One of the major differences is that the SNC region boundary includes the eastern portion of the Sierra Nevada mountains, which is not part of this report's study area.

Beginning in the late 1960s large areas of national forest lands received wilderness and roadless designations and were removed from timber harvest. In addition, new water quality regulations led to sharp reductions in harvests on both federal and private forest lands (Stewart et al. 2016). The decline in statewide timber harvest—coupled with fire suppression and past logging practices—accelerated changes in forest structure.

For example, since 1930 the number of small trees per acre—4 to 12 inches in diameter at breast height (dbh)—has doubled in the Sierra while the number of large trees (>24" dbh) has declined by half (Figure 2) (McIntyre et al. 2015). The amount of surface fuels has likewise increased dramatically over this time (Stephens et al. 2016).

FIGURE 2

Headwater forests have become denser, with more small trees and fewer large trees



SOURCE: McIntyre et al. 2015 supplemental appendix.

NOTES: The data presented here was collected through tree inventory surveys between 1920–30 (Vegetation Type Mapping project) and 2001–10 (USFS Forest Inventory Analysis). The values represent the statistical mean number of trees per acre across several sampling sites representing the highlands of the Sierra Nevada and southern Cascade ranges. Trees are categorized as small if they are 4–12 inches diameter at breast height (dbh), medium if they are 13–24 inches dbh, and large if they are over 24 inches dbh.

This change in structure makes California’s headwater forests prone to severe wildfire and large insect and disease outbreaks. Two of the three largest fires in state history happened in the past five years within or in close proximity to headwater forests. The severity of fire has also increased, leading to higher mortality of large trees, which typically can withstand low- or moderate- intensity fires (Miller and Safford 2012). Insect outbreaks have also become more intense and are accelerating the mortality of large trees (Fettig 2012). In the Sierra Nevada, the western pine beetle attacks large ponderosa pines and the mountain pine beetle attacks large sugar pines. Outbreaks of insect-driven tree mortality in the state grew to more than 4 million acres in 2016, a nearly five-fold increase in the number of acres reported in 2014 (California Forest Pest Council 2016).

Climate change will magnify these difficult conditions. As the climate warms, some areas in the headwaters may become too dry to support conifer forest and convert to shrublands, especially after severe fires. Likewise, warmer weather may lead to more days with optimal fire conditions, exacerbating the conversion of forest to shrublands. The challenge faced by managers is therefore immense: given the current forest structure and increasing temperatures in the future, what management actions are most likely to ensure that forests continue to provide benefits to Californians in the future?

Headwater forests are not monolithic. There are important differences in structure and density—and ultimately forest health—as well as differences in responses by the various types of landowners. There are three notable differences among management approaches:

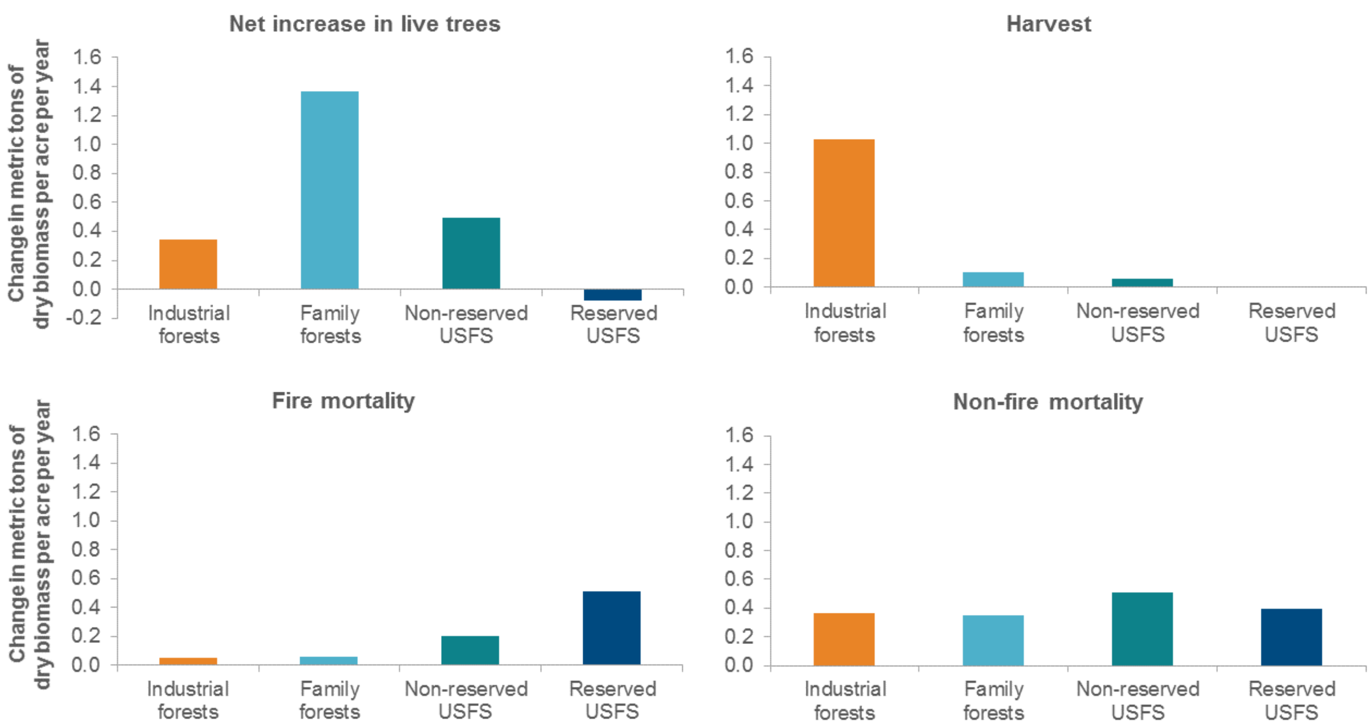
- **Family-owned forests**, which have limited management of biomass and regular suppression of fires, have seen the largest increase in living tree biomass. In contrast, reserved USFS lands, which are also not actively managed but allow fire, have seen a net reduction in living biomass, principally from losses due to large fires.
- **USFS non-reserved and reserved lands** have higher losses in living biomass than private lands due to insects, disease, drought stress, and fire.
- **Industrial forests** have extensive tree removals, much of it for timber products, and therefore significantly less biomass compared to family and USFS forest lands.

These large differences in biomass accumulation and removal reflect how important the management approach is to forest conditions. This suggests that concerted efforts to change management approaches can have significant impacts on forest health at large scales.

Figure 3 summarizes these broad changes in statewide forest conditions in terms of net increase in live trees, harvest, fire mortality, and non-fire mortality across four different types of landownership: industrial forest, family forest, and USFS non-reserved forests and reserved forests (e.g., wilderness and inventoried roadless areas).

FIGURE 3

Change in statewide forest conditions over time varies as a result of different approaches to management



SOURCES: USFS Forest Inventory Analysis (FIA) plot dataset, calculations from a February 10, 2017 letter from Jeremy Fried, USFS Pacific Northwest Forest and Inventory Analysis program to J. Keith Gilless, chairman, California Board of Forestry and Fire Protection.

NOTES: This FIA analysis provides a summary of the statistical estimates of mean changes to all of California's forest lands caused by thinning, harvest, wildfire, and natural mortality. The plots were measured in 2001–03 and re-measured in 2011–13. Change in plot characteristics is presented in tons of dry biomass (MgBiomass/ac/yr). The figure shows change in biomass by type across four management regimes. Non-reserved USFS lands could potentially be managed in ways similar to industrial or family forests. On reserved USFS lands, many forest management actions are prohibited, particularly in designated wilderness and roadless areas. The figure excludes forest lands held by other public agencies (e.g., National Park Service, Bureau of Land Management), for which mortality estimates by cause were not calculated.

Managing Forests for Resilience

Forest management in the headwaters is inherently difficult because increasing one benefit may reduce other benefits in complex and non-linear ways. There are few management choices where all benefits are increased. The California spotted owl provides a high-profile example of this challenge. California spotted owls require dense canopy cover for nesting habitat, but forests with such densities are also fire-prone. Indeed, a recent study indicated that nearly all California spotted owl nesting habitat is likely to burn in the next 75 years under predicted fire patterns, and severely burned forests are unusable nesting habitat for owls (Chiono et al. 2017). However, creating more open forest—which may be less prone to large, severe fire—also reduces owl nesting habitat, leaving difficult choices for land managers attempting to maintain this species. As another example, a similar dynamic plays out with decisions about whether to harvest commercial-sized "sawlogs" during mechanical thinning. Harvesting medium-sized trees creates revenue to pay for forest management projects. But at the same time, some areas lack larger trees, and removing marketable timber may exacerbate this problem.

Given these complexities, there is no single forest management prescription that is right for all headwater forests. The suite of actions focused on reducing the volume of forest biomass will enable forests to provide more reliable benefits now and into the future. Lower biomass (especially downed woody fuels and fewer small and dead trees) reduces the risk of high severity fires, while promoting low- and moderate-severity fires that increase habitat heterogeneity and do not kill many large trees. Lower biomass also reduces the overall water demands of forests. In drier areas, less competition for water will lead to greater tree growth, healthier trees, and eventually more large trees. Lower stand density is also key to preventing massive insect attacks (Box 1). Thinner forests will be better able to adapt to a hotter and potentially drier future, and be better able to resist wholesale conversion in composition. This approach to management—termed "realignment"—relies on historical ecology to understand changing forest conditions, but does not seek to recreate those conditions (Stephens et al. 2010).

In the broadest sense, managing headwater forests to improve resilience means reducing current high fuel loads, increasing the diversity of tree sizes in the forest, reducing mortality from disease and insects, and protecting large trees. The tools currently exist to achieve these goals, but it will require managers to use all available tools and to do so at a grand scale. These tools include the expansion of ecologically beneficial fire with both prescribed fire and managed wildfires, as well as mechanical methods of forest thinning. Early actions to prevent the spread of insect infestations can complement these three essential approaches at local scales (Box 1).

Two Types of Ecologically Beneficial Fire

Reintroduction of fire on the landscape is one of the most promising tools for improving forest conditions (North et al. 2012). One way of accomplishing this is by prescribing fire for specific sites. This approach uses intentionally ignited forest fires to remove surface fuels and small trees from specific areas. Forest managers develop a plan for intentionally igniting forest fires under carefully controlled conditions that can be done alone or in conjunction with mechanical thinning. Managers rely on fire behavior science and ecological principles to design the fire prescription—a process that includes defining the objectives of the fire, its intended size, the conditions under which the fire may take place, and when it must be suppressed. Prescribed fire reduces stand density and surface fuels in the short term. In the longer term it can increase habitat diversity and ecosystem complexity, which improves wildlife habitat (Stephens et al. 2012). Relative to the need, prescribed fire to reduce surface fuels is currently used in California at low rates and at small scales (North et al. 2012).

Box 1: Short-term Management of Pests to Improve Forest Resilience

Forest pests—particularly tree-killing bark beetles—are impossible to manage or control past a certain scale of infestation (Bentz et al. 2009). Over the long term, creating a less dense forest structure is the best prevention against pests, as well as overall resilience to natural disturbances and a changing climate.

Even with such long-term approaches, pest outbreaks can occur. Many bark beetle species erupt quickly in response to environmental conditions such as drought, and put even ideally structured forests at risk of substantial mortality if an outbreak develops. One approach to mitigate beetle outbreaks is to detect and manage small infestations quickly, before they grow to a scale that is untreatable. Mitigation activities include early detection of wind-thrown or highly stressed trees where beetle populations can build, and pest management strategies such as "semiochemicals" (i.e., chemicals produced by the organism to elicit a behavioral change), using freshly cut trees as beetle traps, and harvesting trees containing live beetles (Progar et al. 2013). This type of management requires a proactive and nimble approach.

In some forests, bark beetle infestations are aggressively managed in their early stages to minimize tree mortality and stop the spread of the infestation. For example, USFS Region 8 successfully controls southern pine beetle infestations using prompt suppression methods such as removing and burning infested trees (Coulson et al. 2011). In Canada, suppression activities in southeast British Columbia have minimized the spread of mountain pine beetle infestations (personal communication, Tim Ebata, Government of British Columbia).

An alternative application of prescribed fire, called managed wildfire, provides an opportunity to cost-effectively reintroduce fire into remote locations that may be inappropriate for mechanical thinning (Stephens et al. 2016; North et al. 2012; North et al. 2015b). In the event of a natural ignition such as a lightning strike, fire managers evaluate the conditions (weather, vegetation and soil moisture levels), calculate potential risks, and determine if the fire should be allowed to burn. If the fire is allowed to continue, it can be managed using a combination of prescribed fire and traditional suppression techniques. Managed wildfire encompasses more diverse fire patterns than prescribed fire in terms of intensity, spatial pattern, severity, and duration (Boisramé et al. 2017).

Both prescribed fire and managed wildfires may result in short-term negative impacts. These management approaches produce transitory impacts on air quality, which can result in temporary public health concerns. Likewise, prescribed fire and managed wildfire can temporarily reduce water quality, and post-fire landscapes can be visually unsettling for a few years. Managed wildfires can at times burn for months on end, extending their impacts on air quality. With any prescribed or managed fire there is also some risk that the fire will escape, burning areas not preferred by managers, or even putting houses and infrastructure at risk. The application of these measures requires thorough consideration of the various tradeoffs.

Examples of prescribed fire in the Sierra Nevada (left) and managed wildfire in Coconino National Forest (right)

Photo credits: Susie Kocher (left); Coconino National Forest (right)

Using Mechanical Thinning to Reduce Fuels

In addition to expansion of ecologically beneficial fire, significant expansion of mechanical thinning will be needed to achieve long-term forest resilience. Although mechanical thinning does not serve as a complete surrogate for fire, its application often meets restoration objectives, such as reducing surface and ladder fuels that help fire spread, while mitigating fire hazards, particularly in areas that already have road networks (Stephens et al. 2012; North et al. 2015a).

Mechanical thinning can be accomplished with few unintended environmental impacts when best practices are followed. Research has shown that most ecosystem components (e.g., vegetation, soils, song birds, small mammals) exhibit very subtle changes or no measurable effects following properly done treatments (Stephens et al. 2012). In addition, some empirical evidence suggests that these treatments can be strategically used to protect the quality of surface water runoff and in some cases increase runoff yields from headwater forests (Box 2). While most scientific evidence supports the use of mechanical treatments, some important aspects are not yet well understood (Stephens et al. 2016).[4]

Mechanical thinning operations (left) and a forest stand after mechanical thinning (right)

Photo credits: Michael De Lasaux (left); Eric Knapp for USFS (right)

[4] Stephens et al. (2016) note that the long-term effects of mechanical thinning on carbon sequestration levels and wildlife with large home ranges are poorly understood because of significant uncertainties related to long-term wildfire probability and vegetation recovery following wildfire.

Box 2: Can Forest Management Improve Water Supply and Quality?

Headwater forests are a critical source of high-quality water for California. Two-thirds of the state's surface water supply comes from these forests, with roughly half of this supply temporarily stored in snowpack (Mount et al. 2016). In a general sense, the relationship between forest conditions and water supply is well-known (National Research Council 2008). More than half of the precipitation that falls on forested watersheds is taken up by the forest and returned to the atmosphere through evapotranspiration (ET). Tree removal can reduce losses from ET, leading to increases in water yield, especially in the short term. And intense forest disturbances, such as extreme wildfire or poor logging and land use practices, can degrade water quality.

Some studies have demonstrated that reducing the number of trees in Sierra headwater forest by 40 percent could result in an increase in water yield of up to 9 percent (Bales et al. 2011). Another report suggests that a three-fold increase in forest management activities could result in up to a 6 percent increase in mean annual streamflow for some California headwaters (The Nature Conservancy and Ecosystem Economics 2015). Recent studies have shown that increasing forest density and expansion due to climate warming may lead to dramatic declines in runoff from Sierra rivers (Goulden and Bales 2014). These and other studies illustrate the potential for managing forests to protect and, in some cases, increase water supply for California, and have spurred interest in investment in forest management by downstream users.

There are significant uncertainties, however, regarding the potential to realize such water supply benefits and whether investments needed to increase water yields make economic sense. For example, in water-limited mid-elevation forests in the Sierra Nevada, reducing the number of trees may simply allow the remaining trees to absorb more water and grow more quickly. Additionally, rapid regeneration of small trees and shrubs following treatment will limit increases in water yield. Improvement in supply requires sustained investments in maintaining low densities of trees and vegetation. To date, field research has been conducted at relatively small scale (except Boisramé et al. 2017), and economic assessments are limited, making it difficult to conclude that increased water yield can be scaled up to larger areas or transferred between locations. Continued research across spatial scales and locations is needed to improve confidence in water supply projections.

Similar questions are relevant for water quality gains from forest management. Catastrophic wildfire can lead to short-term pulses of sediment, ash, and fire debris entering the water supply and contributing to reservoir sedimentation. Forest management to reduce fire risk may limit these pulses, reducing the likelihood and intensity of water quality declines (Miller et al. 2013). However, as with water supply yields, this too merits closer investigation. Many factors influence the rate of erosion following fires (including soil types, slopes, and storm intensity), and infrastructure like headwater dams can mitigate downstream impacts on quality.

The answers to these questions are important not only for understanding the full range of potential benefits from more intensive forest management, but also for developing funding models to help pay for this management. Various stakeholders have looked to water utilities as a potential source of funding, based on projected water quantity and quality benefits to downstream water users. Water industry representatives, meanwhile, have pointed to their need to understand the specific benefits to be able to justify charging their customers for upper watershed management activities. This is of particular importance in California, where utilities have constitutional requirements to demonstrate that their fee structures are proportional to the costs of water service to their customers (Gray et al. 2014).

As with prescribed fire and managed wildfire, mechanical thinning may have short-term negative impacts that could elicit a negative public response, particularly when it takes place on public lands. Thinning may reduce habitat for some species in specific areas. Likewise, the use of heavy equipment in the forest can be loud and lead to unsightly landscapes that may not be favored by recreationists. While these effects are temporary, reluctance to incur these negative impacts and associated controversy discourages the use of this tool. Beyond the physical impacts of mechanical thinning, some stakeholders simply do not trust thinning operations to go as planned, due to a history of mistrust between some stakeholders, USFS, and private companies who often carry out the thinning work.[5] For thinning programs that are partially funded by harvesting trees for sale, there is often disagreement about what size and how many trees to leave on the landscape, and at times disagreement about whether operators followed guidelines.

Three Areas for Reform

The strategic removal of high-density smaller trees and fuels is essential to increasing long-term resilience of headwater forests. The tools described here—prescribed fire, managed fire, and mechanical thinning—are all available to California's forest managers, but have been underutilized. Accelerating the pace of forest management is a formidable challenge. Here we focus on reforms that enable the private sector and government agencies to utilize existing tools and funding opportunities more effectively and to foster innovation in forest management and collaboration among federal and state agencies and a variety of stakeholders. These reforms fall under three broad areas: prioritize long-term forest health over short-term objectives; define treatment needs and make the most of available funds; and utilize new tools that create opportunities for cooperation.

TABLE 1

A plan of action for increasing headwater forest resilience

Area of reform	Action needed	Specific proposal
Prioritize long-term forest management	Prioritize long-term forest health on federal lands	Utilize permitting instruments (such as habitat conservation plans) to support long-term management goals on federal lands
	Require justification for continued fire suppression	Analyze the effects of continued wildfire suppression. Comprehensively account for wildfire emissions
	Align timber management with resilience objectives	Embed resilience objectives into updated forest management rules
Define treatment needs and make the most of available funds	Improve forest treatment accounting practices	Fill information gaps on statewide forest conditions
	Bundle harvesting with management projects	Make use of harvesting to offset treatment costs
	Collaborate for funding	Make use of creative collaborations among agencies and stakeholders to increase funding for forest treatments
Utilize new tools that facilitate cooperation	Increase the pace and scale of stewardship contracts on federal lands	Take full advantage of stewardship contracting
	Allow state-led actions on federal lands	Use Good Neighbor Authority
	Explore community approaches for creating economies of scale and pooling resources	Develop forest health districts
	Leverage cooperation to increase infrastructure investments	Utilize new cooperative models and long-term agreements to spur investments

[5] This observation is based on discussions with forest stakeholders during a workshop hosted by the PPIC Water Policy Center in October 2016 and in subsequent follow-up discussions with stakeholders.

Prioritize Long-term Forest Health in Law, Rules, and Management

It took decades for headwater forests to reach their current degraded conditions, and enhancing resilience will also take many years. Yet short-term objectives such as suppressing fires or managing for threatened and endangered species tend to dominate management decisions, and there are few laws or rules that mandate planning for long-term resilience. Likewise, social concern about the effects of forest management on air and water quality, habitat, scenic value, and recreation may constrain landowners' ability to implement actions with long-term benefits.

The evolution of laws and guidelines that influence forest management on federal, state, and private lands have reinforced these concerns. In broad terms, the intent of early federal and state forest management laws centered on bringing order and best practices to timber harvesting. This approach aimed to achieve a level of harvest that could supply the growing need for timber without permanently depleting timber resources for future harvest. This approach changed significantly in the second half of the 20th century as federal and state agencies broadened their functional role to include other uses that competed with timber harvest (such as wildlife, wilderness, and recreation) and became responsible for adhering to environmental protection laws intended to reduce the negative impacts of timber harvest (Hayes 2009). As a result, forest management planning and operations currently have the goal of minimizing short-term environmental impacts. This management context makes it challenging to pursue long-range resilience, since forest treatment generally entails some unavoidable short-term harm.

This dynamic is beginning to change in California, especially at the planning level and through site-specific legislation that has attempted to streamline operations in some areas.[6] Environmental review, however, continues to slow forest management decisions to a far greater degree than other federal projects (US Government Accountability Office 2014). Increasing the frequency and size of forest management projects will require greater flexibility in environmental permitting and changes in rules and laws regarding forest management. Making forest resilience a top land management priority for public and private lands would be a critical first step in reversing the degraded condition of the state's headwater forests.

Reform Proposals

Here we outline specific reforms that would be most appropriate and consequential for federal, state, and private lands. Different approaches will be more or less effective for each of the types of landownership in the headwaters. Federal agencies should build flexibility into their operating approach to work more effectively across their large and contiguous lands. Private landowners will also need more flexibility to pursue long-range forest health objectives. CAL FIRE and USFS should justify fire suppression activities and incentivize forest management work that reduces the risk of wildfire emissions.

1) Make long-term forest health a priority on federal lands

All forest management efforts in California are required to comply with the Endangered Species Act (ESA), the Clean Air Act, and the Clean Water Act. In addition, management projects on federal lands are subject to special species considerations under the National Forest Management Act, while non-federal management projects must follow the requirements of the Forest Practice Act. These laws require forest management projects to account for and avoid specific environmental harms (e.g., air pollution, or taking species listed as threatened or endangered). While there are benefits from protecting these resources, the narrow focus of these

---

[6] For example, the recent updates to the Inyo, Sequoia, and Sierra National Forest Plans include forest-wide strategies for implementing the use of fire as a tool for protecting, restoring, and maintaining headwater forest resilience. These plans describe strategic fire management zones in which wildfire is restored to various degrees based on local vulnerabilities and desired conditions. For example, the Community Wildfire Protection Zone includes areas with risks to human life. In this area, fire prevention and vegetation management activities are prioritized over strategic use of fire. On the other hand, the Wildfire Maintenance Zones pose low threats to communities and thus allow for more intensive use of prescribed and management wildfire. President Obama signed the Water Resources Development Act (WRDA) in 2016. WRDA contained site-specific legislation for streamlining approval of fuel reduction and forest management activities in the Lake Tahoe area.

regulatory programs can hinder the very efforts needed to reduce harm and achieve resilience at larger landscape scales and over the long term.

Forest managers find it hard to plan and implement farsighted actions while operating under these constraints (Stephens et al. 2016; Schoennagel et al. 2017). For example, wildfire smoke in the Clean Air Act is exempt from regulatory compliance standards, while smoke from prescribed fire and managed wildfire is regulated (Stephens et al. 2016). This inconsistency creates disincentives for forest management work. Yet such work reduces the likelihood of large smoke emissions resulting from unplanned wildfire. Managing for resilience will require finding ways to move away from an emphasis on avoiding single resource or species impacts and toward comprehensive approaches that improve conditions more broadly.

Suggested reforms: Given the vast and contiguous nature of its headwater forest holdings and its responsibility for active forest stewardship, USFS has the greatest opportunity to pilot comprehensive management practices over large landscapes and long periods of time. Under current federal laws, forest managers can seek alternative administrative arrangements to achieve these goals. For example, although USFS develops plans with long-term management goals, its operational planning horizon is typically only five years. Longer operational horizons would allow federal forest managers to manage with fewer constraints, as long as they work toward broader objectives. To more effectively address endangered species concerns, USFS forest managers can develop multi-decadal Habitat Conservation Plans (HCPs) or other long-term licenses to operate in individual national forests. Changing management priorities within USFS could be made by administrative action, and may not need congressional approval. However, this approach would benefit from supportive legislation that directs federal regulatory and land management agencies to take a long-term approach while protecting specific resources at the larger landscape scale.

2) Agencies should justify continued fire suppression activities

Today, most forest management actions that affect habitat and water and air quality require multiple permits and extensive justification under the National Environmental Policy Act (NEPA), the California Environmental Quality Act (CEQA), and other regulatory requirements under the above-mentioned environmental laws. In contrast, fire suppression activities that can have significant long-term consequences for forest health—and increase the risk of large wildfires—are exempt from these requirements. USFS and CAL FIRE should be asked to justify fire suppression plans and evaluate their economic and ecological consequences, including the amount and predictability of $C0_2$ emission levels. For example, to facilitate the strategic use of fire for reducing wildfire risk on federal lands, federal agencies could evaluate the long-term impacts of continued fire suppression within their firefighting responsibility area (Stephens et al. 2016). CAL FIRE's current approach of aggressive fire suppression reflects the fact that its firefighting responsibility area is largely private property, which can contain privately owned assets like buildings, livestock, and vehicles. As a result, in the short term, many communities directly benefit from CAL FIRE wildfire suppression activities, even though this may contribute to greater long-term fire risk. CAL FIRE should evaluate the long-term consequences of its wildfire suppression approach and more clearly integrate them into incident-level decision making. The state could perform a comparable analysis of long-term impacts of continued wildfire suppression within the state responsibility area—especially those areas that contain fewer private assets. These changes would institutionalize the importance of using fire to increase forest resilience by reducing the regulatory burden of allowing prescribed and managed fire.

Suggested reforms: Justification of continued fire suppression on federal lands could be advanced by changes to USFS planning rules, the USFS Manual and Handbook, Fire Management Reference System, and Spatial Fire Planning. Planning rules can be changed internally by the USDA, while guidelines, manuals, and handbooks can be modified internally by USFS. There is potential for all of these changes to take place without legislative action. However, Congress could promote these changes in its next authorization of the National Forest Management Act.

Similarly, justification for continued fire suppression within the state's responsibility area could be developed through CAL FIRE's internal decision-making process or with state legislation. One potential vehicle for reform could be a CEQA analysis of long-term consequences of continued aggressive fire suppression to accompany the state or unit-level fire plans. An alternative approach would be to change state air quality rules—enforced by the California Air Resources Board and regional boards—to require consideration of emissions from wildfires alongside emissions from prescribed and managed fires when determining federal and state agency compliance with air quality standards (Stephens et al. 2016). This would encourage a more comprehensive view of emissions, including emissions avoided as a result of fuel reduction work. Strategic use of fire and mechanical treatments that reduce the risk of future air quality problems would then be viewed as a solution to avoiding future emissions from severe and large wildfires (Stephens et al. 2016). This may require revision of Title 17 of the California Code of Regulations, which dictates that wildfire and prescribed fire be treated differently in air quality accounting.

3) Make forest health a statewide goal of timber management on private lands

Opportunities exist to increase resilience on private forest lands as well. Assembly Bill 1492, enacted in 2012, requires the state to develop new ecological performance measures to guide the environmental regulation of timber harvest. Long-term resilience goals can be embedded into these ecological performance measures, to encourage regulators to take a long-term, large-scale view of forest management, rather than the shorter-term, property-specific focus that is more common today. Managing for resilience on private lands may differ from management of federal lands, since forests on private lands—especially industrial forests—typically do not face the same tree density problems common on federal land. The focus on private lands may include limiting sedimentation from roads and timber harvest, protecting riparian areas, and assuring economic feasibility of future timber producers.

Suggested reform: The California Board of Forestry and Fire Protection is developing ecological performance measures under AB 1492, to be completed in 2018. The board has the opportunity to develop these measures in a way that emphasizes long-term goals for forest resilience—i.e., ecological goals that can be met through forest management actions across multiple landowners and over multiple years or decades.

Define Forest Treatment Needs and Make the Most of Available Funds

Although a strong case can be made that it is necessary to increase the pace and scale of forest management, there is much debate over precisely how much area should be treated and exactly which treatments should be used.[7] Moreover, while it is essential to secure sufficient funds to reduce forest density, there is no clear formula for how to pay for this work, with options ranging from increased revenue-generating practices to expanded public and private funding. Here we note three issues that arise in defining forest treatment and funding needs and the options for mobilizing funding sources, and make several recommendations for reform.

---

[7] As an example, the majority of attendees at a stakeholder workshop hosted by the PPIC Water Policy Center in October 2016 agreed that more management work was needed, but they had differences of opinion in how much or by what method.

"Forest treatment" is poorly defined, as are treatment needs

Various organizations report how much forest they treat each year with active management.[8] However, these estimates are often reported in terms of acres treated, with no clear definition of how much biomass is actually removed from the forest with the treatment. This imprecision fuels disagreement about the extent to which current treatment levels are improving forest health. In addition, there is no consensus estimate of the number of acres that are in need of treatment.[9] By one measure, treatments would have to increase by a factor of 2–6 (90,000 acres to 400,000 acres) each year to reach historic disturbance levels within USFS land in the Sierra Nevada (North et al. 2012).[10] These uncertainties complicate efforts to identify how much more treatment is needed and estimate the present and future costs of management.

Costs of treatment vary widely

Another key unknown for forest management budgeting is the large variability in costs. For example, the cost for prescribed fire varies by a factor of 10 depending on the landscape where it is applied. On USFS lands in the Sierra Nevada, gross costs range from $75 to $647 per acre (North et al. 2012). This range applies to a broad swath of national forest lands in the Sierra Nevada range between the north fork of the Feather River in the north and Lake Isabella in the south.

Research on the costs of implementing managed wildfire continues to improve. However, current estimates are often based on small samples and are not useful for purposes of extrapolation (Calkin et al. 2015; Houtman et al. 2013). It is likely that per acre costs in remote areas, where fewer resources are needed for fire suppression, are lower than costs of prescribed fires. Yet costs of managed wildfire can be quite high if firefighters remain actively engaged throughout the fire's duration, which can stretch for months.

For mechanical thinning, a more relevant measure is the net cost, deducting the sales value of harvested products. Mechanical thinning can at times produce enough revenue to make forest treatments profitable (i.e., positive net revenues). For example, per acre costs for mechanical treatment on a forest site in the Central Sierra ranged from net revenues of $497 to $1,890 (Hartsough et al. 2008).[11] However, net costs of this method can be even higher than prescribed fire in areas where few or no sawlog-sized trees can be harvested. These tradeoffs are well illustrated by a modeling study of mechanical thinning costs from forests in Northern California and Oregon (Fried et al. 2017).[12] Where harvest was allowed for trees up to 21 inches in diameter (upper-range medium-sized trees), a net revenue of $884 per acre was achieved. As the diameter cap decreased, net revenue declined. Net revenues were down to $337 per acre when harvest was limited to trees under 16 inches (lower-range medium-sized trees). And when harvest was limited to small trees less than 10 inches—and all non-revenue-generating

---

[8] For instance, USFS reports implementing fuel reduction on roughly 250,000 acres per year on its lands (personal communication, Elizabeth Berger USFS), and CAL FIRE estimates that it recently treated 17,500 acres per year on private land (excluding private commercial forests) (California Natural Resources Agency 2017). But "treatment" is not defined in a way that reflects the intensity of the work or resulting changes in forest conditions.

[9] For instance, the California Natural Resources Agency has recently estimated that 16 million acres of forest—9 million acres of USFS land, 1 million acres of other federal lands, and 5 million acres non-federal lands—are unhealthy and in need of treatment (personal communication, Russell Henly, California Natural Resources Agency). The estimate of federal acres in need of treatment is based on ecological restoration management goals as articulated by USFS Region 5, but the methodology for developing this estimate is unclear. The estimate of private acres in need of treatment is calculated using maps prepared for the Forest and Rangelands Assessment that depict wildfire threats to maintain ecosystem health.

[10] Although this study covers a large area, it is a subset of all USFS lands included in the definition of headwater forests used throughout this report. This management example is not directly applicable to headwater forest lands owned by private and other public entities.

[11] The Fire and Fire Surrogates study by Hartsough et al. (2008) recorded the actual project costs of mechanical thinning and prescribed burning projects at 13 sites located in western forests at risk of uncharacteristically severe wildfire. One of the study areas was located in the Central Sierra Nevada at the Blodgett Experimental Forest. The treatments performed at this site were designed with the intention of reducing ladder fuels and increasing the resilience of forest stands to future wildfire. Most of the trees harvested during the mechanical treatment phase could be utilized for high-value products such as dimensional lumber. The mechanical thinning treatment also included on-site mastication of ladder fuels and taller surface fuels.

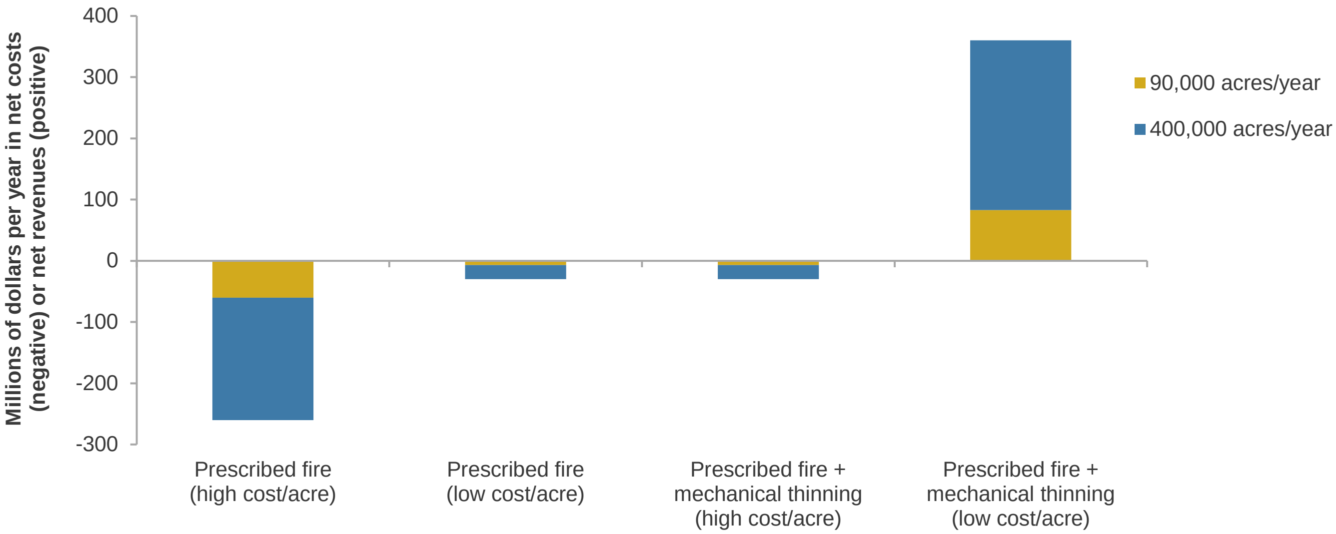
[12] Using a 40-year timespan to treat a 21 million acre forest, this study examined how the net cost of treatment varied by the diameter of tree allowed for harvest. The study used historic costs and revenues for forest management operations in California and Oregon, but did not include planning, permitting, and supervision costs.

stands were treated—the project switched from generating net revenues to incurring net costs of $832 per acre (Fried et al. 2017).[13]

The wide variation in the net costs of forest treatments—and the uncertainties in how many acres require treatment annually—make it difficult to estimate an overall price tag for building forest resilience. Figure 4 illustrates a potential range of costs, using information from projects within the headwater study area. While these numbers are for illustration only—especially since mechanical thinning revenues did not account for all location-specific wildlife habitat constraints—they demonstrate two key facts: the overall cost of treatment depends not only on the ability to achieve economies in fire management practices, but also on the number of sawlog-sized trees managers are willing to remove from the forest.

FIGURE 4

The net cost of expanding forest treatments could vary widely, depending on project conditions and treatment mix



SOURCES: Author estimates using data in North et al. 2012 and Hartsough et al. 2008.

NOTES: The figure shows the net cost (or revenues) of additional treatments needed to bring forests back to historic disturbance levels. The estimates of additional acres needing treatment (90,000 and 400,000 acres per year) are from North et al. (2012) for USFS lands in the Sierra Nevada. Net cost estimates for prescribed fire projects range from $75 to $647 per acre (North et al. 2012, for USFS lands). Net cost estimates for mechanical thinning range from $1,890 in net revenues per acre (low net cost) to a high of $497 in net revenues per acre (high net cost) (Hartsough et al. 2008 for a Central Sierra Nevada study area). Dollars are adjusted to 2016 using a CPI deflator. The prescribed fire plus mechanical thinning scenarios assume a 50-50 split in the use of these two methods.

Funding portfolios are needed, but not well developed

There are several ways to fund forest treatments, including direct investment by landowners and public agencies with oversight responsibilities, offsets from revenues generated by harvesting commercially valuable wood products, and compensation by various agencies and stakeholders for the benefits they receive from management practices. All are likely to be needed to scale up forest resilience practices.

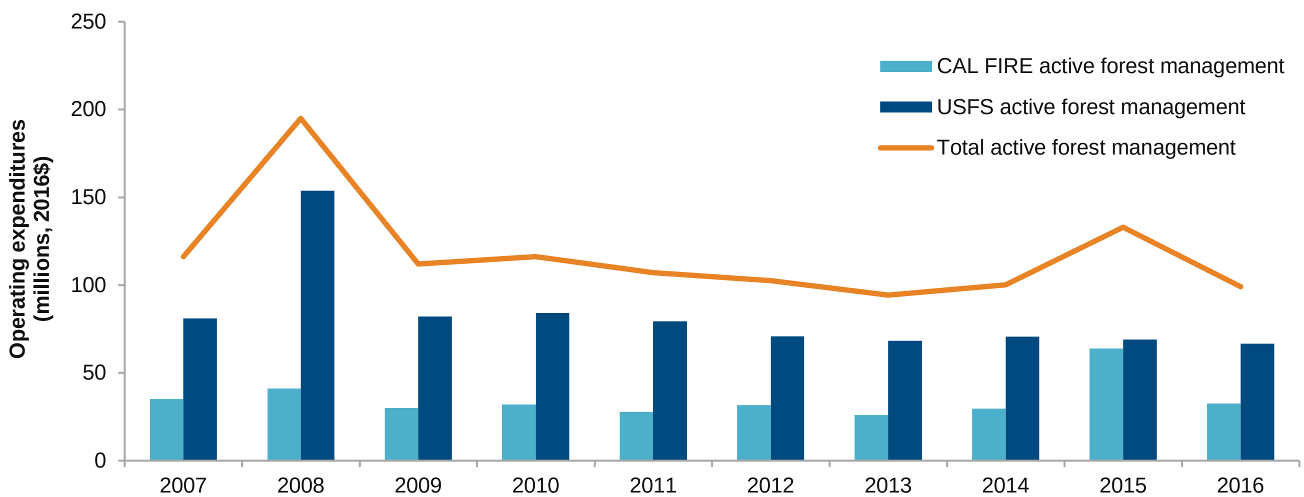
Direct investment. Spending on forest management by private landowners—who own about one-third of the headwater forests—is poorly documented and understood. For public agencies, estimates are available for the

[13] This study demonstrates that there is significant revenue generation possible even when harvesting is limited to medium-sized trees. As described above, trees are categorized as small if they are 4–12 inches diameter at breast height (dbh), medium if they are 13–24 inches dbh, and large if they are over 24 inches dbh (McIntyre et al. 2015).

state and USFS, but not for other federal landowners or local governments. CAL FIRE and USFS spending on active forest management—around $100 million per year—is a fraction of the total these agencies spend on wildfire suppression, which recently grew to about $2 billion annually.[14] In real terms, USFS spending on active management has declined somewhat over time, from more than $80 million per year in the late 2000s to less than $70 million in recent years (Figure 5).[15] The state's contribution to this area has hovered around $30 million annually.[16] Whether increases in public spending on forest treatments are needed depends on a variety of factors, including the extent to which costs can be offset with forest product revenues, and the scope for mobilizing other funding sources.

FIGURE 5

Spending on forest management by CAL FIRE and USFS Region 5 has been fairly steady throughout the past decade



SOURCES: Governor's budget 3-year positions, 2007–17. USFS budget justifications fiscal years 2009–18.

NOTES: Active forest management spending at CAL FIRE includes actual expenditures on the resources protection and improvement subprogram (about 3% of CAL FIRE's total operating expenditures). The figure excludes the other forest resource management subprograms including forest practice regulations, forest resource inventory and assessment, and professional foresters registration program. USFS Region 5 active forest management activities include the hazardous fuels and vegetation and watershed management subprograms (about 8 % of USFS Region 5 total operating expenditures). This figure excludes forest resource management activities such as forest products, wildlife and fisheries habitat management, cooperative forest landscape restoration program, planning and inventory, and all state and private forestry subprograms. Dollars are adjusted to 2016$ using a CPI deflator. The State of California fiscal year starts in July, and the federal fiscal year starts in October. We were unable to confirm the reason for the one-time increase in USFS spending in 2008. In fiscal year 2015, CAL FIRE received an additional $24 million from the Greenhouse Gas Reduction Fund for local assistance to active forest management projects that sequester carbon.

---

[14] In California, both federal and state spending on wildfire suppression remained significantly higher than spending on forest management activities over the past decade, with the state generally spending more than twice as much as USFS on fire suppression (author calculations using the governor's budget 3-year positions, 2007–17; USFS Budget Justifications Fiscal Years 2009–18; and correspondence with Nicole Williams USFS Region 5). Their combined spending on fire suppression has been more volatile, ranging from under $1 billion in 2011 (a year that followed a very wet winter) to nearly $2 billion or more during recent droughts. We calculated CAL FIRE expenditures on wildfire suppression as the sum of fire control, cooperative fire protection, and emergency fire suppression subprograms, while excluding the fire prevention and conservation camps subprograms. We excluded the fire preparedness subprogram from the calculation of USFS Region 5 emergency wildfire suppression expenditures. Wildfire suppression costs are predicted to rise, as USFS projects continued growth in the national 10-year average cost of fire suppression through 2025 (USDA Forest Service 2015b).

[15] A recent study highlighted the USFS practice of temporarily shifting funds from non-fire forest management activities to cover the costs of fire suppression, but it is not clear that USFS Region 5 is directly affected by this practice (USDA Forest Service 2015b). At the national scale, USFS can collect under-utilized funds that have already been distributed to individual regions and use these funds to pay for fire suppression in other regions. According to budget staff, USFS Region 5 has few under-utilized funds and has largely avoided the temporary withdrawal of non-fire forest management funds for fire suppression (personal communication, Nicole Williams, USFS Region 5).

[16] One reason for the large difference between CAL FIRE and USFS spending on active forest management is that the agencies play different roles. CAL FIRE has more regulatory and fewer direct stewardship responsibilities than USFS Region 5. USFS Region 5 has more responsibilities related to direct land stewardship.

Offsets from forest product revenues. As shown above, offsetting the cost of forest management with revenues from harvest of commercially valuable products can decrease the net cost of treatment projects. There are, however, constraints to generating revenues from mechanical thinning based on limitations on the maximum size and availability of trees to be harvested. In addition, many areas lack infrastructure (sawmills, biofuel plants) to process materials generated by thinning and harvest. Likewise, there are limited markets for some forest products (such as dead trees and forest debris) and harvesting these products alone—even if important for improving forest health—is unlikely to generate positive net revenues.

Compensation for benefits of management. A new area of interest in funding forest management activities involves strategically "selling" the benefits of these activities to stakeholders who get a direct service from improved forest health.[17] This might include improvements in water quality and quantity, air quality, healthier ecosystems, and reduced costs of fire suppression. Some arrangements of this type already exist—for instance, some water utilities have made direct contributions to forest management to protect water sources.[18] The extent to which improving water quality and supply has wider potential to generate funding for forest work is still an open question (Box 2). In addition to individual arrangements with beneficiaries, experiments are underway to develop financial instruments—such as forest resilience bonds—which could involve investors paying for forest management, based on the returns from better management.[19] Another example of this arrangement is the use of state Greenhouse Gas Reduction Fund (GGRF) proceeds to fund forest management work. To date, nearly $50 million from the GGRF has been allocated to the CAL FIRE Forest Health grant program (California Climate Investments 2017). This funding supports grants for projects that are able to demonstrate carbon sequestration benefits—including reforestation, fuel reduction, pest management, conservation, and biomass utilization.

Reform Proposals

Federal and state agencies have a major role to play in more clearly defining the need for forest treatment and estimating the costs of needed forest improvements in the headwater region. Forest managers across all landownership types can benefit from opportunities to reduce project costs by bundling revenue- and non-revenue-generating activities. Forest managers also have options to leverage resources and procure funding through collaborative efforts.

1) Improve forest treatment accounting practices

Forest management projects that require a Timber Harvest Plan (THP) or receive grant funding from the Greenhouse Gas Reduction Fund are required to report changes in biomass and carbon equivalent as a result of the work.[20] USFS fuel reduction work in the state—estimated at 250,000 acres per year—generally does not require a THP, and is not characterized in terms of change in biomass or carbon. This contributes to a lack of

---

[17] Forest management activities refers to several types of activities including reforestation, fuel reduction, pest management, conservation, and biomass utilization.

[18] For example, Denver Water has partnered with USFS, the State of Colorado, and the Natural Resource Conservation Service to expand fuel reduction treatments in source watersheds, especially forests posing risks to Denver's water supply infrastructure. This collaboration recently signed an MOU for $33 million with a goal of maintaining existing treatments and treating an additional 40,000 acres. In California, water suppliers with significant land holdings in headwater areas—such as the San Francisco Public Utilities Commission and Placer County Water Agency—also fund forest management. Some NGOs in California also directly invest in headwater forests with the goal of achieving multiple benefits for human and natural communities.

[19] The Forest Resilience Bond concept, as presented by Blue Forest Conservation, involves using forest management techniques to create benefits in the form of increased water quality and quantity and fire-risk reduction. The benefits will be quantified and monetized, and subsequently paid for by entities that directly benefit (e.g., water and electric utilities, USFS, and CAL FIRE). Revenues from services rendered will then be used to repay the bond obligations to investors.

[20] AB 1504 (2010) requires forest managers to estimate and report carbon sequestration benefits and emission reductions for projects requiring submission of a timber harvest plan. In addition, California Air Resources Board has developed a quantification methodology for determining net greenhouse gas reduction and forest health benefits from forestry projects that receive grants from the Greenhouse Gas Reduction Fund. This methodology is designed to ensure compliance with SB 859 (2016) which requires that all GGRF grant funding for forest projects shall reduce greenhouse gas emissions and improve forest health. Although the methodology accounts for the emissions benefits of carbon stored in wood products like housing construction, and furniture, it may be undervaluing them. Fully accounting for these benefits would provide stronger financial incentives for sequestering carbon through timber harvesting and wood product utilization.

understanding about how much fuel reduction progress is being made each year in the state's forests, and whether the current rate of treatment is adequate to improve forest health. These are important pieces of information for informing public policy decisions and ensuring effective investment.

Another critical component of estimating fuel reduction needs is an idea of how carbon stocks are changing at a larger scale. This context can be provided by USFS FIA datasets, which report on the 10 percent of forest sample plots measured every year. The Board of Forestry and Fire Protection has already started developing a forest carbon inventory using USFS FIA data and analysis. This inventory has the benefit of characterizing carbon changes across ownership boundaries and at a large spatial scale, providing much needed information on how forests are changing and what is driving change. This information has the ability to guide future investments in forest management and to allow tracking of progress made due to investments and management work.

Suggested reforms: Improving statewide accounting of human and natural impacts on forest conditions will require state and federal collaboration. CAL FIRE and the Board of Forestry and Fire Protection should consider working with USFS to broaden and standardize project-level carbon accounting capabilities into areas of the headwater forest that are being actively managed by USFS. The board should continue to invest in developing an inventory of forest growth and mortality on federal, non-federal public, and privately owned headwater forests using the USFS FIA. This might include increasing the frequency of plot sampling and developing the capacity to regularly analyze plot measurements. This would make it possible to more quickly identify changes in forest health and to more systematically characterize these changes across the landscape. The development of regional forest carbon assessments as a basis for carbon accounting has been proposed in Oregon; this approach could be adapted for California.[21]

2) Bundle ecologically responsible harvesting with other management activities

One proven method for reducing the net cost of forest management projects is to include revenue-generating opportunities (Fried et al. 2017; North et al. 2012). For example, bundling mechanical thinning and prescribed fire into the same scope of work offers promise. In some cases, this may require expanding the scale of the project to incorporate adjacent areas that offer better revenue-generating opportunities. Where feasible, this approach has the capacity to stretch public and private funds and make the most of available funding opportunities.

Suggested reforms: All parties should seek to expand opportunities to reduce costs of forest management, including bundling ecologically responsible mechanical harvesting with treatment projects. Beyond addressing the regulatory and institutional constraints to mechanical thinning, there may be value in using analytical tools to identify opportunities for bundling. For example, researchers are currently refining a model called BioSum (Bioregional Inventory Originated Simulation Under Management) to help forest resource planners and policymakers evaluate the net costs of management strategies in their region. If the tool is successful, it may help accelerate the development of larger and more effectively bundled management projects across a wide array of ownerships (Fried et al. 2017). Making forest health a top priority (discussed above) and encouraging more collaboration between public and private stakeholders (discussed below) will also facilitate projects that bundle revenue- and non-revenue-generating activities at larger scales.

---

[21] The Oregon Global Warming Commission's biennial report to the legislature in 2017 concluded that the state needed a better method for tracking forest carbon dynamics to inform public policy on forest and grassland management for carbon outcomes. The commission recommended the use of the USFS Forest Inventory Analysis for quantifying forest carbon stores across publicly and privately owned forests—with the ability to summarize results at a regional scale (by ecoregion) (Oregon Global Warming Commission 2017).

3) Collaborate to mobilize other funding sources

With the trend of decreasing federal funds for forest management likely to continue in the near term, innovative approaches to combine funds from a variety of sources are needed. Pursuing alternative funding models, including revenues from entities—such as water suppliers—who benefit from improved forest management, may be promising for some projects. In addition, collaborative approaches such as the Good Neighbor Authority and stewardship contracting (both discussed at length in the next section) can help build collaboration, decrease costs, spread the financial burden, and produce on-the-ground results. Continued engagement by all actors will be key to increasing management at a time when federal funding is insecure.

Make Greater Use of Tools that Create Opportunities for Collaboration

The diverse ownership of California's headwaters creates a mosaic of different approaches to stewardship. For example, federal owners may be managing their holdings to balance multiple and sometimes competing uses of national forest lands. Industrial forest owners may be managing their land to achieve the highest potential yield of timber. Each family forest owner is approaching management according to a unique mix of stewardship ethos, objectives, and available resources. Despite considerable fragmentation in ownership and management approaches across the landscape, some management objectives—such as wildfire risk reduction and forest health—run across ownership boundaries. In this setting, collaboration and cooperation can improve forest management by allowing diverse parties to pool resources, take advantage of economies of scale, and spread risk in pursuit of shared forest management objectives.

Collaborative work on USFS lands is increasingly feasible with new tools like stewardship contracting authorities and the Good Neighbor Authority. Stewardship contracting authorities allow USFS to improve the way it engages with foresters, with forestry contracts that are longer-term and contain a more diverse scope of management activities. The Good Neighbor Authority allows state and other stakeholders to fund and execute forest management work on USFS lands—especially where the benefits of management extend beyond the borders of the USFS land. These tools make it easier for state agencies and other stakeholders to exchange resources and expertise to manage forests on USFS land. These tools are available for use but are currently underutilized.

Nowhere is the divergence in approaches to stewardship more apparent that within the patchwork of private forest owners. However, wildfire risk reduction and forest health are fundamental goals shared by a broad base of these landowners. If neighboring private forest owners can define common forest management goals, they can collaborate to create the means for achieving them. Pooling resources and taking advantage of economies of scale can make planning, permitting, and implementation of forest management work more affordable.

We recommend that all forest landowners and stakeholders make use of the existing tools for collaboration described below. Collaboration can increase the pace and scale of management across ownership boundaries. It can also produce steady streams of forest products that support new or revitalized infrastructure, a critical component for supporting long-term forest management work. Other benefits include leveraging available funding, expertise, and technologies; creating a stronger scientific, social, and economic justification for forest management treatments, and building social acceptance of forest management practices.

Reform Proposals

Collaborating to increase the pace and scale of treatment will take on different forms on federal and private forest lands. USFS has access to tools developed specifically for facilitating cooperation on USFS land: stewardship contracting authorities and the Good Neighbor Authority. Successful use of the Good Neighbor Authority requires active engagement by state agencies and cooperation between state and federal agencies and other stakeholders.

Private landowners also have options for collaboration, based primarily on their ability to define common management objectives, pool resources, and share costs.

1) Take full advantage of stewardship contracts

Contracting to do work in federal forests can be challenging for private companies. For example, traditional service contracts for fuels management or prescribed fire are limited to five years in duration—often too short to provide a sustainable supply of materials or services to prospective contractors. According to USFS rules, timber-sale contracts are awarded to the highest bidder without considering other important factors such as the contractor's expertise, ties to the local economy, and past performance (Roessing 2014).

A relatively new public-private partnership instrument called "stewardship end-results contracting" may help to address some of these challenges. Prescribed fire and mechanical fuels management are among several types of forest management projects eligible for this new instrument. As authorized by the 2014 Farm Bill, stewardship contracts give USFS an array of authorities that, if used strategically, can leverage non-agency resources and private expertise to improve the effectiveness and efficiency of forest management work. These authorities allow USFS to engage in multi-year contracts (up to 10 years), collaborate on project design based on desired end results, trade goods for services, bundle service activities, and other practices (Kittler 2014).[22]

Importantly, these authorities allow USFS to streamline forest management work by bundling revenue- and non-revenue-generating management activities into a single long-term contract. A single contract is issued for all management activities pertaining to the management objectives, and the contractor can then sub-contract out individual activities. This type of contract focuses on the desired management outcome while allowing some operational flexibility for private contractors. Stewardship authorities represent a departure from traditional USFS contracting models and hold significant potential for increasing the pace and scale of forest management work in California.

Stewardship projects continue to grow in popularity across the national forest system. Since the initial authorization by Congress in 2003, both the number and size of projects using stewardship contracting authorities nationally is increasing (Pinchot Institute 2016). Stewardship contracts currently play a role in California's headwater forests, but at a relatively small scale.[23]

Suggested reforms: Leaders within USFS (both at the individual forest and regional office levels) should create more and larger stewardship contracting opportunities in California's headwater forests. Collaboration (formal or informal) is a required element of every proposed stewardship project. Lack of funding to facilitate project planning is currently a key impediment to the use of stewardship contracts. NGOs can play a vital role here by helping to procure funding for and facilitating the planning phase.[24] California has three formal regional collaborative groups formed under the USFS Collaborative Forest Landscape Restoration (CFLR) program. These collaborative groups already have strong ties with USFS and may be ideal partners to facilitate stewardship contracting at a larger scale.[25]

---

[22] Best-value contracting is a process for selecting contractors based on factors other than bid cost, such as prior performance, experience, skills, and ties to local economy.

[23] There were 71 ongoing approved stewardship project proposals in USFS Region 5 between 2012 and 2015—some of which are likely located in headwater forests (personal communication, Brian Kittler, Pinchot Institute for Conservation). For example, stewardship contracts have been utilized for fuels reduction and vegetation management in the Sierra, Stanislaus, Sequoia, and El Dorado National Forests. While the stewardship authorities appear to be actively used in Region 5, they play a relatively smaller role in hazardous fuels reduction or wildfire suppression compared to other USFS programs. Stewardship authorities should be invoked to develop larger and longer-term active management projects with the capacity to increase forest resilience at a landscape scale.

[24] NGOs without the up-front resources to fund forest management planning might benefit from opportunities to apply for planning grants. For example, the Sierra Nevada Conservancy offers awards up to $75,000 to qualifying nonprofit organizations and eligible tribal organizations for planning and pre-project activities that support forest health projects.

[25] Across the West, formal collaborative groups formed under CFLR have played a vital role in shaping elements of existing projects, such as guiding the design of management projects, developing social license for management work, and supporting the work throughout the NEPA process (Raaf 2014).

2) Use the Good Neighbor Authority to generate sustainable funding

One of the challenges in managing for forest resilience is paying for projects that create no direct revenue but provide broad benefits, such as reducing the intensity of fires or improving habitat. The key is to find ways to use revenue-generating projects to help cover these costs. California already has the tools to do this through the Good Neighbor Authority (GNA).

The GNA allows USFS and BLM to enter into cooperative agreements or contracts with states to perform watershed restoration and forest management services on national forest lands (USDA Forest Service n.d.). These agreements allow the state to provide administrative, technical, and financial support for forest management on some federal lands and be reimbursed for these costs from future timber harvest sales.[26] Any income generated by these projects that remains after state agency costs are reimbursed may be spent by USFS and the state on projects that are less likely to generate sufficient revenue to cover costs. This includes projects like prescribed fire, stream restoration, and trail maintenance.

GNA programs can be designed to be financially self-sufficient over the long-term. For example, the use of GNA programs in Wisconsin (by the Department of Natural Resources) and Idaho (by the Department of Land) has resulted in state administration of timber sales on federal lands. Both of these programs aim to become self-sufficient sources of funding for a range of forest management activities (Watts 2016; Idaho Department of Lands and US Forest Service 2016). GNA programs have also been useful in developing forest management projects in mixed ownership areas, as they allow the state to work on federal lands.[27]

The California Natural Resources Agency and USFS initiated a GNA program upon signing a master agreement in January 2016. This 10-year agreement provides a basis for collaboration between national forests and the California Natural Resources Agency and its departments (USDA Forest Service 2017b).[28] The first project initiated under the GNA program resulted in the transfer of USFS funds to CAL FIRE for hazardous fuels removal on federal and surrounding non-federal lands around the El Dorado National Forest. While the enactment of the GNA and initial work under that agreement are positive first steps, there is still significant opportunity to create self-sufficient funding for non-revenue-generating forest management activities.

Suggested reforms: The California Natural Resources Agency and USFS should examine the feasibility of developing more projects under the state's GNA program that incorporate timber sales and other revenue-generating activities into scopes of work. Because of its role in forestry management and fire suppression, CAL FIRE may be the most appropriate entity to take the lead in promoting the use of the GNA program for administering timber sales on federal land. This could include designing fuel reduction projects and forward-looking management programs, particularly on federal lands that are near state and private land. Early outreach between state agencies, USFS, and local communities can be important for building trust, aligning objectives, and discussing expectations. NGOs can help facilitate these communications.[29] Since fuel reduction projects have high potential to limit emissions from wildfire, funding could potentially be considered under the Forest Health grant program funded by the GGRF, which supports activities that reduce greenhouse gas emissions.[30]

---

[26] GNA authority may not be used for projects that require reconstruction of roads and projects in wilderness areas or lands where removal of vegetation is prohibited or restricted (USDA n.d.).

[27] This feature was an important motivating factor for the use of GNA in Idaho (Idaho Department of Lands and US Forest Service 2016).

[28] Departments with the California Natural Resources Agency include CAL FIRE, California Conservation Corps, Department of Conservation, Department of Fish and Wildlife, Department of Parks and Recreation, and the Department of Water Resources.

[29] Stakeholders involved in Wisconsin's GNA program describe institutional trust building and alignment as critical prerequisites to a successful program (Watts 2016).

[30] Other states have provided funding to support their GNA programs. For instance, Wisconsin dedicated two years of seed funding from the state's forestry account to fund the additional workload resulting from the GNA program (Watts 2016). In Idaho, timber companies made a $1 million commitment to the GNA program as a seed grant (Barker 2017).

3) Develop forest health districts

Nearly a quarter of the headwater forests are on family-owned properties of 5,000 acres or less. The small size of these properties creates unique management challenges. Due to the demanding nature of obtaining a timber harvest permit in California, it is often not economically feasible for smaller landowners to actively manage their forests (Stewart et al. 2016). As a result, forests on many of these properties are less resistant to drought, insects, and wildfire, making them a potential hazard to neighboring properties.

An innovative solution to this problem may be the formation of forest health districts. These districts would function in a manner similar to irrigation districts: land is privately owned, but decision making may be shared across all landowners in the district. This model could be used to bring public, private, and NGO landowners and managers together to set and pursue forest health and resilience goals at larger scales. All parties would benefit from the economies of scale that come from planning forest management over larger spatial areas. Planning for larger areas costs much less on a per unit basis than developing forest management and timber harvest plans for many smaller areas. Likewise, timber harvest activities may be more profitable when plans can be developed over larger areas, and are more likely to attract necessary investments in sawmill or biomass power plants. Equally important, wildfire and insect outbreaks do not respect property boundaries. Therefore, poor management by one landowner may have adverse impacts on neighboring landowners as well, while good management will bring benefits. Forest health districts could help ensure that all landowners are using best practices.

Suggested reforms: Forest health districts may be established under the existing state law authorizing special district formation. If this is not possible, state legislation may be needed to authorize property owners to create forest health districts and to define the scope of the districts' powers and responsibilities. In the absence of state action, it may be possible for individual landowners to form cooperatives that bring some of the same benefits. Establishing such cooperatives may be difficult without outside assistance, however, and there is likely a role for NGOs to help facilitate their establishment.

4) Leverage new cooperation to increase infrastructure investments

Reducing forest density will require removing wood from the forest. However, there is a lack of capacity for processing this wood. California has 38 woody biomass power plants, but 26 of them are currently inactive due to low power prices. Another 16 biomass facilities are no longer operational. There are also roughly 30 operational sawmills in the state—just one-third of the state's sawmill capacity in 1990. The location of existing infrastructure is not well suited to serve many of the state's headwater forests. For example, the greatest need for forest thinning is in the southern Sierra Nevada, a region served by only two sawmills. Communities in Northern California have reported that limited access to timber processing infrastructure hinders their ability to participate in fuel reduction efforts (US Government Accountability Office 2017). Poor access to processing facilities results in high transportation costs, lowering the revenue potential of harvesting activities. USFS and private landowners struggle to find markets for their harvested biomass and timber.

Suggested reforms: Use cooperative models such as stewardship contracts, the Good Neighbor Authority, and forest health districts to spur investment in infrastructure. Private-sector investments in woody biomass power facilities and sawmills require assurance that a supply of forest products and timber will exist in both the short and long term. One way to induce investment is by having USFS sign longer-term (10-year) stewardship agreements with harvesters to guarantee a given amount of biomass and timber. Likewise, the establishment of GNA projects can also ensure biomass power plants and mill owners of a steady supply of timber, potentially for long time periods. The same is true of forest health districts that lead to increased active management. Increased production can be coupled with small state investments in infrastructure to facilitate projects. For example, in the Malheur National

Forest in Oregon, a 10-year stewardship contract project was complemented by private and state investment in a biomass facility near the project site (Business Oregon n.d.). This coupling of long-term contracting and public investment led to a successful and sustainable project that could be a model for California.

Conclusion

Management practices for California's headwater forests must be reformed. Decades of fire suppression, approaches that emphasized short-term priorities, weather extremes, and long-term climate change have set the stage for a decline in forest health. Management options exist—prescribed fire, managed wildfire, mechanical thinning, and forest pest management treatments—that can begin to build resilience in these forests and prepare them for the future. The technological challenges are not great. But administrative, regulatory, financial, and cultural barriers must be overcome. We believe many of these changes can take place at low or no cost, primarily requiring vision, determined leadership, and the backing of an informed public.

A nearly universal goal is to reduce the number of small trees and remove surface and ladder fuels that are the main fire hazard in headwater forests today. Many of our suggested reforms will directly address this problem: enshrining long-term resilience management practices into law, changing default rules on air quality regulation and other aspects of environmental permitting that hinder long-term forest management, clearly defining funding needs to inform public policy decisions, and encouraging better use of existing collaborative tools on federal and private lands.

Increasing the pace and scale of work will result in higher costs, depending on the mixture of treatments needed and the amount of area receiving treatment. These costs are also driven by the ability to bundle treatments with revenue-generating harvesting opportunities and access to infrastructure and markets. Some of the policy recommendations made here will require changes in approach (e.g., accounting for changes in forest conditions, developing stewardship contracts, using the Good Neighbor Authority, and establishing forest health districts). While some of our suggested reforms may require new funding and investments, others can be done at relatively low cost if agency executives and high-level managers are willing to champion and enact these changes. These reforms will, however, require risk-taking on the part of state and federal agencies. Efforts to reduce stand density—whether through mechanical thinning, prescribed wildfire, or managed wildfire—will generate controversy and strong opposition from some sectors. Agencies such as USFS could benefit from legislation to encourage forest resilience. For example, Congress could direct the USFS to make forest health a top priority in forest management, which could help defuse public opposition to short-term actions.

While active management to arrest the decline in forest resilience will take place far from urban centers, all Californians will benefit from actions to improve forest health through continued supplies of high quality water, habitat for wildlife, forest products, and recreational landscapes. It is said the best time to plant a tree is 20 years ago and the second best time is today: so it is with reforms to forest management. Management shortcomings of the past cannot be undone without enacting reforms today.

REFERENCES

Allen, C. D., A. K. Macalady, H. Chenchouni, D. Bachelet, N. McDowell, M. Vennetier, T. Kitzberger, A. Rigling, D. D. Breshears, E. H. (Ted) Hogg, P. Gonzalez, R. Fensham, Z. Zhang, J. Castro, N. Demidova, J. H. Lim, G. Allard, S. W. Running, A. Semerci, and N. Cobb. 2010. "A Global Overview of Drought and Heat-Induced Tree Mortality Reveals Emerging Climate Change Risks for Forests." *Forest Ecology and Management* 259: 660–84.

Asner, G. P., P. G. Brodrick, C. B. Anderson, et al. 2016. "Progressive Forest Canopy Water Loss during the 2012–2015 California Drought." *Proceedings of the National Academy of Sciences* 113: E249–E55.

Bales, R. C., J. J. Battles, Y. Chen, M. H. Conklin, E. Holst, K. L. O'Hara, P. Saska, and W. Stewart. 2011. *Forests and Water in the Sierra Nevada: Sierra Nevada Watershed Ecosystem Enhancement Project*. Sierra Nevada Research Institute report number 11.1, University of California, Berkeley.

Barker, Rocky. 2017. "Otter Says Feds Aren't the Enemy, Embraces Good Neighbor Plan." *Idaho Statesman*, January 12.

Belmecheri, S., F. Babst, E. R. Wahl, et al. 2016. "Multi-century Evaluation of Sierra Nevada Snowpack." *Nature Climate Change* 6: 2–3.

Bentz, B., C. D. Allen, M. Ayres, et al. 2009. *Bark Beetle Outbreaks in Western North America: Causes and Consequences*. University of Utah Press.

Boisramé, Gabrielle, Sally Thompson, Brandon Collins, and Scott Stephens. 2017. "Managed Wildfire Effects on Forest Resilience and Water in the Sierra Nevada." *Ecosystems* 20(4): 717–32.

Business Oregon. n.d. "John Day Lumber Plant Rises Yet Again With New Supply of Timber."

California Climate Investments. 2017. Annual Report: Cap-and-Trade Auction Proceeds.

California Department of Finance. 2017. "Department of Forestry and Fire Protection." *Governor's Budget: January, 2017–2018.*

California Department of Forestry and Fire Protection. *California Forest and Rangelands: 2010 Assessment*.

California Forest Pest Council. 2016. *2016 California Forest Pest Conditions*.

California Natural Resources Agency. 2017. *California Forest Carbon Plan: Managing our Forest Landscapes in a Changing Climate.* Draft for Public Review.

Calkin, D. E., M. P. Thompson, and M. A. Finney. 2015. "Negative Consequences of Positive Feedbacks in US Wildfire Management." *Forest Ecosystems*, 2.

Chiono, Lindsay A., Danny L. Fry, Brandon M. Collins, Andrea H. Chatfield, and Scott L. Stephens. 2017. "Landscape-Scale Fuel Treatment and Wildfire Impacts on Carbon Stocks and Fire Hazard in California Spotted Owl Habitat." *Ecosphere* 8(1).

Coppoletta, M., Merriam, K. E. and Collins, B. M. 2016. Post-Fire Vegetation and Fuel Development Influences Fire Severity Patterns in Reburns. *Ecological Applications* 26: 686–99.

Coulson, R. N., and Klepzig, Kier. 2011. *Southern Pine Beetle II. Gen. Tech. Rep. SRS-140*. US Department of Agriculture Forest Service, Southern Research Station.

Engel, Kirsten H. 2013. "Perverse Incentives: The Case of Wildfire Smoke Regulation." *Ecology Law Quarterly* 40: 623.

Fettig, C. J. 2012. Forest Health and Bark Beetles. Chapter in *Managing Sierra Nevada Forests.* Ed. Malcolm North. Gen. Tech. Rep. PSW-GTR-237. U.S. Department of Agriculture.

Fried, Jeremy S., Larry D. Potts, Sara M. Loreno, Glenn A. Christensen, and R. Jamie Barbour. 2017. "Inventory-Base Landscape Scale Simulation of Management Effectiveness and Economic Feasibility with BioSum." *Journal of Forestry* 115(4) 249-57.

Goulden, M. L. and R. C. Bales. 2014. "Mountain Runoff Vulnerability to Increased Evapotranspiration with Vegetation Expansion." *Proceedings of the National Academy of Sciences.* 111, 14071–75.

Gray, Brian, Dean Misczynski, Ellen Hanak, Andrew Fahlund, Jay Lund, David Mitchell, and James Nachbaur. 2014. "Paying for Water in California: The Legal Framework." *Hastings Law Journal*: Vol. 65: 1603.

Griffin, D., and K. J. Anchukaitis. 2014. "How Unusual is the 2012–2014 California Drought?" *Geophysical Research Letters* 41: 9017–23.

Gunderson, Lance H. 2000. "Ecological Resilience—In Theory and Application." *Annual Review of Ecology and Systematics* Vol. 31.

Gustavsson, Leif, Kim Pingoud, and Roger Sathre. 2006. "Carbon Dioxide Balance of Wood Substitution: Comparing Concrete- and Wood-Framed Buildings." *Mitigation and Adaptation Strategies for Global Change* 11, no. 3: 667-91.

Hartsough, Bruce, R., Scott Abrams, R. James Barbour, Erik S. Drews, James D. McIver, Jason J. Moghaddas, Dylan W. Schwilk, and Scott L. Stephens. 2008. "The Economics of Alternative Fuel Reduction Treatments in Western United States Dry Forests: Financial and Policy Implications from the National Fire and Fire Surrogate Study." *Forest Policy and Economics* 10.

Hayes, Samuel P. 2009. *The American People and the National Forest: The First Century of the US Forest Service*. University of Pittsburgh Press.

Houtman, R. M., C. A. Montgomery, A. R. Gagnon, D. E. Calkin, T. G. Dietterich, S. McGregor, and M. Crowley. 2013. "Allowing a Wildfire to Burn: Estimating the Effect on Future Fire Suppression Costs." *International Journal of Wildland Fire*, 22, 871-82.

Idaho Department of Lands and US Forest Service. 2016. "Good Neighbor Authority in Idaho: Frequently Asked Questions."

Kittler, Brian. 2014. "A Landmark Policy for Restoring Federal Forests: Permanent Authorization of Stewardship Contracting in the Farm Bill." Pinchot Institute for Conservation.

McIntyre, Patrick J., James H. Thorne, Christopher R. Dolanc, Alan L. Flint, Lorraine E. Flint, Maggi Kelly, and David D. Ackerly. 2015. "Twentieth-Century Shifts in Forest Structure in California: Denser Forests, Smaller Trees, and Increased Dominance of Oaks." *PNAS*. Vol. 122, no. 5.

Millar, C. I. and N. L. Stephenson. 2015. "Temperate Forest Health in an Era of Emerging Megadisturbance." *Science* 349: 823–26.

Miller, J. D., and H. Safford. 2012. "Trends in Wildfire Severity: 1984 to 2010 in the Sierra Nevada, Modoc Plateau, and Southern Cascades, California, USA." *Fire Ecology* 8:41–57.

Miller, W.W., D. W. Johnson, N. Gergans, E. M. Carroll-Moore, R. F. Walker, T. L. Cody, and B. Wone. 2013. "Update on the Effects of a Sierran Wildfire on Surface Runoff Water Quality." *Journal of Environmental Quality* 42, 1185.

Mount, Jeffrey, Ellen Hanak, Van Butsic, Ted Grantham, Yufang Jin, Scott Stephens, and Joshua Viers. 2016. *California's Water: Protecting Headwaters.* PPIC Water Policy Center.

National Research Council. 2008. *Hydrologic Effects of a Changing Forest Landscape*. Washington, D.C. The National Academies Press.

North, Malcom, April Brough, Jonathan Long, Brandon Collins, Phil Bowden, Don Yasuda, Jay Miller, and Neil Sugihara. 2015a. "Constraints on Mechanized Treatment Significantly Limit Mechanical Fuels Reduction Extent in Sierra Nevada." *Journal of Forestry* 113(1).

North, Malcolm, Brandon M. Collins, and Scott Stephens. 2012. "Using Fire to Increase the Scale, Benefits, and Future Maintenance of Fuels Treatments." *Journal of Forestry*. 110(7).

North, M. P., S. L. Stephens, B. M. Collins, J. K. Agree, G. Aplet, J. F. Franklin, and P. Z. Fulé. 2015b. "Reform Forest Fire Management: Agency Incentives Undermine Policy Effectiveness." *Science*, vol. 349 issue 6254.

Oregon Global Warming Commission. 2017. *Biennial Report to the Legislature*.

Pinchot Institute for Conservation. 2016. Presentation: National Stewardship Contracting Meeting: Case Studies from Recent Projects.

Progar, R. A., N. Gillette, C. J. Fettig, and K. Hrinkevich. 2013. "Applied Chemical Ecology of the Mountain Pine Beetle." *Forest Science* 60: 414–33.

Raaf, Teresa. 2014. Malheur National Forest. Presentation for Stewardship Contracting: Overview, Updates, and Examples. National Forest Foundation. July 24, 2014.

Roessing, Meg. 2014. Forest Service Stewardship Contracting Overview. Presentation for Stewardship Contracting: Overview, Updates, and Examples. National Forest Foundation. July 24, 2014.

Schoennagel, Tania, Jennifer Balch, Hannah Brenkert-Smith, Philip Dennison, Brian Harvey, Meg Krawchuk, Nathan Mietkiewicz, Penelope Morgan, Max Moritz, Ray Rasker, Monica Turner, and Cathy Whitlock. 2017. "Adapt to More Wildfire in Western North American Forests as Climate Changes." *PNAS* early edition.

Seager, Richard, Mingfang Ting, Isaac Held, Yochanan Kushnir, Jian Lu, Gabriel Vecchi, Huei-Ping Huang, Nili Harnik, Ants Leetmaa, Ngar-Cheung Lau, Cuihua Li, Jennifer Velez, and Naomi Naik. 2007. "Model Projections of an Imminent Transition to More Arid Climate in Southwestern North America." *Science*. 25.

Sierra Nevada Conservancy. 2011. System Indicators: Demographics and Economy.

Stephens, Scott L., Brandon M. Collins, Eric Biber, and Peter Z. Fulé. 2016. "US Federal Fire and Forest Policy: Emphasizing Resilience in Dry Forests." *Ecosphere* 7(11).

Stephens. S. L., C. I. Millar, and B. M. Collins. 2010. "Operational Approaches to Managing Forests of the Future in Mediterranean Regions within a Context of Changing Climates." *Environmental Research Letters* 5: 024003.

Stephens S. L, D. Fry, E. Franco-Vizcano. 2008. "Wildfire and Forests in Northwestern Mexico: The United States Wishes it Had Similar Fire 'Problems'." *Ecology and Society*. 13(2): 10.

Stephens, Scott L., James D. McIver, Ralph E. Boerner, Christopher Fettig, Joseph Fontaine, Bruce Hartsough, Patricia Kennedy, and Dylan Schwilk. 2012. "The Effects of Forest Fuel-Reduction Treatments in the United States." *BioScience* 62: 549–60.

Stephens, Scott, R. E. Martin, and N. E. Clinton. 2007. "Prehistoric Fire Area and Emissions from California's Forests, Woodlands, Shrublands and Grasslands." *Forest Ecology and Management* 251:205–16.

Stewart, William, Benktesh Sharma, Rob York, Lowell Diller, Nadia Hamey, Roger Powell, and Robert Swiers. 2016. Forestry. Chapter in *Ecosystems of California*. Eds.: Harold Mooney and Erika Zavaleta. University of California Press.

The Nature Conservancy and Ecosystem Economics. 2015. *Estimating the Water Supply Benefits from Forest Restoration in the Northern Sierra Nevada*.

US Census Bureau. 2016. Characteristics of New Housing.

USDA Forest Service. 2012. *The Process Predicament: How Statutory, Regulatory, and Administrative Factors Affect National Forest Management*.

USDA Forest Service. 2015a. *Collaborative Forest Landscape Restoration Program 5-Year Report*. US Forest Service, FS-1047.

USDA Forest Service. 2015b. *The Rising Cost of Wildfire Operations: Effects on the Forest Service's Non-Fire Work.*

USDA Forest Service. 2017a. *Fiscal Year 2018 Budget Justification, US Forest Service*.

USDA Forest Service. 2017b *Good Neighbor Authority*.

USDA Forest Service. n.d. *Good Neighbor Authority*. Accessed on May 2, 2017.

US Government Accountability Office. 2014. *National Environmental Policy Act: Little Information Exists on NEPA Analyses*. GAO-14-369.

US Government Accountability Office. 2017. *Wildland Fire Risk Reduction: Multiple Factors Affect Federal-Nonfederal Collaboration, but Action Could Be Taken to Better Measure Progress*.

Watts, Andrea. 2016. "Good Neighbor Authority: Gaining Ground in Wisconsin." *The Forestry Source*. September.

Weed, A. S., M. P. Ayres, and J. A. Hicke. 2013. "Consequences of Climate Change for Biotic Disturbances in North American Forests." *Ecological Monographs* 83: 441–70.

ABOUT THE AUTHORS

Van Butsic is an assistant cooperative extension specialist and adjunct professor at the University of California, Berkeley in the department of environmental science policy and management. He conducts research on land system science, environmental policy, and coupled human and natural systems. He holds a PhD in forestry and an MS in agricultural and applied economics from the University of Wisconsin–Madison, and a BA in economics from Reed College.

Henry McCann is a research associate at the PPIC Water Policy Center, where he manages policy research projects and provides core research support. Recent areas of research include water information and accounting systems, urban drought resilience, and headwater forest management. He holds an MA in urban and regional planning from the University of California, Los Angeles, and a BA in geography from the University of Chicago.

Jodi Axelson is an assistant cooperative extension specialist with the University of California, based on the Berkeley campus. She is a forest health specialist with expertise in western forest insects, primarily native bark beetles and defoliators. Her research focuses on how ecosystems respond to and recover from insect outbreaks and shifts in disturbance regimes. She has conducted forest research and operational forest management of damaging pests with both federal and provincial agencies in Canada. Her research in California is focused on assessing ecosystem processes and continued bark beetle mortality throughout the Sierra Nevada and developing tools for forest managers for the early detection of tree mortality due to bark beetles or other environmental stressors. She holds degrees in geography from the University of Victoria (BSc and PhD) and University of Regina (MS) in Canada.

Brian Gray is a senior fellow at the PPIC Water Policy Center and professor emeritus at the University of California, Hastings College of the Law in San Francisco. He has published numerous articles on environmental and water resources law and coauthored a variety of PPIC reports, including the 2011 interdisciplinary book on California water policy, Managing California's Water: From Conflict to Reconciliation. He has argued before the California Supreme Court and the US Court of Appeals in cases involving wild and scenic rivers, water pricing reform, takings, and water rights and environmental quality. He is a recipient of the William Rutter Award for Excellence in Teaching and the UC Hastings Outstanding Professor Award. He holds a JD from the University of California, Berkeley, and a BA in economics from Pomona College.

Yufang Jin is an assistant professor in the Department of Land, Air, and Water Resources at the University of California, Davis, specializing in remote sensing and ecosystem change. Her research focuses on monitoring and understanding eco-hydrological dynamics at a landscape scale. She has developed geospatial tools to detect area burned and tree mortality, quantity ecosystem productivity, and estimate consumptive water use. Her studies on fire-climate relationships and ecological response to changing climate and fire disturbances have provided insight for forest management strategies in both boreal and Mediterranean regions. She has published more than 35 peer-reviewed journal articles. She holds a PhD in geography from Boston University and a BS in atmospheric physics from Peking University.

Jeffrey Mount is a senior fellow at the PPIC Water Policy Center. He is an emeritus professor at the University of California, Davis, in the Department of Earth and Planetary Sciences and founding director of the Center for Watershed Sciences. A geomorphologist who specializes in the study of rivers, streams, and wetlands, his research focuses on integrated water resource management, flood management, and improving aquatic ecosystem health. He has served on many state and federal boards and commissions that address water resource management issues in the West. He has published more than a hundred articles, books, and other publications, including the seminal book *California Rivers and Streams* (UC Press). He holds a PhD and MS in earth sciences from the University of California, Santa Cruz.

Scott Stephens is a professor of fire science at UC Berkeley. Stephens' areas of expertise focus on interactions of wildland fire and ecosystems. This includes how prehistoric fires once interacted with ecosystems, how current wildland fires are affecting ecosystems, and how management and climate change may change this interaction. He is also interested in wildland fire policy and how it can be improved to meet the challenges of the next decades. He has published more than 150 journal papers and has given invited testimony to the White House, Congress, and the California Legislature. He holds a PhD in wildland resources from the University of California, Berkeley and a BS in electrical engineering from Sacramento State University.

William Stewart is a cooperative extension forestry specialist and co-director of the Center for Forestry and Center for Fire Research and Outreach at the University of California, Berkeley. He specializes in the economic aspects of forest management, family forest succession strategies, reforestation programs, watershed management, and climate change mitigation strategies involving forests and forest products. He has published numerous articles and book chapters on these topics and does considerable outreach on these topics to interested groups throughout the state. He holds an MS and PhD in forest economics and policy from the University of California, Berkeley and a BS in environmental earth sciences from Stanford University.

ACKNOWLEDGMENTS

This study would not have been possible without contributions from participants at PPIC's "Building Drought Resiliency in California's Forested Watersheds" workshop (October 2016), along with other policymakers, stakeholders, and researchers who provided valuable input over the course of this research. Several individuals lent their time and data resources, including Liz Berger, Barnie Gyant, Russ Henly, Brian Kittler, and Nicole Williams. In addition, we wish to thank the following individuals who provided reviews that greatly improved the final version: Eric Biber, Caitrin Chappelle, David Cleaves, David Edelson, J. Keith Gilless, Max Moritz, Dan Porter, and Hugh Safford. Lori Pottinger and Lynette Ubois provided expert editorial support, and Ellen Hanak served as lead reviewer. The authors alone are responsible for any remaining errors or omissions.

This publication was developed with partial support from Assistance Agreement No.83586701 awarded by the US Environmental Protection Agency to the Public Policy Institute of California. It has not been formally reviewed by EPA. The views expressed in this document are solely those of the authors and do not necessarily reflect those of the agency. EPA does not endorse any products or commercial services mentioned in this publication.

PPIC | PUBLIC POLICY INSTITUTE OF CALIFORNIA

The Public Policy Institute of California is dedicated to informing and improving public policy in California through independent, objective, nonpartisan research.

Public Policy Institute of California
500 Washington Street, Suite 600
San Francisco, CA 94111
T: 415.291.440
F: 415.291.4401
PPIC.ORG/WATER

PPIC Sacramento Center
Senator Office Building
1121 L Street, Suite 801
Sacramento, CA 95814
T: 916.440.1120
F: 916.440.1121