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The Benefits of Headwater Forest Management

Technical Appendix: Review of the Scientific Literature

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Introduction

California's headwater forests are in poor health, and need a substantial increase in the pace and scale of management efforts to make them more resilient to wildfire, drought, and pests. While promising management techniques have been identified by academic and forest management researchers, the financial, policy, and governance solutions needed to implement management across large landscapes are not materializing fast enough. Developing a clear understanding of the benefits and beneficiaries of increased forest management—while acknowledging uncertainties and possible tradeoffs—is a critical step in motivating long-term stewardship and identifying potential partners to support it.

The accompanying report, *The Benefits of Headwater Forest Management*, provides a concise overview of the benefits and beneficiaries of improving forest health. This technical appendix takes a more detailed look at these concepts and the research behind them. In our review of the scientific literature, we find credible evidence that a "mosaic structure" is a good model for forest management going forward. In our examination of the benefits of this approach, we explore the tradeoffs and uncertainties for each benefit. Where possible, this appendix also highlights the quantification of benefits as published in existing research and real-world examples.

This appendix follows a similar structure to *The Benefits of Headwater Forest Management* to facilitate easy cross-referencing. The first section gives an overview of how headwater forests have changed over time, and describes the consequences of those changes on forest health. We then review how managing for a mosaic structure can improve resilience to current and future pressures from wildfire, drought, and pests.

The second section describes the portfolio of benefits generated from managing headwater forests. We summarize five broad categories of benefits explored in the scientific research, and find that forest management has the potential to bring the following results: support for rural communities, reduced smoke impacts on public health, secure storage of carbon and reduced greenhouse gas emissions, protection of water quality from post-fire erosion, and increased water supply. We selected these benefits because they are more easily quantified and valued in monetary terms, making them the most likely to motivate long-term stewardship efforts.

Managing for a Mosaic Structure in Headwater Forests

Before European settlement in the mid-19th century, the mixed-conifer headwater forests of the western Sierra Nevada and southern Cascade Range were shaped by local fire patterns and water availability (Lydersen and North 2012). Overall, these forests were lower in density and had more large trees compared to present conditions (Safford and Stevens 2017). They also had a more complex structure. Significant variation in the factors driving growth created a complex patchwork—or mosaic—of trees with varying density, size, and species within each acre (Figure 1) (Safford and Stevens 2017). Widely spaced pine trees were the norm on dry southern-facing slopes, which were prone to frequent burning (every 5 to 30 years). Frequent surface fires in these stands prevented the accumulation of understory vegetation that facilitates tree-killing "crown fires" that spread across treetops (Lydersen and North 2012). Fire also regularly reduced understory fuels and reduced competition among large trees for water and other resources, thereby improving their ability to maintain health during drought and insect outbreaks (Safford and Stevens 2017). On north-facing slopes and in riparian areas where soil moisture was higher, patches of dense fir and pine forest provided cover to animals who prefer higher canopy cover, snags, and downed logs. These forest landscapes had fine-scale differences in density, size, and tree species—a structure that limited catastrophic tree death from fire, drought, and insect infestations while providing a diversity of habitats (North et al. 2009).

FIGURE 1
Mosaic forest structure is highly variable with large trees, openings, and stands of various densities

SOURCE: Illustration by Robert Van Pelt. SNEP 1996.

Headwater forests experienced significant change over the past 150 years. The longstanding practice of intentional forest burning by California's indigenous tribes to enhance cultural and ecosystem values was significantly curtailed by 1860 (Dettinger et al. 2018). By the early 20th century, local, state, and federal governments made suppression of all fires a primary goal. Industrial forest management techniques during this period resulted in the mass removal of large-diameter trees and the introduction of even-age forests. Cumulatively, these decisions have made forests denser and more homogenous over time (Safford and Stevens 2017). As a result, wildfires today burn more intensely and cause many more tree deaths compared to the historical norm. Moreover, increased competition for water and other resources makes forests that have not yet burned vulnerable to widespread tree death from drought and bark beetle attacks (Kolb et al. 2016; Fettig et al. 2007; Grant et al. 2013). Widespread tree death may increase the risk of wildfires in the future (Stephens et al. 2018). There is also a growing concern that patches of forest burned by recent large, high-severity wildfires may not recover as mixed-conifer forest, coming back instead as shrublands (Collins and Roller 2013).
Climate change could generate extensive changes in forests and the benefits they provide (Franklin et al. 2018; North 2012a). California is already experiencing hotter temperatures, a shrinking snowpack, shorter and more intense wet seasons, and more-variable precipitation—with wetter wet years and drier dry years (Mount et al. 2018). These changes are already increasing stress on the headwater forests (Dettinger et al. 2018). In the long term, climate change is expected to affect tree growth rates and the distribution of tree species on the landscape. Researchers predict that wildfire activity in the headwater region will increase in frequency, severity, and area burned, likely increasing the number of trees killed by wildfires over time (Safford and Stevens 2017). More-variable precipitation and prolonged drought may also accelerate tree mortality in dense forests (Goulden and Bales 2019).

Scientists have identified many of the potential effects on forests from climate change. However, accurately predicting the long-term response in forests remains difficult, because forest ecosystems are influenced by complex, often interrelated factors. Uncertainty about factors driving forest growth and disturbances make it difficult to accurately predict future conditions at a scale that is meaningful for management. These uncertainties also make it difficult to assert that the management objectives outlined in this report—and the benefits they produce—will remain effective in the future climate.

Yet this uncertainty is not grounds for inaction. Although future patterns of disturbances are unlikely to resemble those of the past, historical ecology provides a useful example of how headwater forests persisted despite frequent wildfire, drought, and insect outbreaks. Reestablishing the complex patchwork of forest densities, openings, and large trees that typified historic forests will increase the capacity of contemporary forests to absorb and recover from disturbances in the future (Stephens et al. 2008; North et al. 2009; Restaino et al. 2019). Forest managers can take action to improve forest health in anticipation of future conditions by acting on best available knowledge for reducing opportunities for high-severity wildfire and die-off. This will also support the stream of benefits headwater forests provide. Here we focus on the benefits from shifting the management of publicly owned and small privately owned forests to regain a mosaic forest structure, while recognizing that larger privately owned, industrial forests are also an important part of the forest ecosystem in some areas (Box 1).

Box 1. Industrial Timber Production and the Mosaic Forest

While this report focuses on non-industrial private lands and publicly owned lands, the question of how industrial timber production fits into the concept of a mosaic forest is an important one. Privately owned headwater forests managed for industrial timber production (plots larger than 5,000 acres) represent about 10 percent of the 15-million-acre headwater region. These forests typically do not have the excess density issues seen on other lands.

Silvicultural practices on industrial timberlands vary. Key factors include how long timber rotations last (and therefore the age of trees harvested), the size of clearings made by harvesting trees (clear cutting versus more selective tree selection), how many trees are planted after harvest and how many species are used, and how these trees are managed through maturity (how many times trees are thinned before final harvest). Each management decision determines the degree to which these forests emulate the characteristics of mosaic forests.

Whether industrial forests provide the portfolio of benefits associated with mosaic forests is a matter of fierce debate. California forest-practice rules allow clear-cuts of up to 30 acres on flat lands (20 acres on hills) and require that an adjacent area of the same size is left uncut. Forest openings of this size were likely rare in Pre-European forests, as were plots of this size with similar- aged trees. But there are also places where industrial planting and harvesting methods increase variability in tree age and generate many of the attributes of mosaic forests. In most cases, however, large, old trees—key to a number of the benefits found in mosaic forests—are unlikely to be found on industrial timberland.

Establishing and maintaining resilient mosaic forests can be done with existing forest management techniques, particularly mechanical thinning and the strategic use of fire:

- **Mechanical thinning:** The use of mechanized equipment to cut and transport vegetation. This technique can be used in headwater forests to create the structural characteristics of mosaic forests, especially when combined with strategic use of fire (McGarigal et al. 2018). Thinning can take many forms, from simply removing understory plants and burning or chipping this material in the forest to harvesting some marketable timber.[1]
- **Strategic use of fire:** The use of prescribed fire and managed wildfire to establish and maintain resilient mosaic forests. Prescribed fire is the intentional use of fire to clear small trees, brush, shrubs, and management residue from the landscape. This technique is typically used when the risk of fire escaping is low. Ideally, prescribed fire can remove understory growth and smaller trees. Managed wildfire—

[1] There are clear tradeoffs between the amount of vegetation removed from the forest and the cost of the operation, with the amount of merchantable timber removed playing a key role in the calculus. How much, if any, timber should be removed in a thinning operation depends on local conditions and project goals.

allowing wildfire to spread in non-populated areas when weather and fuel conditions are favorable, and only suppressing it under defined conditions—can also be useful for managing forests. By allowing lower-severity fires to burn, strategic use of fire can decrease the risk of large, severe wildfires and increase forest resilience to wildfire, drought, and pests (Boisramé et al. 2017).

The forest management objectives described in this report focus on reducing the risk of large high-severity wildfires. Wildfire behavior (spread rate, intensity, and severity) is influenced by several factors, some of which are beyond human control. Many of the recent high-severity wildfires—including the Thomas and Woolsey Fires (2017 and 2018, both in Ventura County)—were outside the headwater region, in areas where major wildfires are primarily driven by extreme winds in fall. Large-scale vegetation management in such areas is not likely to influence fire behavior (Box 2) (Keeley and Syphard 2019; Jin et al. 2015).

Box 2. Fuel-driven vs. Wind-driven Wildfires

California's recent large, devastating wildfires fall into two broad categories: 1) fires driven by the over-accumulation of fuels; and 2) fires driven by extreme offshore winds (Keeley and Syphard 2019). Understanding the differences between these categories is essential for targeting strategies to reduce risk and protect communities and resources.

Fuel-driven is the dominant form of wildfire in interior conifer forests—especially the headwater region. With some exceptions, these fires occur during the dry summer months and are ignited by natural sources such as lightning. When these fires ignite, the thick understory and dense canopies of fire-suppressed forests can cause them to rapidly grow in size and severity. Examples in the headwater region include the Rush (Lassen, 2012), Rim (Tuolumne, 2013), and Rough (Fresno, 2015) fires.

Wind-driven wildfires are primarily caused by extreme offshore winds that occur in fall in many parts of the state. They include some of the largest and most destructive wildfires in state history. Ignition sources tend to be human caused. Ignitions coinciding with dry, high-velocity winds can generate intense wildfires that spread rapidly. The destructive nature of these fires is in part due to the fact that they tend to occur in close proximity to communities in the wildland-urban interface.

One important difference between these two types of wildfires is the role of vegetation management in influencing fire behavior. Large-scale vegetation management is a promising strategy where fuel-dominated fires are the principal concern. In contrast, this strategy is not likely to be effective at reducing threats from wind-dominated wildfires. Instead, fire prevention and local fuel reduction near populated areas are important strategies for wind-driven wildfires.

Wildfire behavior is complex, and some wildfires do not fit neatly into either category. For example, recent large, destructive wildfires—including the Tubbs (Sonoma, 2017) and Camp (Butte, 2018) fires—were driven by a complex set of factors including the composition of fuels *and* extreme wind.

In contrast, most large wildfires in the headwater region are driven by the over-accumulation of fuels. In headwater forests, reducing the abundance of fuels while increasing variability in forest structure will, under most circumstances, limit the spread of wildfire (Collins et al. 2009). One major constraint, however, is that the pace and scale of forest management must be greatly increased to influence regional wildfire behavior (North et al. 2012; Schoennagel et al. 2017; Butsic et al. 2017). While mechanical thinning and strategic use of fire do not need to be applied to every acre of forest to generate desired outcomes, implementation should be coordinated across large landscapes. For example, an estimated 20–30 percent of the landscape must be strategically treated and maintained to limit the growth of large wildfires (Finney et al. 2007, Tubbesing et al. 2019). This will require a long-term commitment of resources to large-scale management efforts across a complex array of ownerships. Momentum is building at local, state, and federal levels to increase forest management efforts, but much more work is needed to overcome financial, policy, and governance obstacles.

Benefits of Managing for Mosaic Forests

Managing for resilient mosaic forests will require mechanical thinning and strategic use of fire to establish lower-density, highly variable forest landscapes—and to maintain these conditions over time (North et al. 2009). Key outcomes of this approach include limiting opportunities for large, high-severity wildfire and increasing the forests' ability to survive in an environment with frequent disturbances. Forest management that sustains these key outcomes will reduce costs imposed on society from large, high-severity wildfire and support a steady stream of benefits to society, the economy, and the environment, including:

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.

The following sections describe these benefits. This not an exhaustive list: we chose to highlight benefits that are more easily quantified and potentially valued in monetary terms, as these may be most likely to motivate long-term stewardship efforts.[2] For example, this report does not fully evaluate the effects of managing for mosaic forests on biodiversity (Box 3). For each benefit, we describe potential beneficiaries. In addition, we review factors that influence the magnitude and extent of benefits.

Support the Well-being of Rural Communities

Benefits and beneficiaries

Rural communities in the headwater region face a host of challenges. Many have experienced long-term economic hardship from contractions in the timber industry, mill operations, and other manufacturing and construction activities. Many communities are economically distressed, characterized by stagnant or declining population, high

[2] Headwater forest ecosystems generate a broad array of benefits to people (also known as ecosystem services). Material contributions include energy, food, animal feed, wood products, and medicinal, biochemical, and genetic resources. Non-material contributions include learning and inspiration, physical and psychological experiences, and supporting identities. These ecosystems can also provide habitat and regulate air quality, climate, and freshwater flows. Ecosystems produce bundles of contribution to people (Raudsepp-Hearne et al. 2010). Ecosystem type and health (or condition) as well as management regime determine the bundle produced, including the exact type, quality, and quantity of contributions an ecosystem provides (Palomo et al. 2016).

unemployment, and declining household incomes (Sierra Nevada Conservancy 2011).[3] In addition to economic challenges, communities adjacent to or surrounded by overly dense public and private forests are under particular threat from wildfires.

Managing for mosaic forests provides an opportunity to rebuild local economies around forest management, mill operations, restoration, and other related businesses. First and foremost, it will increase opportunities for forest management contractors specializing in vegetation removal. Increasing the stream of marketable wood products and woody biomass can also provide revenue-generating opportunities for local businesses, including mills and biomass energy producers (Forest Climate Action Team 2018). Stimulating the forest management supply chain can also support additional opportunities for workforce training, employment, and earnings across a wide range of expertise, including brush clearing, prescribed fire operations, and ecological monitoring and analysis (Forest Climate Action Team 2018). As discussed below, the opportunity to rebuild local economies around forest management should be accompanied by investments in workforce development and wood processing infrastructure.

Resilient forests can also support outdoor recreation and tourism. Half of the 16 counties in the headwater region have economies that depend heavily on recreation and tourism (US Department of Agriculture 2017).[4] Severe wildfires and large-scale tree death disrupt tourism and outdoor recreation (Dettinger et al. 2018). Limiting opportunities for severe wildfires can also reduce wildfire smoke impacts and threats to infrastructure and scenic landscapes.

Wildfires pose significant threats to homes, business, and critical community infrastructure such as water and energy utility systems, transportation networks, and medical facilities. Large-scale forest management can reduce the speed and intensity of fires that move from forests into communities (Franklin et al. 2018). This approach can support local fire management activities.

The Sierra Institute for Community and Environment has helped facilitate several forest management efforts with the goal of increasing community economic development opportunities. The institute is working with the South Lassen Watersheds Group on enhancing local job creation as part of forthcoming forest management work in the North Fork Feather River and Deer Creek watersheds (Sierra Institute 2019). Further south, the Lake Tahoe West Restoration Partnership's 60,000-acre forest management project is supporting tourism-dependent local economies, maintaining recreational opportunities, and reducing wildfire threats to communities (Lake Tahoe West Restoration Strategy 2019).

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[3] Many headwater communities were hit hard by the Great Recession of 2007–09. Since the end of the recession, population and unemployment have largely stabilized in these communities (personal communication Jonathan Kusel November 15, 2019). See Kusel et al. (2015) for a detailed account of the current economic health of rural communities in the region.

[4] Recreational opportunities in the headwater region include hiking, skiing, off-road vehicle travel, snow vehicle travel, mountain biking, horseback riding, fishing, hunting, golfing, and boating (Sierra Nevada Conservancy 2018).

Box 3. Forest Biodiversity and Habitat for Sensitive Species

Managing for a mosaic structure will likely increase forest biodiversity, but the effects of this strategy on specific species is less certain. The mosaic approach involves establishing and maintaining a dynamic network of fine-scale differences in tree densities, species, sizes, and ages. Landscapes managed this way will be more complex and contain a greater variety of forest structures compared to current conditions. Increasing landscape heterogeneity is a fundamental tenant of enhancing forest biodiversity (Lindenmayer and Franklin 2002). Diversity in forest structure supports more diverse plant and animal communities that depend on one or more forest structures for survival (Franklin et al. 2018).

The specific effects of forest management on habitat for sensitive species such as the California spotted owl, Pacific fisher, and northern goshawk remain long-standing concerns. Studies suggest that these species prefer resting in dense forests with high canopy cover, large trees, snags, and downed logs. Retaining these forest conditions has been the guiding approach to conserving sensitive species. However, dense forest conditions are increasingly prone to severe wildfires, which can have devastating effects on many species. For example, the 2014 King Fire resulted in major losses to local California spotted owl populations (Jones et al. 2016). Research predicts that increases in this type of wildfire over time may eventually lead to the elimination of habitat for some sensitive species, such as the California spotted owl (Stephens et al. 2016).

Managing for mosaic forests has been previously proposed as a strategy for achieving forest resilience objectives while reducing wildfire threats to habitat for sensitive species (North et al. 2012; Stephens et al. 2016; Jones et al. 2016). This entails promoting dense, high-canopy cover forest in areas with sufficient soil moisture to sustain growth and keep fire risk low. By contrast, forests on dry, fire-prone slopes would be managed to be more open—reducing the risk of destructive wildfires. How this mosaic approach affects the habitat needs of sensitive species is a matter of debate. At the root of the debate is uncertainty about how successfully sensitive species will adapt to mosaic conditions that are overall less dense than current forests. This uncertainty is driven by the lack of data on historical populations, habitat extent and distribution, and behavior of these sensitive species in historic mosaic forests (Stephens et al. 2016). Data gaps limit opportunities to test hypotheses on the adaptability and success of sensitive species in a managed mosaic forest.

Despite these uncertainties, it is clear that current forest conditions pose a direct wildfire threat to sensitive species. Forest and wildfire managers must weigh the value of actions that prevent future losses to sensitive species from wildfire (in addition to several other benefits) against uncertainties about how well they will adapt to resilient forest conditions.

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 (prescribed burn crews, restoration practitioners) and infrastructure (wood-processing facilities) needed to support a sustained increase in forest management (Kusel et al. 2017). A suite of targeted economic development strategies can enable an increase in management activity while driving opportunities for local economic development. This includes new investments in wood-processing infrastructure, streamlined permitting for new infrastructure projects, and workforce training across the forest management supply chain (SB 859 Wood Products Working Group 2017).

Forest management alone is insufficient to reduce community vulnerability to wildfires—other local and regional actions are essential. Improving community resistance to wildfires also requires home hardening, defensible space, and advance wildfire emergency planning (Pottinger 2019). Property owners must make changes to lower the risk of wildfire damage to their structures. This includes home-hardening measures such as replacing roofs with fire-resistant materials and installing air vents that prevent embers from entering homes. It also includes removing vegetation around homes and critical infrastructure. Reducing ignition sources—such as from electrical transmission lines—is another priority. In addition, communities must have evacuation plans and emergency communication systems in place before wildfires occur. New state laws enacted in 2019 will support local efforts to build community resilience in this regard (McCann 2019).

Reduce Wildfire Smoke Impacts on Public Health

Benefits and beneficiaries

Wildfire smoke is a public health hazard. Black carbon—a fine-particle pollutant that is a component of wildfire smoke—causes adverse respiratory and cardiovascular effects (Navarro et al. 2016). Short-term exposure to black carbon in wildfire smoke (lasting from days to weeks) can result in negative health consequences in healthy and vulnerable populations alike (US EPA 2016). In recent years, high-severity wildfires in headwater forests (e.g., Rim, King, and Rough Fires) have generated large plumes of smoke capable of traveling long distances and covering large areas, exposing rural and urban populations to smoke pollution for weeks at a time (Schweizer and Cisneros 2017; Forest Climate Action Team 2018).

Aggressive suppression of wildfires in the headwater region over the past century has caused a buildup of flammable materials, which has amplified the intensity and number of people exposed to harmful smoke incidents when the region's forests do burn (Stephens et al. 2016, Schweizer et al. 2019). Smoke from large, high-severity wildfires contains higher volumes of fine particulate pollutants and disperses more widely compared to less-severe wildfires, greatly increasing the public health impacts (Long et al. 2017; Schweizer et al. 2019). For example, the Rim Fire (2013) plume reached high altitudes and travelled into Nevada and western Idaho (National Aeronautical and Space Administration 2013). At the ground level, smoke from this fire exposed 1.2 million people across ten counties in California and western Nevada to several days of fine-particulate matter above federal standards (Navarro et al. 2016). Residents of Tuolumne and Mariposa counties—the closest to the wildfire perimeter—experienced several weeks of fine-particulate exposure that exceeded federal standards by 6- to 31-fold (Navarro et al. 2016). Research predicts that air quality problems from unmanaged wildfire smoke will grow as the size, frequency, and severity of wildfire increases with climate change (Hurteau et al. 2014).

Expanding the use of mechanical thinning and strategic use of fire is essential for proactively avoiding long-term wildfire smoke impacts on public health from large, high-severity wildfires. While strategic use of fire generates smoke, it poses a much lower threat to public health because its smoke remains closer to the burned area and has lower levels of pollutants (Schweizer et al. 2019; Long et al. 2017; Schweizer and Cisneros 2014). In a comparison of low- and high-severity wildfires in the headwater region between 2010 and 2016, researchers estimated that smoke exposure from an acre burned at lower severity is just one-tenth the level of an acre burned at higher severity (Schweizer et al. 2019). Unlike large, high-severity wildfires, forest managers can determine the desired location and timing of lower-severity wildfires to strike a balance between benefits to forests and smoke impacts on public health. Advance planning and communication with communities and public health officials can minimize smoke impacts to human populations and lower risks to public health. Likewise, forest management using mechanical thinning does not release smoke—unless is it is accompanied by subsequent prescribed burning of debris residue.

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 strategic use of fire in the headwater region—where flammable vegetation has built up over time—will result in an increase in the amount of smoke generated from management. Current policies limit the strategic use of fire because they prioritize the avoidance of immediate smoke exposure over reducing the risk of high-severity wildfires (Stephens et al. 2016; Butsic et al. 2017). The strategic use of fire will be constrained until these policies are changed.

Smoke from management activities will become more common over the long term. Once the mosaic landscape is established, forest managers will need to maintain forest conditions over the long term, including by using prescribed burning and managed wildfire. Frequent application of these techniques will generate smoke patterns similar to the Pre-European period when forests regularly experienced smoke in the summer and late fall from intentionally and naturally ignited wildfires (Stephens et al. 2007). Smoke emissions from these low- and mixed-severity fires would have been frequent but localized (Schweizer and Cisneros 2017).[5] Chronic exposure to low-concentration smoke may be acceptable to some residents in the headwater region as a cost of improving forest health. Smoke generated from strategic use of fire is reduced over time when areas are repeatedly burned (Levine et al. 2020). From a public health perspective, more research is needed to determine the long-term effects of smoke from forest management burns on sensitive populations.

Mechanical thinning does not generate smoke impacts. The use of mechanical thinning alone can avoid smoke impacts to public health. This is especially true when the thinned debris is turned into long-lasting wood products. Using mechanical thinning before prescribed or managed wildfire can reduce the amount of smoke generated by fire-based management techniques (Franklin et al. 2018). If debris from mechanical thinning has no uses outside of forests, it is usually gathered into piles and burned when risk of fire escaping the area is low and weather conditions limit human smoke exposure. Mechanical thinning is often more expensive than strategic use of fire, especially when treatment costs cannot be offset by revenues from sales of woody materials (Butsic et al. 2017). And it is impractical on steep or remote terrain.

Store Carbon Securely and Reduce Carbon Emissions

Benefits and beneficiaries

Forests store and release carbon dioxide and other greenhouse gases (GHGs) that contribute to climate change. Trees sequester atmospheric carbon dioxide as they grow—storing this as organic carbon in wood, leaves, and soil. Nearly two billion metric tons of carbon are stored in California's forested ecosystems (CARB 2019). The forests of the headwater region store nearly half of this carbon (Dettinger et al. 2018). When trees die, they release stored carbon at varying rates into the atmosphere. There are three main pathways for release: 1) dead leaves and wood slowly decay in the forest; 2) tree tissue is consumed by wildfire; or 3) the tree is harvested and much of its carbon is converted into long-lasting wood products (Fahey et al. 2009).

Forests act as a net sink for atmospheric carbon when the amount of carbon sequestered in trees over time exceeds the volume released into the atmosphere through decay, fire, and respiration. Two prominent methods used to account for changes in forest carbon have come to different conclusions on whether California's forests are sources or sinks of atmospheric carbon (Holland et al. 2019). Nevertheless, forest carbon researchers agree that

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[5] Aggressive fire suppression over the past century has been largely successful at delaying the release of smoke from wildfires. It has also contributed to the public's expectation of lower levels of smoke than occurred historically (Stephens et al. 2007).

increased wildfire activity, reduced growth rates of trees, and increased tree mortality have reduced the amount of carbon sequestered in headwater forests over the past decade (Gonzalez et al. 2015; Christensen et al. 2018; Forest Climate Action Team 2018).

The consensus view of a group of experts surveyed by Lalonde et al. (2018) is that climate change is expected to accelerate the reduction in the carbon storage capacity of headwater forests. Warming temperatures will result in increased evaporative demand, more high-severity fires, conversion of forested lands to shrublands, and increased tree deaths.[6] Consistent with this view, model projections assuming a business-as-usual scenario indicate that by mid-century, forests in the headwater region will lose more than 25 percent of the carbon they stored as a result of increased wildfire, drought, and insect outbreaks (Dettinger et al. 2018).[7] Such predictions are an important consideration in California's work to improve forest health (California Forest Management Task Force 2019). The goal is to reduce GHG emissions from wildfires and maintain the carbon storage capacity of forests by reducing risks of catastrophic tree death (Forest Climate Action Team 2018).

Estimates suggest that carbon emissions from wildfires have increased statewide over the past two decades (CARB 2019). Climate change could accelerate this trend, making forest management an important strategy in the effort to securely store carbon in trees. For example, management that reduces understory fuels that contribute to large, high-severity wildfires can result in a two-fold increase in tree survival following a wildfire (North and Hurteau 2011).[8] The improved survival of large trees cuts carbon emissions in half compared to untreated forests (North and Hurteau 2011).

Managed mosaic forests also maintain their carbon storage capacity over the long term. Forest carbon researchers suggest that reducing threats to large trees from wildfire and drought is critical because large trees store more carbon each year than smaller trees (Hurteau et al. 2019). Managing for low-density forests dominated by large, fire-resistant trees protects forest carbon stocks over longer periods compared to unmanaged forests (Hurteau and North 2009). Other research suggests that fuel treatments optimized to reduce large, high-severity wildfire can reduce long-term losses of forest carbon in headwater forests compared to no management (Krofcheck et al. 2017). In addition, frequently removing understory vegetation with mechanical thinning and strategic use of fire reduces water stress for large trees during drought. This can reduce vulnerability to insect outbreaks, which tend to target larger trees (Young et al. 2017; Stephenson et al. 2019).

Storing carbon and reducing GHG emissions are two core objectives of the CAL FIRE Forest Health Grant Program. SB 901 (2018) signaled the legislature's intent to provide five years of funding for this cost-share program, which is primarily funded with cap-and-trade revenues through the state's Climate Change Investments fund. Since 2018, the grant program has provided funding to more than a dozen forest health projects across the state each year on both private and federal forestlands. Forest thinning projects must demonstrate net GHG reductions to be eligible for program funding (CAL FIRE 2019). This requirement has promoted large-scale efforts to change forest structure in ways that concentrate carbon in large, fire-resistant trees and reduce the likelihood of large, severe wildfires. In 2018, about one-third of Forest Health program funding was awarded to the Tahoe–Central Sierra Initiative. This effort will improve carbon storage and reduce emissions on more than 20,000 acres of headwater forest (Legislative Analyst's Office 2018).

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[6] Forest carbon experts also suggest that increased precipitation, enhanced carbon-dioxide fertilization, and management interventions could counterbalance some of the expected reductions in carbon storage capacity caused by climate change (Lalonde et al. 2018).

[7] This projected loss in forest carbon stocks does not account for the potential sequestration of dead trees in long-lasting wood products.

[8] In this study, on average 97 percent of the trees in the untreated stands died from wildfire, versus 53 percent of the trees in the treated stands (North and Hurteau 2011).

Considerations

Accounting for forest carbon is difficult. California has a pressing need to measure its forest carbon accurately (California Forest Action Team 2018). Yet, doing this at a scale that can inform GHG reduction strategies is challenging (Woodall et al. 2015). Recent revisions in the Forest Inventory and Analysis (FIA) program have greatly improved the inventory of forest carbon (Bechtold and Patterson 2005). However, carbon estimates that rely exclusively on FIA data will be limited by the low frequency of FIA measurements and broad scale at which they are reported (Christensen et al. 2017). Combining satellite-based data with plot-level information provides a means to improve the resolution of forest biomass maps (Gonzalez et al. 2015; Kennedy et al. 2018). However, key questions remain about their accuracy and feasibility (Holland et al. 2019).

In addition, there is a need to improve understanding of the longevity of emission reductions from forest management. Research shows that mosaic forests can reduce emissions from wildfire and increase the longevity of forest carbon stocks. But exactly how long forests will remain carbon sinks is difficult to predict—it largely depends on the ability of forests to recover from wildfire (Hurteau et al. 2016; Liang et al. 2017). The ability of forests to recover from wildfire is influenced by multiple—and sometimes confounding—factors. Although scientific understanding is improving, uncertainties are high. Predicting long-term carbon storage and releases requires scientists to develop plausible scenarios that specify hard-to-predict future details.

The choice of management techniques will affect the overall carbon balance. Managing headwater forests to increase the long-term durability of carbon stored in large trees will require the removal of small trees, understory vegetation, and woody fuels that have accumulated over the past century (North and Hurteau 2011; Battles et al. 2018). Typical forest management treatments result in removing between one-quarter and one-third of live forest carbon (Hurteau et al. 2011). These reductions in forest carbon can be minimized by using mechanical thinning to convert thinned trees to lumber or other long-lasting wood products (Hurteau et al. 2011). Woody materials removed from forests can also be used to generate biomass energy, which in some circumstances can replace more carbon-intensive forms of energy production (California Forest Action Team 2018).

Protect Water Quality from Post-wildfire Erosion

Benefits and beneficiaries

High-severity wildfires can rapidly degrade water quality in streams, rivers, and lakes—creating challenges for water and hydropower infrastructure operators and aquatic ecosystems. Lands where high-severity fire has significantly removed ground cover, or heated soils to the point of becoming water-repellant, are less able to infiltrate water into the ground (DeBano 1981). After a wildfire, the speed and volume of storm runoff from severely burned lands increases—moving soil and ash into rivers, streams, and lakes. This runoff can also erode the banks of waterways and trigger destructive landslides and debris flows (Neary et al. 2008). The flow of sediment and debris into streams and rivers can increase the concentration of nutrients, turbidity, and other pollutants in water courses and reservoirs (US Geological Survey 2018).[9] The 2014 King Fire (Placer and El Dorado counties) illustrates the costly impacts from major post-fire erosion in waterways (Box 4).

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[9] Changes to water chemistry are a commonly cited result of increasing ash and sediment in watercourses following high-severity wildfire. This increases nitrogen, phosphorous, and dissolved organic carbon (Hacker 2015). Researchers have also observed increases in trace metals in watercourses following a wildfire (including manganese, iron, lead, mercury, zinc, copper, aluminum, and barium) (Smith et al. 2011). Post-fire erosion can transport toxic heavy metals from abandoned mines into watercourses and reservoirs (The Sierra Fund 2008; Dettinger et al 2018).

The threat of wildfire damage to critical water supply and hydroelectric power infrastructure has motivated several forest management projects in the headwater region. A key priority for these efforts is reducing opportunities for post-fire erosion and debris flows to harm multi-purpose reservoirs, off-channel hydroelectric-power-generating infrastructure, and aquatic ecosystems.[10] For example, the North Yuba Forest Resilience Project includes management of 15,000 acres of forestland in the North Yuba River watershed; the goal is to reduce the risk of severe wildfire and protect water resources. The Yuba Water Agency contributed $1.5 million to the $4.6 million effort (World Resources Institute 2018). In fall 2019, project partners announced that this project would be expanded to cover nearly 300,000 acres of the watershed (The Union 2019). Similar efforts to protect source water quality are being undertaken by utilities that depend on the headwater region for water supply and hydroelectric power generation. This includes efforts such as the Caples Ecological Restoration Project (El Dorado Irrigation District) and work in the upper Mokelumne River watershed by the Upper Mokelumne River Watershed Authority—a joint power authority that includes six water agencies (including the East Bay Municipal Utility District).

Many reservoirs in the headwater region receive inflows from steeply sloped tributaries lined with fire-prone forests (Figure 2). These reservoirs provide water supplies, flood management, hydropower generation, recreation, and aquatic ecosystem management. Post-fire erosion can impair the operation of dams and reduce the capacity of reservoir storage (Buckley et al. 2014).

Some hydropower infrastructure in the headwater region relies on water diverted from streams and reservoirs and conveyed via canals, flumes, and tunnels to generating stations. Post-fire sediment and debris can impair the functioning of water conveyance and hydropower generating equipment.

Aquatic ecosystems are also harmed by post-fire erosion (Barkley 2013). The movement of large quantities of ash and sediment into water bodies can increase turbidity and the concentration of nitrogen, phosphorous, and dissolved carbon (among other pollutants) that are harmful to aquatic species. Stream water temperature can increase when fire eliminates shade-producing vegetation—degrading habitat for species that depend on cold water for survival. High runoff following a wildfire can physically change the shape of the streambed by redepositing silt and eroding stream channels; these changes can damage habitat and disrupt food webs (Paige and Zygmunt 2013). In contrast, prescribed fires produce very few negative effects to stream ecosystems, and most impacts are short-lived (Bêche et al. 2005).

[10] In addition to reducing post-fire erosion threats, many of these efforts will also reduce the risk of direct damage from wildfire on critical infrastructure.

Box 4. 2014 King Fire and the French Meadows Project

The 2014 King Fire illustrates the costly damages to waterways and infrastructure from post-fire erosion. This high-severity fire began in September 2014 near Pollock Pines, and burned 97,000 acres in the American River watershed. Intense rains the following year led to debris slides that carried downed trees and topsoil into the Rubicon River (Roseville Today 2015). This caused high sedimentation and turbidity in the waterway. The debris also impaired the operation of local hydropower facilities. Placer County Water Agency and other local agencies spent $8 million repairing water and energy infrastructure damaged immediately after the fire; ongoing cleanup costs will cost millions more (Fecko 2015). Ratepayers and local taxpayers are expected to bear these costs (Placer County Water Agency 2019).

Extensive damage and high costs of post-fire erosion following the King Fire motivated a collaborative large-scale forest management effort in the watershed (Edelson et al. 2019). In 2016, Placer County Water Agency, Placer County, and an array of other partners—including the US Forest Service, The Nature Conservancy, American River Conservancy, Sierra Nevada Conservancy, and Sierra Nevada Research Institute—launched the French Meadows project. The project aims to use ecological forest management to limit opportunities for large, high-severity wildfire on 12,000 acres—reducing the risks of damage to critical water and energy infrastructure.

Considerations

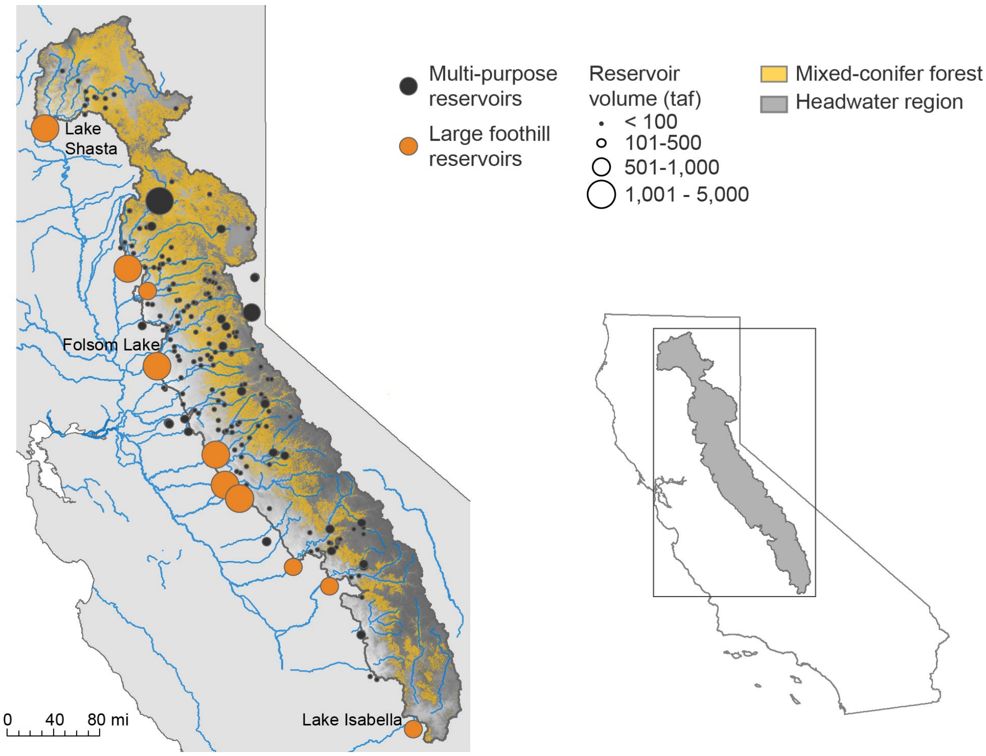
Large foothill reservoirs are somewhat buffered from post-fire erosion impacts. The presence of upstream reservoirs provides lower-elevation reservoirs with some protection. By trapping sediments and debris, smaller upstream reservoirs can reduce post-fire sedimentation of larger downstream reservoirs that are essential to the statewide surface water delivery system (Minear and Kondolf 2007). Over time, however, accumulated sediment reduces water storage capacity of these upstream reservoirs. Most of the major river systems in the headwater region are regulated by multiple reservoirs. Efforts to quantify the benefits of reducing post-fire erosion within watersheds should recognize this upstream sediment-trapping effect.

Every tributary has a different level of post-fire erosion risk. Each tributary in the headwater region has a unique mix of wildfire risk, post-fire erosion risk, and assets that are vulnerable to the effects of increased runoff, sediment, and debris following a wildfire. One principal challenge is estimating the risk to specific assets given the very low probability that a large wildfire will be followed by major storms that result in erosion.[11] Techniques for assessing post-fire erosion risks are improving (Wagenbrenner and Robichaud 2013; Buckley et al. 2014). Even a simplified analysis can be helpful in determining levels of vulnerability, identifying priority areas for forest management, and evaluating the economic rationale for forest management activities (Elliot et al. 2016).

[11] In addition to water supply and hydropower infrastructure and aquatic ecosystems, other critical assets at risk from post-fire erosion include road and railroad networks, utility pipelines, and transmission equipment.

FIGURE 2

Nearly 200 small and mid-sized reservoirs are downstream of fire-prone headwater forests



SOURCE: Developed by the authors using information from the California Department of Water Resources. Cal Fire FRAP CalVeg FVEG (vegetation layer).

NOTES: "Taf" is thousands of acre-feet. Reservoirs are scaled based in reservoir max storage capacity. Rivers are shown in blue.

Increase Water Supply

Benefits and beneficiaries

Much of the state's surface water supplies originate as rain and snow that falls each year on the headwater forests (Bales et al. 2011). The rivers and streams that emanate from headwater forests bring multiple benefits to California. They provide the bulk of the state's surface water supply, generate almost all of the state's hydropower, and support a large and diverse recreation industry. This runoff also sustains aquatic habitat within forests and downstream, where runs of salmon and steelhead depend upon reliable cold water. The infrastructure to manage surface water for these multiple objectives is one of the most elaborate in the West.

Forests play an important role in storing and regulating the release of rain and snow into headwater tributaries. Most of the precipitation that falls on forests returns to the atmosphere through evapotranspiration—when trees, shrubs, and grasses absorb water for growth and then release water vapor through their leaves (Tague et al. 2019). Some precipitation is intercepted by canopies and does not reach the ground. Rain and snowmelt that is not consumed by vegetation will usually move through the soil and into shallow groundwater before entering streams, delaying runoff and maintaining stream water quality. Forests also regulate the accumulation of snow and the rate of snowmelt by intercepting snow, shading it, and affecting wind patterns. All of these processes influence a forest's water balance, including the volume, timing, and quality of runoff into rivers and streams.

For decades, scientific studies have sought to improve understanding about the effects of forest management on streamflow and snowpack accumulation in the headwater region (Bales et al. 2011). Yet several factors have limited the practical application of these studies. The variability of California's climate—with large year-to-year swings in precipitation—along with the diversity of its landscapes makes it difficult to draw definitive conclusions from individual studies. Though recent advances in measurement techniques have improved scientific understanding, it remains difficult to precisely measure changes in water balance from different forest treatments, and to extrapolate the results to large scales (Saksa et al. 2017; Boisramé et al. 2019). Finally, forests change over time following fire or other treatments as vegetation grows back. There are very few long-term studies that capture the hydrologic changes through time (Tague et al. 2019). Thus, for California, research on the relationship between active forest management and changes in runoff timing and magnitude should be considered a work-in-progress with high levels of uncertainty at larger spatial and temporal scales.

Despite methodological limitations, research suggests that reductions in forest density may increase streamflow in wetter headwater tributaries. Mechanical thinning or strategic use of fire that removes trees and shrubs reduces the overall amount of precipitation intercepted by canopies or consumed by vegetation. The portion of precipitation that is no longer taken up by vegetation can infiltrate into soils that add to local groundwater storage and runoff into rivers and streams. Simplified estimates of this effect in the headwater region suggest that reducing the number of trees in headwater forests by 40 percent could result in an increase in annual water yield of up to 9 percent (Bales et al. 2011). Recent high-resolution estimates have tentatively confirmed the effect of reducing forest density on increasing streamflow in wet and dry years in some catchments in the headwater region (Roche et al. 2018; Boisramé et al. 2019; Saksa et al. 2017; Saksa et al. 2019). Modeled estimates of increased average annual streamflow as a result of forest thinning ranged from negligible to 14 percent. These studies generally confirm that the volumetric increase in water yield from forest thinning is highest during the wet season and wet years when precipitation greatly exceeds the amount demanded by vegetation. While additional water yield from thinning may be lower in dry years, it can be more significant as a share of total streamflow—and therefore potentially more valuable to water users who are facing reduced supplies. Importantly, some of these studies found that thinning had a stronger effect in portions of tributaries where annual tree growth is not limited by lack of water (Roche et al. 2018, Saksa et al. 2017).[12] In drier areas, reducing vegetation may simply allow the remaining trees and shrubs to absorb more water, rather than augmenting streamflow (Stevens et al. 2020).

Research also suggests that thinning forests can increase snowpack accumulation and delay the melting of snowpack—two processes that enhance water quality for aquatic species and the delivery of surface water to downstream users (Bales et al. 2011). But quantifying this effect across larger areas and longer time periods is complex, in part due to the influence of other important factors—including temperature, solar radiation, and the geometry of canopy openings—on snowpack dynamics. In mountainous terrain, these factors can vary significantly within watersheds.

Boisramé et al. (2019) evaluated changes in snowpack accumulation in the Illilouette Creek watershed, a large experimental forested area where a low- and moderate-severity fire regime has been restored over the past 45 years. Fire management there has reduced tree cover by approximately 25 percent and increased diversity in tree size and distribution. Researchers estimate a negligible increase in snow water equivalent across the basin (around 1 percent) due to changes in vegetation structure. The location and volume of snowpack accumulation also varied greatly across years within the watershed. However, snowpack accumulation patterns may have influenced

[12] In general, the central and northern portions of California's headwater region are wetter than the southern portion. There are also elevation gradients in precipitation: higher elevations are wetter than lower elevations. Bales et al. (2011) also noted that extremely wet tributaries, where precipitation exceeded 60 inches per year, were less likely to experience changes in runoff from forest thinning.

localized increases in soil moisture, which can be important for reducing water stress in trees during droughts and increasing forest resilience to wildfire and pests (Boisramé et al. 2018).

Lundquist et al. (2013) aggregated the results of several studies on the relationship of forest density to timing of snowmelt to understand the role of winter temperatures in the forest-snowpack relationship. This study posits that snowmelt during spring and summer happens faster under closed canopies than in more open canopies in the Sierra Nevada region. The research suggests that closed-canopy forests transfer solar energy to the snowpack more effectively than open-canopy forests—hastening melting. This study also notes this region has considerable variation in local site conditions that influence snowmelt timing, leading to a wide range of outcomes in the same watershed.

Efforts are underway to integrate water supply benefits into forest management projects in the headwater region. For example, Blue Forest Conservation's Forest Resilience Bond monetizes the benefits of improving forest health as a way to fund forest health improvement projects (Blue Forest Conservation 2017). Forest management techniques are used to create benefits (e.g., increased streamflow) that are quantified, and paid for by entities that directly benefit (e.g., water suppliers and hydroelectric producers). Revenues from services rendered are then used to repay the bond obligations to investors. Increasing water supply is one of the benefits being tested in the North Yuba Forest Resilience Project, with the Yuba Water Agency being the key beneficiary (World Resources Institute 2018). The package of benefits included in this project also include reducing threats from post-fire erosion and other wildfire damages. Blue Forest Conservation intends to use this inaugural project as a model to be replicated with other beneficiaries of healthy forests (Koren 2018).

Considerations

The benefits of increased water supply decline as vegetation grows back. Due to the short timeframe of most existing studies, research has only been able to confirm temporary gains in annual water yield from forest management. These gains are likely to diminish as vegetation grows back and water demand by trees and shrubs rebounds. The effect of increasing runoff and snowpack retention through forest management must be sustained through ongoing treatment. The cost of new water generated by forest management may be prohibitively high.[13]

There is high uncertainty about water supply benefits at scale. Continued research in this area will lead to more refined estimates of the magnitude and timing of potential increases in water yield across the headwater region. It is particularly important that future research illustrate the limitations of realizing these benefits in water-limited forests. It should also clearly demonstrate how maintaining mosaic forest conditions over time is essential to long-term water supply benefits. Improved understanding of this complex ecological process will help guide discussions about the role of water augmentation as a by-product of improving forest health.

[13] Escriva-Bou (2019) estimated the cost of options to improve water availability in the San Joaquin Valley. New water generated by thinning in Southern Sierra headwater forests cost on average $4,515 per acre-foot (in 2016 dollars, accounting for co-benefits to hydropower production). The cost is considerably higher than other feasible options for augmenting local water supplies.

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