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**Henry McCann,
Van Butsic,
John Battles,
Ricardo Cisneros,
Yufang Jin,
Susie Kocher,
Matthew D. Potts,
and Scott Stephens**

with research support from
Claudia Herbert and
Samantha Smith

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The Benefits of Headwater Forest Management

SUMMARY

Forests in California are increasingly vulnerable to major wildfires and droughts that threaten the benefits they provide. Improving the health of headwater forests in the Sierra, in particular—where most of the state's surface water supplies originate—will provide an array of social, economic, and environmental benefits across multiple sectors and geographies. Research by forest ecologists and wildfire behavior experts finds that the best way to realize these benefits is to reestablish and maintain lower densities of trees, which will help make these forests more resilient to fire, drought, and pests.

Healthier forests can support rural communities, reduce air quality impacts from wildfires, securely store carbon and reduce greenhouse gas emissions, protect water quality from post-fire erosion, and increase water supply. The broad base of beneficiaries of headwater forest management includes rural communities in the headwater region, regions that are vulnerable to smoke impacts from major wildfires, and major urban areas and agricultural regions that receive water and hydropower from headwater forests.

Improving forest health will require a substantial lift from an array of private and public entities—along with new policies and sources of funding to facilitate complex, collaborative management. Clarifying the benefits and beneficiaries of forest management is a critical step in motivating long-term stewardship, and will inform efforts to craft financial tools, policies, and other governance solutions needed to make this heavy lift. By assessing what is known about the benefits of forest management, this report provides crucial information for ongoing policy discussions on long-term stewardship of California's headwater forests.

This report is based on an extensive review of the scientific literature. The details of that literature review—including references—are in the accompanying *Technical Appendix: Review of the Scientific Literature*.

CONTENTS

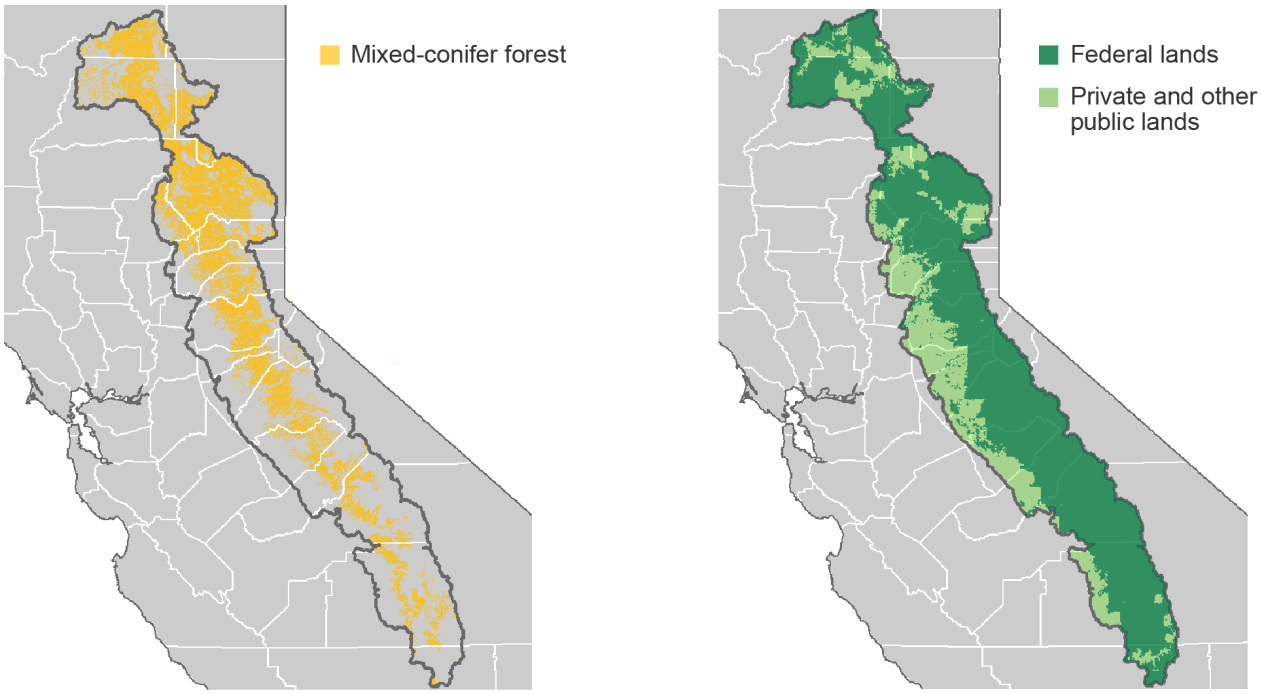
A technical appendix to this report is available on the PPIC website.

Introduction

Forests in California and other western states are increasingly vulnerable to major wildfires and droughts that threaten the social, economic, and environmental benefits they provide. In particular, headwater forests in the Sierra Nevada and southern Cascade ranges are in poor condition, and have experienced widespread tree death and numerous severe wildfires in recent years. There is an urgent need to step up practices that increase these forests' resilience to fire, drought, pests, and a warming climate. More than two-thirds of these forests are US Forest Service lands and small family-owned forests that mostly have not been actively managed for decades (Figure 1). Accelerating management will generate a suite of benefits for this region and the state as a whole, including support for the well-being of rural communities, reduction in widespread smoke impacts, more-secure storage of carbon and reduced greenhouse gas emissions, and improved water quality and supply.

FIGURE 1

The headwater region is dominated by mixed-conifer forests that are vulnerable to wildfire, drought, and pests



SOURCES: USDA Natural Resources Conservation Service GeoSpatialDataGateway for watershed boundaries; California Forests and Rangelands Assessment FVEG (2015) for forest vegetation characterization; California Forests and Rangelands Assessment California Multi-Source Landownership (2009) for land ownership boundaries.

NOTE: The headwater region is delineated by major watersheds based on hydrological unit maps (HUC8) as modified by the authors. White boundaries show counties. The dark gray boundary denotes the headwater region.

Various changes in practices since the mid-19th century have vastly increased the density of small-diameter trees in headwater forests. As a result, these forests are more vulnerable to severe wildfires and prolonged drought. Climate change is expected to amplify these threats. Managing forests for resilience can reduce these vulnerabilities and improve forest health.

This report provides an overview of benefits from headwater forests that could be enhanced by expanding forest management. We identify the beneficiaries of resilient headwater forests, highlighting potential partners who could support current and future management efforts. We also describe limitations and uncertainties regarding where, when, or how much benefit is likely. And we review the implications of research findings for policy and management.

Improving forest health will require a substantial lift from an array of private and public entities—along with new policies and sources of funding to facilitate complex, collaborative management. Understanding the various benefits of management can help motivate these efforts. Beneficiaries who have the most to gain from improving forest resilience can be key partners in promoting forest management and helping to fill funding gaps.

This report is the second in a series on headwater forest management (a companion technical appendix describes in greater detail the research summarized here). The first report, *Improving the Health of California's Headwater Forests*, laid out the case for increased management. Subsequent efforts will examine forest management funding gaps and the role that beneficiaries can play in addressing them.

Some Key Forest Management Terms

Fire severity: The extent to which wildfire consumes or kills live vegetation. Wildfire burning at high severity removes understory vegetation and kills almost all large trees in the burned area. Wildfire burning at low or moderate severity removes understory vegetation but kills substantially fewer trees. Most wildfires have at least some low-, moderate-, and high-severity patches. Wildfires with large contiguous patches of high-severity burning have the highest social, economic, and environmental costs.

Forest structure: The abundance, size, and distribution of trees in a forest. Structure is measured using variables such as the number of trees per acre, the size of living and dead trees, and their spatial organization. Forest structure influences fire severity.

Headwater forest: This report focuses on approximately 10 million acres of mixed-conifer forests in the mid-elevations of the western Sierra Nevada and southern Cascade mountain ranges. These forests are between the oak-conifer forests in the foothills and the high-elevation (upper montane) forests. More than half of California's surface water supplies originate as rain or snow in this region.

Healthy headwater forests: Forests that can withstand and recover from disturbances, with recovery defined as a return to pre-disturbance condition.

Mosaic forest structure: Forests with a patchwork structure composed of varied tree densities, sizes and species, with numerous openings with few or no trees. This structure is resilient to wildfire, drought, and pests. It can be established and maintained with forest management techniques such as mechanical thinning, prescribed fire, and managed wildfire.

Managed wildfire: Monitoring and managing wildfires to improve forest health under conditions that limit the risk of damage and threats to public health and safety.

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

Prescribed fire: Intentional setting of fires to improve forest health under conditions that limit the risk of damage and threats to public health and safety.

Managing for a Mosaic Structure in Headwater Forests

Headwater forests once had structural features that made them more resilient to wildfire, drought, and pests. The landscape was a complex mosaic that was generally lower in density and had more large trees than current forests. Local fire patterns and water availability heavily influenced this highly variable forest landscape. Dry slopes prone to frequent fires (every 5 to 30 years) had widely spaced trees and low levels of understory vegetation. This limited opportunities for large-tree-killing crown fires that spread between treetops. Frequent understory fires reduced competition between trees, which improved their ability to withstand drought and insect outbreaks. This landscape was dotted with dense stands of fir and pine as well as open areas containing few trees.

Today's headwater forests are more homogenous, having fewer large trees and more small trees, often in very dense stands. Many large trees were removed as a result of timber harvest practices in the late 19th and early 20th centuries. Small-diameter trees have proliferated since the end of intentional burning by California's indigenous tribes after 1860 and aggressive fire suppression since the early 1900s. Research by forest ecologists and wildfire behavior experts finds that these structural changes have made forests more vulnerable to catastrophic events. In dense and homogenous forests, wildfires spread quickly and burn more intensely, killing large swaths of trees; trees also have greater competition for water, worsening stress during drought. In this condition, bark beetles can cause widespread tree death, as happened during the 2012–16 drought.

Mixed-conifer headwater forests have become more dense and homogenous over time.

PHOTO CREDIT: George E. Gruell. 2001. *Fire in Sierra Nevada Forests: A Photographic Interpretation of Ecological Change Since 1849*. Mountain Press.

Many complex factors influence forest health, making it hard to predict the long-term effects of climate change on headwater forests at a scale that is meaningful for management. However, climate scientists are confident that the headwater region will see more intense droughts and increased wildfire activity over time. In their current condition, some forests may not recover from these events and will transition to shrublands.

There is growing consensus among academic experts and practitioners that management should prioritize making forests more resilient to wildfire, drought, and pests. The overarching goal is to establish and maintain complex forest mosaics that are overall lower in density than forests today. This approach provides a model for improving forest resilience, while also allowing flexibility to accommodate landowner preferences and experimentation by

forest managers. A forest mosaic can be achieved through prescribed fire, managed wildfire, and mechanical thinning. Long-term coordinated application of these techniques can bring multiple benefits. The cost and effectiveness of each type of treatment depends on a host of site-specific characteristics, including site accessibility, risk to communities and the environment, and availability of markets for wood products.

Improving forest health requires increasing the pace and scale of such efforts—including both initial treatments and ongoing maintenance. Experts estimate that limiting the growth of large wildfires requires active management on 20–30 percent of lands—a much larger scale than current practices. And because forests that are not regularly maintained will eventually lose their resilience to wildfire and drought, expanding treatments must be complemented by plans for long-term stewardship. Clarifying the benefits and beneficiaries of forest management can inform efforts to craft financial tools, policies, and other governance solutions for improving forest health.

Benefits and Beneficiaries of Forest Management

Mosaic forests are resilient to wildfire, drought, and pests. Such forests reduce the chances of large, severe wildfires and widespread tree death from other causes, thereby supporting a portfolio of social, economic, and environmental benefits. Developing a clear understanding of the benefits of increased forest management—while acknowledging uncertainties and possible tradeoffs—is a critical step in motivating long-term stewardship. This report focuses on five benefits explored in the scientific research, and finds that forest management has the potential to bring the following results:

Support the well-being of rural communities: Reduce wildfire threats, preserve landscapes on which local economies rely, and increase economic opportunities in forest management.

Reduce smoke impacts on public health: Reduce large wildfire smoke events that degrade air quality in rural and urban communities.

Store carbon securely and reduce emissions: Limit threats from wildfire, drought, and pests on carbon stored in large trees, while reducing greenhouse gas emissions from large wildfires.

Protect water quality: Avoid threats to downstream water quality from post-fire erosion following high-severity wildfires.

Increase water supply: Increase streamflow, snowpack accumulation, and snowpack retention in some parts of the headwater region.

This list of benefits is not exhaustive. We highlight benefits that are more easily quantified and potentially valued in monetary terms—factors that are most likely to motivate long-term stewardship. For example, this report does not fully evaluate how managing for mosaic forests can affect biodiversity. For each benefit, we also describe key beneficiaries and consider factors that influence the scale and extent of benefits, potential tradeoffs, and uncertainties.

 Support the Well-being of Rural Communities

Rural communities in the headwater region face many challenges. Socioeconomic research confirms that many communities are economically distressed from the long-term decline in timber harvesting, mill operations, and other industrial activities. Communities near overly dense forests are also very vulnerable to wildfires. Increasing the pace and scale of forest management can reduce these risks.

Forest management brings economic opportunities across a wide range of sectors and expertise, including brush clearing, ecological analysis, wood utilization, and other services. It can also present additional opportunities for workforce training, employment, and earnings.

Expanding forest management creates opportunities for workforce development. Here, local high school students learn forest management techniques as part of the Plumas Conservation, Restoration, and Education in Watersheds program.

PHOTO CREDIT: Sierra Institute for Community and Environment.

Resilient forests also support continued opportunities for outdoor recreation and tourism—a key element in local economies. Half of the region's 16 counties rely heavily on spending from recreation and tourism. Decreasing wildfire risks can help reduce smoke, park closures, damage to infrastructure and scenic landscapes, and other disruptions to these activities.

Large wildfires pose significant threats to homes, businesses, and critical community infrastructure such as transportation, water and energy utility systems, and hospitals. By reducing the speed and intensity of these fires, forest management can complement and bolster local fire management efforts.

Large-scale forest management projects have begun to include these types of benefits. For example, the Sierra Institute for Community and Environment and South Lassen Watersheds Group are incorporating local job creation into planned forest management work in the Upper Feather River watershed. In the Lake Tahoe Basin, bolstering tourism-based economies and reducing wildfire threats to communities are two key objectives of the Lake Tahoe West Restoration Partnership's effort. The project will reduce wildfire risk and limit disruptive smoke impacts by managing 60,000 acres of forest on the west side of Lake Tahoe.

Beneficiaries

- **Residents of headwater forests.** Sustained forest management can improve economic prospects for residents of economically distressed rural communities. It can also reduce the risk of wildfires moving into communities.
- **The forest management sector.** Increased management will generate employment opportunities, including for businesses that provide related services such as sawmills, biomass energy production, and transportation. There could also be new job opportunities in areas such as forest ecology, hydrology, and advanced wood engineering.
- **Tourists and recreational visitors, and the businesses that serve them.** Visitors to the region and the businesses they support will benefit from fewer disruptions from large, severe wildfires. Local landscapes will be more resilient to fire and pests.

Considerations

- **Investments in infrastructure and job training are needed to increase management activities and realize socioeconomic benefits.** Many economically distressed communities currently lack the workforce and infrastructure (e.g., wood processing facilities) needed to support an increase in forest management. Targeted investments can help scale up efforts while driving opportunities for local economic development.
- **Forest management alone is insufficient to reduce community vulnerability to wildfires—other local and regional actions are essential.** Protecting communities from wildfire also requires home hardening and defensible space to lower threats to structures. Reducing ignition sources—such as from electrical transmission lines—is another priority. Advance wildfire emergency planning is also critical: communities need evacuation plans and emergency communication systems in place before wildfires occur.

Reduce Wildfire Smoke Impacts on Public Health

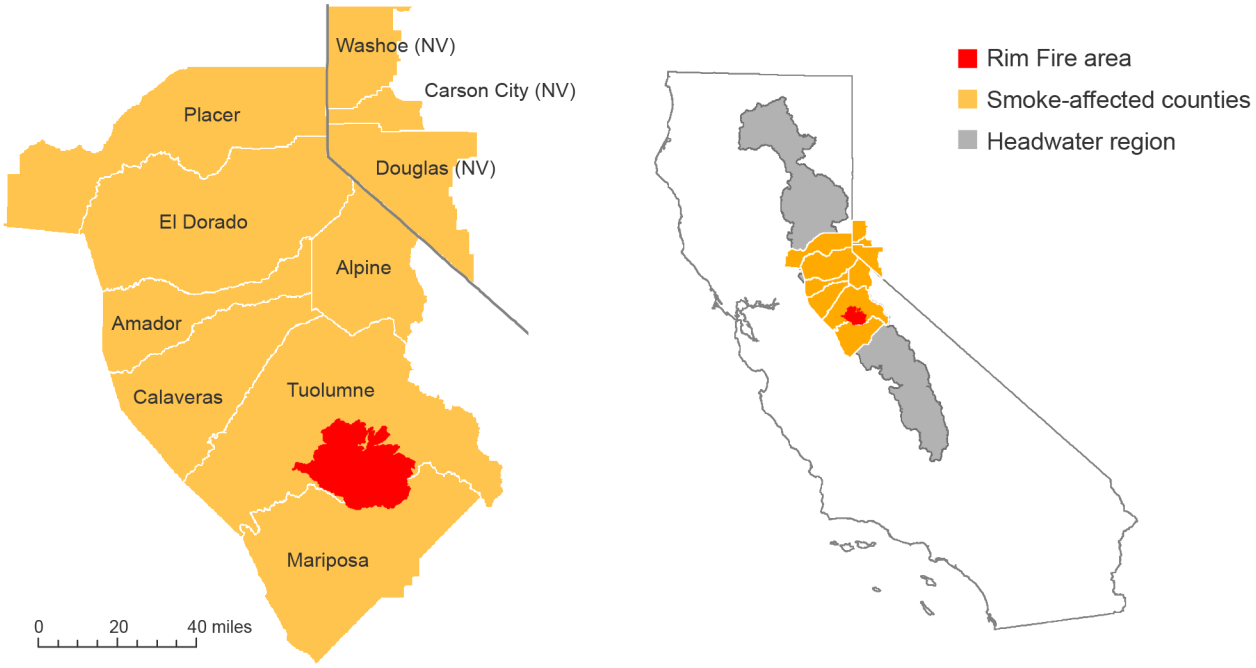
Wildfire smoke can cause respiratory and cardiovascular problems. Even short-term exposure to pollutants and fine particles in wildfire smoke (ranging from days to weeks) can affect both healthy and vulnerable populations. In recent years, large wildfires in headwater forests generated smoke that traveled long distances and covered large areas, exposing rural and urban populations to unhealthy smoke for weeks at a time. For example, the plume from the 2013 Rim Fire caused significant air quality impacts throughout the headwater region and western Nevada (Figure 2). A study on the smoke impact of this fire estimated that 1.2 million people across 10 counties were exposed to several days of fine particulates above federal air quality standards.

Mosaic forests are at much lower risk of causing these public health impacts. Research suggests that forest management can help shift the current pattern of large, uncontrolled wildfires to less-severe fires. Smoke from less-severe fires contains fewer pollutants and disperses over smaller areas. One study estimated the smoke exposure from an acre burned at lower severity is just one-tenth the level of an acre burned at higher severity.

Forest managers can also exert more control over the smoke impacts of prescribed and managed fires. This means timing burns for when weather conditions carry smoke away from communities. Other steps to reduce impacts on public health include advance planning and improved communication with communities, and distributing household air filters to vulnerable populations.

FIGURE 2

The 2013 Rim Fire exposed residents of 10 counties to days of smoke



SOURCE: Adapted by authors from Navarro, K.M., R. Cisneros, S.M. O'Neill, D. Schweizer, N.K. Larkin, and J.R. Balmes. 2016. "Air-Quality Impacts and Intake Fraction of PM 2.5 during the 2013 Rim Megafire." *Environmental Science & Technology*. 50 (21).

NOTES: This study estimated the volume of fine particulate matter generated by the 2013 Rim Fire inhaled by individuals over the active period of burning from August 17–September 19, 2013. Estimates are based on ground-level measurements of fine-particulate matter concentrations in air. Note that the inset map truncates the northern portion of Washoe County, NV.

Beneficiaries

- **Communities prone to impaired air quality from smoke.** Headwater communities, in addition to those in neighboring Central Valley, eastern Sierra, and western Nevada regions, will benefit from efforts that reduce exposure to unhealthy smoke. This is especially true for individuals who are sensitive to particulate pollution, such as the elderly, children, and people with heart and lung disease.
- **Health care providers and insurers.** Health care providers and insurers often take steps to avoid the need for their patients or enrollees to receive emergency care. Large spikes in emergency care can be costly. Proactive forest management would help avoid large smoke episodes that rapidly increase demand for emergency care in affected areas.

Considerations

- **Establishing mosaic forests will require much greater use of prescribed fire and managed wildfire, both of which have upfront smoke impacts.** The initial application of these techniques in forests that have accumulated decades of fuel will generate smoke in the headwater region, though less than uncontrolled severe wildfires would. Forest managers can limit exposure risks through advance planning, communications, and strategic burning techniques.
- **Smoke from management activities will become more common over the long term.** Once the mosaic landscape is established, managers will often need to maintain forest conditions through periodic prescribed burning and managed wildfire. Smoke from management projects may become a more persistent presence in the region. The risk of chronic exposure to low-concentration smoke is one reason these management techniques are not always supported by local communities today, although it may become more acceptable if residents see it as a by-product of a sustained improvement in forest health.

- **Mechanical thinning does not generate smoke impacts.** Mechanical thinning generally does not create smoke (the exception is when most of the mechanical thinning residue is burned in place rather than removed for other uses). But it tends to be more expensive per acre compared to strategic use of fire, and it is not suitable in all topographies.

Store Carbon Securely and Reduce Carbon Emissions

Forests play an important role in the storage and release of greenhouse gases. Trees capture atmospheric carbon dioxide and store it as organic carbon when they grow. Trees release carbon at varying rates into the atmosphere when they die, depending on whether it was from old age, drought, pests, wildfire, or harvest. Nearly 2 billion metric tons of carbon are stored in California's forested ecosystems—and nearly half of it in headwater forests. In response to recent major wildfires and widespread tree death during the 2012–16 drought, state agencies are working to maintain the carbon storage capacity of forests through active management.

The proliferation of small trees has increased the amount of carbon stored in headwater forests over time, but has also increased vulnerability to wildfire, drought, and pests. Overly dense forests are more prone to severe wildfires and tree die-offs that kill large trees. Large trees store more carbon and at higher rates than smaller trees.

Estimates suggest that carbon emissions from wildfires have increased statewide over the past two decades, and this upward trend is likely to persist as the climate changes. By reducing wildfire risk, mosaic forests can reduce associated carbon emissions. A study that modeled the effects of wildfire on carbon storage in headwater forests found that wildfire carbon emissions in unmanaged forests were double those in managed ones. This was because large trees in treated forests were less likely to be killed by wildfire than those in denser, unmanaged forests.

Studies using different accounting methods arrive at different results about whether the state's forests are sequestering as much carbon as they are losing through wildfire emissions and drought-induced tree death. However, the scientific community largely agrees that unmanaged headwater forests will likely shift to becoming sources rather than sinks of carbon as stressors intensify over time. Research suggests that managed mosaic forests—dominated by large, fire-resistant trees—do a better job of protecting carbon stored in trees over time compared to dense, unmanaged forests.

Storing carbon and reducing greenhouse gas emissions are two core objectives of CAL FIRE's Forest Health Grant Program. Following the passage of Senate Bill 901 in 2018, this cost-share program has supported more than a dozen forest-health projects across the state each year. To be eligible for funding, forest-thinning projects must clearly demonstrate net greenhouse gas reductions by channeling carbon into large fire-resistant trees and reducing the likelihood of large wildfires.

Cap-and-trade revenues support forest health projects that protect carbon in large trees. This photo shows the French Meadows project in the American River watershed; it received funding from CAL FIRE's Forest Health Grant program.

PHOTO CREDIT: Placer County Water Agency.

Beneficiaries

- **California.** Managing forests as reliable sinks of carbon helps the state achieve its goal to reduce greenhouse gas emissions.
- **Participants in forest carbon sequestration markets.** Participants in California's carbon offset program who manage their forests to reduce wildfire risk can receive a financial benefit for their efforts.
- **Society at large.** Forest carbon sequestration benefits everyone.

Considerations

- **Accounting for forest carbon is difficult.** California has a pressing need to accurately measure its forest carbon. Yet doing so at the scale needed to inform greenhouse gas reduction strategies is challenging. Combining satellite-based measurements and field data collection could improve the monitoring of forest carbon changes, but questions remain about the accuracy and feasibility of such an approach.
- **The choice of management techniques will affect the overall carbon balance.** Managing forests to increase long-term carbon storage in large trees requires removing small trees and understory vegetation. Managed wildfires and prescribed fires result in the immediate release of that carbon to the atmosphere. In contrast, mechanical thinning can result in some continued carbon storage from the harvested wood if it is used as dimensional lumber or other long-lasting wood products. And woody debris can be used to generate biomass energy, which can sometimes replace more carbon-intensive energy sources.

Protect Water Quality from Post-wildfire Erosion

California's headwater region has steep slopes and heavy seasonal rains—factors that make it highly susceptible to erosion after high-severity wildfires. Storm runoff following severe wildfires can carry sediment, debris, chemicals, and other matter that can rapidly degrade water quality in streams, rivers, and lakes—creating challenges for water and hydropower infrastructure operators and harming aquatic ecosystems. Severe fires can heat soils to the point of becoming water-repellant. During big rains, runoff from these soils causes erosion, landslides, and debris flows that harm waterways and pose risks to the public. High levels of sediment and debris can also reduce reservoir capacity and impair the operation of dams, hydropower facilities, and water conveyance systems. Removing sediment and debris from this infrastructure can be costly.

Post-fire erosion can severely damage aquatic habitat in streams, wetlands, and lakes. Large quantities of ash and debris increase turbidity, nutrient loads, and siltation that are harmful to aquatic species. Loss of vegetation along rivers and streams can significantly increase water temperature. This increases stress on cold-water-dependent species such as steelhead and salmon.

Forest management can reduce the risk of wildfires and lower the threat of post-fire erosion. This strategy is being implemented in several watersheds. For example, the 2014 King Fire resulted in costly damage to water and hydropower infrastructure from sediment and debris flows in the American River watershed. This wildfire initiated the French Meadows project—a large-scale, collaborative forest management effort to avoid future damages and costs from post-fire erosion. Water supply and hydropower managers in other watersheds are engaging in similar efforts. Beyond reducing post-fire erosion threats, forest management in all these cases has the added benefit of reducing the risk of direct damage from wildfire on critical infrastructure.

The 2014 King Fire severely burned thousands of acres in the American River watershed, which resulted in significant post-fire erosion the following winter and spring.

PHOTO CREDIT: Placer County Water Agency.

Beneficiaries

- **Reservoir operators.** Reservoirs in the headwater region support many services, including local water supply, flood control, hydropower generation, recreation, and aquatic ecosystem management. Forest management can help avoid costly post-fire erosion damages that impair these services.
- **Off-channel hydropower producers.** Some hydropower facilities rely on water diverted from streams or reservoirs and conveyed to generating stations via canals, tunnels, and flumes. Avoiding damage from post-fire erosion is important for reliable hydropower supplies and avoiding clean-up and equipment replacement costs.
- **Aquatic ecosystems.** These ecosystems benefit from avoiding major post-fire erosion that can damage streams, wetlands, and lakes.

Considerations

- **Large foothill reservoirs are somewhat buffered from post-fire erosion impacts.** Larger reservoirs at lower elevations, which are essential to California's surface water delivery system, are buffered from post-fire erosion by upstream reservoirs that trap sediment and debris.
- **Every tributary has a different level of post-fire erosion risk.** Each tributary has a unique mix of wildfire risk, post-fire erosion risk, and vulnerable assets. Estimating the risk to specific assets is a challenge, but analytical techniques are improving. Even simplified analysis can help determine levels of vulnerability to key assets, identify priority areas for reducing fire risk, and evaluate the economic rationale for such management.

Increase Water Supply

Headwater tributaries provide much of California's surface water, generate almost all of its hydropower, support the region's water-based recreation industry, and sustain aquatic ecosystems. Forests play an important role in storing and regulating the release of rain and snow into headwater tributaries, thereby influencing the volume, timing, and quality of runoff into rivers and streams.

Most precipitation that falls in the headwaters is taken up by plants and returned to the atmosphere through evaporation from soils and transpiration from needles and leaves (a process called evapotranspiration). Precipitation not returned to the atmosphere eventually enters streams as runoff. Preliminary research suggests that reducing tree density through forest management may also increase streamflow in some parts of the headwater region, particularly in wetter years and snow-dominated landscapes. Estimates of increased average annual streamflow from forest thinning range from negligible to 14 percent.

Early-stage research on forests and snowpack dynamics suggests that forest density can also influence the rate of snowmelt in headwater forests. Contrary to conventional wisdom, lower-density forests may retain snowpack for longer periods compared to higher-density headwater forests. Future research may indicate that delaying snowpack melting is another benefit of managing for mosaic forests.

A pilot project in the North Yuba River watershed will test the concept of increasing streamflow by improving forest health. This multi-year effort on 15,000 acres is supported in part by the Yuba Water Agency. In addition to the potential benefits of enhanced streamflow, the agency stands to benefit by avoiding future costs from post-fire erosion damages to its water and hydropower systems.

Beneficiaries

- **Water suppliers and consumers.** The headwater region supports a wide array of agencies that capture, store, and deliver water to cities and farms. Increasing the availability and predictability of high-quality water supplies will allow these entities to meet the needs of their customers more reliably.

- **Hydropower producers.** Increasing water supplies could increase hydropower production for meeting peak demands. This is a low-carbon alternative to burning fossil fuels.
- **Aquatic ecosystems.** Aquatic ecosystems in the headwaters depend upon the storage and release of cold water from snow and groundwater. Improved forest management can increase the amount and reliability of these water sources, improving conditions for fish and other aquatic species in rivers and streams.
- **Water-based recreation sector.** Forest management that increases reservoir water levels and summer streamflow supports water-dependent recreation and related businesses.

Considerations

- **The benefits of increased water supply decline as vegetation grows back.** Due to the short timeframe of existing studies on the impacts of thinning forests on streamflow, research has only been able to confirm temporary gains in annual water yield. Sustaining increased runoff and snowpack retention will require ongoing maintenance. The cost of new water generated by forest management may be prohibitively high.
- **There is high uncertainty about water supply benefits at scale.** Small-scale research efforts suggest that thinning forests can increase streamflow and delay snowpack melting. But quantifying these effects across larger areas and longer time periods is difficult due to California's variable climate and the diversity of its forested landscapes. Ongoing research continues to refine estimates of the magnitude and timing of potential hydrological effects from managing for mosaic forests in the headwater region.

Forest thinning has been shown to increase streamflow in some headwater forests. These researchers are setting up instruments to measure annual water cycle changes in the Kings River basin.

PHOTO CREDIT: Roger Wynan, courtesy of the Sierra Nevada Research Institute.

Implications for Policy and Management

Improving the health of California's headwater forests will provide an array of social, economic, and environmental benefits across multiple sectors and geographies. The best way to realize these benefits is to establish and maintain lower-density mosaic forests.

While several major efforts to improve forest health are currently underway, there is an urgent need for financial tools, policies, and governance solutions to drive sustained management activity across the headwater region. Clarifying the benefits and beneficiaries of forest management can help build consensus and motivation among those who can support these efforts. Several major takeaways can foster success:

- **Managing forests for multiple benefits is a matter of design.** Research suggests that a mosaic structure plays an important role in improving resilience to wildfire, drought, and pests, while also generating a broad portfolio of benefits. Therefore, the mosaic structure is a useful model for designing forest management projects. But there is no single blueprint for success. Implementation of this approach should allow for experimentation by forest managers and accommodate landowner preferences.
- **Mechanical thinning has advantages over strategic use of fire in terms of air quality, carbon sequestration, and support for rural communities.** Mechanical thinning entails fewer risks, including smoke impacts on public health. It can generate a stream of usable wood material that continues to store carbon and supports economic development. Yet in remote locations or challenging terrain, mechanical thinning may not be a feasible alternative to strategic use of fire. And it is often more costly.
- **Benefits extend beyond the headwater region.** Increasing water supply, protecting water quality, reducing smoke impacts, and sequestering carbon all bring benefits well beyond the headwater region. More general funding models may be appropriate for efforts that benefit groups outside of the region.
- **Uncertainties need to be addressed.** Several benefits discussed in this report are subject to uncertainties about location, magnitude, and duration. This is especially true for increasing water supplies and securely storing carbon in forests. Filling important knowledge gaps will enable more precise articulation of benefits and beneficiaries.
- **Beneficiaries can play important roles in improving forest health.** The beneficiaries described in this report represent a broad range of geographies, with a diverse range of objectives, resources, and positions of influence. The roles they can play in motivating and implementing forest management are also diverse. Beneficiaries can advocate for increasing forest management efforts. They can organize groups of stakeholders and other beneficiaries around forest management objectives. They can provide funding for forest management efforts that benefit themselves and others. And they can help develop policies that facilitate larger and more effective forest management efforts.

Conclusion

Managing headwater forests to be more resilient to wildfire and drought can sustain and even improve the portfolio of benefits that forests provide. This will require vastly expanding forest management efforts. Despite some uncertainties, the evidence suggests that improving resilience of forests to current and future stressors will provide the broadest portfolio of social, economic, and environmental benefits.

Establishing healthy forests will be a heavy lift at local, state, and federal levels—requiring actions over very large scales and in some cases at high costs. Management must be persistent and durable to ensure long-term benefits: decades of effort and funds to improve and maintain these forests are required. It is critically important that forest managers identify revenue streams and determine long-term management responsibilities.

Looking forward, the principal challenge is developing financial resources, policies, and governance solutions to support long-term forest stewardship. The benefits and beneficiaries identified here will play a key role in motivating future actions.

ABOUT THE AUTHORS

Henry McCann is a research associate at the PPIC Water Policy Center, where he manages research projects and provides core research support. His recent projects have focused on headwater forest management, water information and accounting systems, and urban drought resilience. He previously managed research projects within the Smart Water Systems initiative at the UCLA Luskin Center for Innovation. 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.

Van Butsic is an assistant cooperative extension specialist and adjunct professor in the Department of Environmental Science, Policy, and Management at the University of California, Berkeley. 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.

John Battles is a professor of forest ecology at the University of California, Berkeley, and a field scientist engaged in long-term research of temperate forest ecosystems. His goal is to understand how and why forests change. His research seeks to understand the dynamic response of forest communities to disturbances such as air pollution, invasive species, forest management, extreme drought, and fire. His recent work has focused on understanding the interactions among disturbances in order to assess their potential to reshape forests. He holds a PhD in forest science from Cornell University and a BS in biology from Yale University.

Ricardo Cisneros is an assistant professor of environmental public health at the University of California, Merced. He is an authority on the air quality impacts of wildfire. He conducts research that recognizes the interdependence of ecological and human health with air pollution research and exposure assessment. He has conducted several environmental research studies, including determining the impacts of wildfires on air quality. He holds a PhD in environmental systems from the University of California, Merced, and completed a two-year postdoctoral appointment in exposure science from the Department of Public Health Sciences at the University of California, Davis.

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 burned area and tree mortality, quantify 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.

Susie Kocher is a natural resources advisor for the University of California Cooperative Extension in the Central Sierra. She conducts outreach, extension, and applied research on forest management in El Dorado, Amador, Calaveras, and Tuolumne Counties. Her work has focused on pre- and post-fire forest management, development of fire-adapted communities, and prescribed fire. She has held numerous workshops for landowners on prescribed fire, forest stewardship, and forest recovery after fire- and beetle-induced tree mortality. She is the author of many extension publications aimed at helping private landowners better manage their forest land. She is a California registered professional forester. She holds an MS in forest resources management from the University of Washington and a BA in anthropology from the University of Iowa.

Matthew D. Potts is an associate professor in the Department of Environmental Science, Policy, and Management at the University of California, Berkeley and currently holds the S. J. Hall Chair in Forest Economics. He has a broad interdisciplinary background with formal training in mathematics, ecology and economics and more than two decades of field experience working on forestry issues. His interdisciplinary lab is focused on understanding the drivers of biodiversity and responses to disturbance, biodiversity conservation, and ecosystem services production in working landscapes, and the impact of human actions, values, and technology on ecosystem service production. He has published more than 60 peer-reviewed publications in ecology, environmental economics and engineering. He holds a PhD in applied mathematics from Harvard University and a BS in mathematics from the University of Michigan.

Scott Stephens is a professor of fire science and the Henry Vaux Distinguished Professor in Forest Policy at the University of California, Berkeley. He focuses on interactions between wildland fire and ecosystems—including how prehistoric fires 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 coming decades. He has published more than 200 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.

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Public Policy Institute of California
500 Washington Street, Suite 600
San Francisco, CA 94111
T: 415.291.4400
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