Title
Valuing forest restoration for healthier and more resilient forests

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Publication Date
2023

UNIVERSITY OF CALIFORNIA, MERCED

Valuing forest restoration for healthier and more resilient forests

A dissertation submitted in partial satisfaction of the requirements for the degree
Doctor of Philosophy

in

Environmental Systems in the Graduate Division of the University of California, Merced

by

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2023

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Acknowledgements

First and foremost, I would like to express my sincere gratitude to my advisors, Dr. Roger Bales and Dr. Martha Conklin. Your guidance, support, and mentorship have been invaluable throughout my PhD journey. I am grateful for your patience, encouragement, and willingness to share your knowledge and expertise with me. Your insights and feedback have helped me to grow as a scholar and to produce the best possible dissertation.

I would also like to thank my dissertation committee members, Dr. Benis Egoh and Dr. Jeffrey Jenkins for their time and support, which are essential to my research and writing.

To the Environmental System Graduate Group, thank you for providing me with a supportive and stimulating environment in which to pursue my PhD. I am grateful for the resources, opportunities, and support that I have received from all members of the group.

Finally, I would like to thank my family and friends for their unconditional support, companionship, understanding and encouragement throughout this journey.

Abstract

Wildfires in the Western U.S. have been on the rise in recent years. Forest restoration involving fuels treatments has been recognized as an effective way to mitigate catastrophic wildfire and restore the health and resilience of forests. However, the pace and scale of the restoration activities are far below the demand due to insufficient funding and capacity.

To address this challenge, we developed valuation tools using state-of-the-science data to value multiple benefits of forest restoration across the Sierra Nevada. Two water-related benefits, enhancing hydropower and water supply, are a result of lower forest water use and greater potential runoff following forest thinning. Four additional benefits are associated with reducing the probability and projected severity of wildfire: carbon storage, timber provisioning, erosion regulation, and air-quality regulation.

The results demonstrate the great potential for forest restoration in the Sierra Nevada, with overall monetized benefits up to tens of thousands of dollars per hectare, much higher than the costs, benefiting both private and public sectors. The evaluation and optimization of projects using these monetized benefits can inform the decision making around investments in restoration activities by incorporating a suite of stakeholders in sharing project costs and repaying investors when environmental and social benefits are realized.

Expanding funding sources helps accelerate the pace and scale of forest restoration, thereby achieving the goal of restoring forest sustainability and improving the well-being of local communities.

Chapter 1: Introduction

1.1 Background

Forests provide wide range of ecosystem services that are essential to humans' continued existence and wellbeing, including critical provisioning, regulating and cultural ecosystem services, such as carbon storage, timber provisioning, erosion regulation, air-quality regulation, recreation, provision of habitat, and more (Taye et al., 2021). In California, the Sierra Nevada accounts for approximately 25% of California's total land area, is 62% forested (North et al., 2017), and acts as a crucial part of the state's natural infrastructure. Runoff from the Sierra Nevada provides nearly two-thirds of state's surface-water supply and 15 percent of its electricity from hydropower plants (Butsic et al., 2017), and nearly half of the forest carbon stocks in California are there (wildfiretaskforce.org). In addition, outdoor recreation is a huge endeavor in the Sierra Nevada, providing diverse experiences, psychosocial values, and public health benefits to residents of California and beyond (Halofsky et al., 2021).

Forests across the Sierra Nevada have experienced dramatic change over the past several decades (Dolanc et al., 2014). Logging, natural regeneration and fire suppression have led to an increase in forest density and a decrease in the number of large trees compared to the past, resulting in a high density of small trees and unusually high levels of surface fuels (Butsic et al., 2017). Combined with climate change and short-term stressors such as low precipitation, the Sierra Nevada region is experiencing an unprecedented scale of tree mortality due to drought and accompanying insect infestation (Stephens et al., 2018). The accumulation of dead wood and small trees provides ladder fuels that move fire from the ground to the canopy, which, combined with a warming climate, leads to larger and more-severe wildfires (Collins et al., 2017). Catastrophic wildfires will negatively impact vegetation composition and structure, water quality, nutrient status or nutrient cycling, air quality, and erosion rate (Vukomanovic & Steelman, 2019), and the cost of extinguishing them, property losses, natural-resource destruction and frequent loss of life are often unprecedented (Williams, 2013).

To address these challenges, we need more-sustainably managed forests. The sustainability of forested landscapes can be defined as having three pillars: i) ecological resilience, defined as the degree to which the forest can absorb disturbances while still retaining ecological function, biodiversity, and other important attributes, ii) ecosystem services or benefits to humans, and iii) environmental justice, how the health of these forests impacts rural communities and future generations (Bales et al., 2023). Forest restoration involving fuels treatments has been recognized as an effective way to mitigate catastrophic wildfire and restore sustainability of forests (Prichard et al., 2021, Stoddard et al., 2021, Stephens et al., 2021; Knapp et al., 2017). Forest restoration can reduce surface fuels, increase height from ground to live crown, and decrease tree density. Reducing surface fuels can also reduce flame length, making it less likely that fire will move from ground to crown. In addition, decreasing tree density makes tree-to-tree fire less probable (Agee and Skinner, 2005). These activities can also reduce competition for water among trees, making the forest more resilient to wildfire and droughts.

However, the pace and scale of forest restoration falls far short of what is needed. As the US Forest Service estimated, it needs to be increased from approximately 0.1 million ha per year to 0.2 million ha per year; and 2.5-3.5 million ha out of the 8 million ha the US Forest Service manages in California need restoring immediately (California Forest Management Task Force, 2021). Substantial declines in timber revenues, limited Congressional appropriations, and a greater emphasis on fire suppression compared to the attention and resources devoted to preventive management, have limited the funds available for forest restoration (Quesnel Seipp et al., 2023).

1.2 Significance of the research

Therefore, the funding sources for forest restoration need to be expanded and a paradigm shift in funding approaches is required. Compared to the abundant research on the biophysical impacts of forest restoration on ecosystems, such as changes of wildfire behaviors and water balance (Chiono et al., 2017, Urza et al., 2023, Saksa et al., 2020, Roche et al. 2020, Bart et al. 2021), the economic value and beneficiaries of restoration have been under studied. Although some studies assigned monetized values to ecosystem services, including carbon storage, hydropower, water supply, timber, and habitat provision (Piaggio and Siikamäki, 2021, Fu et al., 2014, Strand et al., 2018, La Notte et al., 2012), there is a lack of a method to assess the value of forest restoration showing the marginal benefits at certain spatial and temporal resolutions, which is a barrier when promoting partnerships and large-scale implementation of forest restoration.

Benefits from any single category are not sufficient to offset treatment costs (Hunter & Taylor, 2022), and strong support from a range of private and public entities, as well as new policies are needed to facilitate complex, collaborative management (Mccann et al., 2020). A promising solution to bridging these gaps are multi-benefit partnerships aimed at restoring public and private lands, while providing an array of benefits to rural communities and the public as well as to holders of water and other property rights (Edelson & Hertslet, 2019, Eriksson et al., 2022). Failing to incorporate benefits into a multi-benefit framework is an obstacle to identifying the main beneficiaries, forming an effective organizational mechanism, and promoting the implementation of restoration projects in a cooperative manner. This multi-benefit analysis is complicated given that several factors must be considered and integrated, such as wildfire prediction, treatment effectiveness, ecosystem services and their values, which few studies have examined comprehensively.

To bridge the research gaps, this study focused on valuing the economic benefits arising from forest restoration on enhancing multiple ecosystem services. We develop valuation tools using state-of-the-science data for the valuation aiming at six ecosystem services across the Sierra Nevada, of which two water-related benefits, enhancing hydropower and water supply, are expected to benefit from lower forest water use and greater potential runoff following forest thinning, and four additional benefits are associated with reducing the probability and projected severity of wildfire: carbon storage, timber provisioning, erosion regulation, and air-quality regulation.

We examined the following questions. First, how significant are the respective and total benefits of each of the six ecosystem services, compared to the costs of forest restoration; second, how do these potential benefits vary across the landscape, and what conditions and characteristics dominate the benefits; and third, how could the resulting benefits be utilized to inform the decision of restoration activities by incorporating a suite of stakeholders to expand the funding sources?

This chapter provides the background and motivation for the study and serves as an introduction to the entire dissertation work. While each chapter can be read independently, they are interdependent, with Chapter 2 valuing the water-related benefits, Chapter 3 valuing the fire-regulation-related benefits, and Chapter 4 extending and applying the results of the previous two chapters. Finally, Chapter 5 provides the overall conclusions of the study.

Chapter 2: Valuing the benefits of forest restoration on enhancing hydropower and water supply in California's Sierra Nevada

2.1 Introduction

Forests across the Western United States are becoming increasingly stressed, and lack the resilience needed to thrive in a warming climate and changing land use (Hessburg et al., 2019). Many have excessive vegetation density and are overstocked with small trees and brush, the result of historical fire suppression and unsustainable timber harvesting (Collins et al., 2017). Competition for water is exacerbated by overstocked forests, and combined with drought due to climate change has led to massive tree mortality (Anderegg et al., 2015; Goulden and Bales, 2019). Historically, forests of the Sierra Nevada had higher and later water yields in summer than today because less-crowded forests consume less water and allow deeper snowpacks (Bales et al., 2011, Zheng et al., 2019).

In the face of deteriorating conditions, there is a greater urgency to restore the health and resilience of forests (Kelsey, 2019). Although dead trees provide important habitat and forest structure, the Sierra Nevada region is experiencing an unprecedented scale of tree mortality due to drought and accompanying insect infestation (Scott L. Stephens et al., 2018). The accumulation of dead wood and small trees provides ladder fuels that move fire from the ground to the canopy, which, combined with a warming climate, leads to larger and more-severe wildfires (Collins et al., 2017). Wildfire severity and extent in California have increased greatly in recent years (Williams et al., 2019). Severe wildfires continue to negatively affect vegetation composition and structure, water quality, nutrient status or nutrient cycling, air quality, and soil erosion (Vukomanovic and Steelman, 2019). The costs associated with recent wildfires are unprecedented, including harm to physical assets, health, ecosystem processes, and economic activities (Feo et al., 2020).

Forest treatment, which refers to forest thinning, prescribed burning, and other forest-management activities, is helping forests become more resilient to fire, drought, and pests (Prichard et al., 2021, Stoddard et al., 2021, Stephens et al., 2021; Knapp et al., 2017). Forest restoration can reduce surface fuels, increase height from ground to live crown, and decrease tree density. These activities can reduce competition for water among trees, making the forest more resilient. Reducing surface fuels can also reduce flame length, making it less likely that fire will move from ground to crown. In addition, decreasing tree density makes tree-to-tree fire less probable (Agee and Skinner, 2005). Based on estimates by the U.S. Forest Service, the pace and scale of treatment needs to be increased from approximately 0.1 million ha per year to 0.2 million ha per year; and 2.5-3.5 million ha out of the 8 million ha it manages in

California need restoring immediately (California Forest Management Task Force, 2021). Yet government allocations and the economic benefits of timber harvesting alone are far from sufficient to meet the demand. Therefore to expand support for forest restoration, beyond the direct and indirect investments from landowners and managers, partnerships involving additional beneficiaries are important to expand resources for forest management (Edelson and Hertslet, 2019).

In California, forests are critically important for water supply. The forested land within the Sierra Nevada provides 60% of California's developed water supply (ACWA, 2015). Yet the quantity and quality of water coming from source-water areas are threatened by overcrowded forests, degraded meadows, and a changing climate. In addition to mitigating the risk of high-severity wildfires, forest restoration can enhance water supply. Removing trees makes more water available for the remaining trees, for in-stream flows, and for downstream hydropower generation and water supply. Several studies have shown that forest restoration will increase water yield (Zou et al. 2010, Simonit et al.2015, Robles et al. 2014, Saksa et al., 2020, Roche et al. 2020, Bart et al. 2021).

Compared to the abundant research on estimating the change of water yield due to forest restoration, the economic value and beneficiaries of increased water yield have been under studied. Some studies have estimated the value of water-related ecosystem services, including hydropower, water supply, and habitat provision (Piaggio and Siikamäki, 2021, Fu et al., 2014, Strand et al., 2018, La Notte et al., 2012), yet have not considered the impacts of forest restoration on their values. Other studies assessed the value of watershed conservation through investigation of the willingness-to-pay from end users (Zander et al., 2013, Aguilar et al., 2018, Abebe et al., 2019). Despite there being indirectly estimated values for watershed restoration, there lacks a direct evaluation and analysis of economic benefits and beneficiaries, which is a large gap when promoting partnerships and large-scale implementation of forest restoration. The increased runoff can augment hydropower generation, and thus potentially revenue from electricity sales. Moreover, California water-rights holders can sell water, enhancing statewide flexibility in meeting shortages during dry periods. For example, water-rights holders can sell water to users needing to avoid costly drought impacts, or sign long-term water-sales contracts to accommodate population and economic growth (Ayres et al., 2021).

To bridge the research gaps, this study assessed the value of water-related benefits of forest restoration, focused on two monetizable benefits of hydropower and water sales, using treatment areas from two ongoing projects. By using a scalable top-down approach to track annual ET following forest disturbance, coupled with hydropower simulations that include energy-price information, and marginal prices for water sales, we examined the following questions. First, what are the characteristics of areas identified as high priority for forest-restoration projects leading to greater water-related benefits? Second, how significant are the water-related benefits compared to the costs of forest restoration? Third, how do the benefits change under a drier climate? We also discuss how these results can support implementing forest-restoration projects.

2.2 Materials and Methods

2.2.1 Study Area

We focused on the Upper Yuba and North Fork American watersheds, two densely forested watersheds within the Sierra Nevada that are at risk of severe wildfire (Figure 2.1). Productive mixed-conifer forests cover 68% and 61% of land of the two watersheds respectively (Yang et al., 2018). Over the past 35 years there have been 17 wildfires over 500 ha in the larger Yuba and American watersheds, with the 2 largest being in the past 10 years. The elevation ranges are 27 to 2750 m for the Upper Yuba watershed and 123 to 3027 m for the North Fork American watershed. The 30-year average annual precipitation (1991-2020) for the two watersheds are 1659 mm (565-2814 mm, across the watershed), and 1565 mm (648-2807 mm) respectively, derived from the Parameter elevation Regression on Independent Slopes Model (PRISM). In California, water-rights holders have legal authority (essentially property rights) to use specified amounts of water for beneficial purposes. The Yuba Water Agency (YWA) and the Placer County Water Agency (PCWA) are two primary water-rights holders within the two study areas, holding water rights for power generation and water sales to downstream users, and are thus direct beneficiaries of forest-restoration projects. Both agencies are also involved in partnerships to advance forest restoration. We analyzed two proposed projects with potential to benefit the two water-rights holders, one in each watershed, for Yuba Project and French Meadows Project (Figure 2.1). The French Meadows Project is located just upstream of the French Meadows Reservoir and covers an area of approximately 15.6 km^2, and the Yuba Project covers an area of 23.1 km^2 upstream of New Bullards Bar Reservoir. The mean slope for the Yuba Project area is 24% and for the French Meadows Project area is 18%. The parent materials for the two project areas are dominated by granite, metamorphic rock, acidic tuff and glaciofluvial deposits, and the soil types are dominated by Inceptisols and Alfisols (The Natural Resources Conservation Service, 2021).

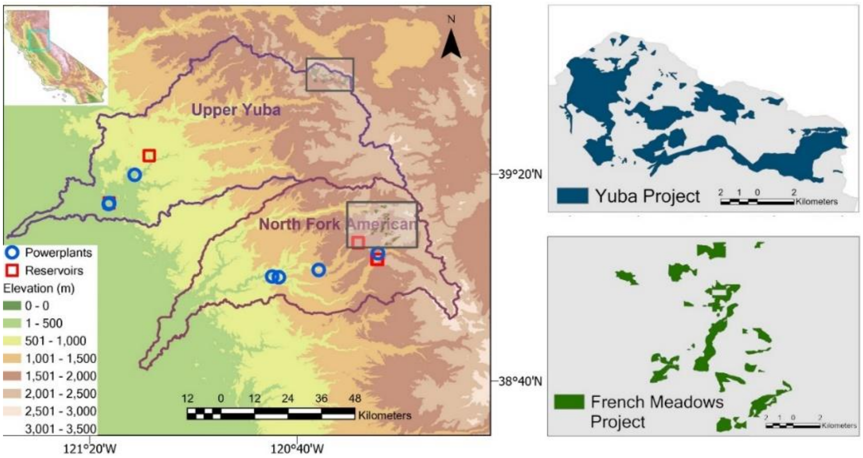

Figure 2.1. Map of the study areas, with 500-meter elevation bands, with reservoirs and powerhouses included in the models shown as squares and circles. Also the maps

the two proposed projects, the Yuba Project and the French Meadows Project.

2.2.2 Summary of approach

Our method for estimating the benefits of additional water yield from forest restoration involved three steps. First, we used hydropower models to simulate historical hydropower generation and mapped historical generation and potential economic benefits across the study watersheds. Second, we estimated the effect of forest-treatment projects with different treatment intensities on the reduction of ET. Third, coupling the time-series estimates of ET reduction post-treatment with the hydropower model and marginal prices for water sales, we evaluated the economic benefits and conducted a stochastic analysis to account for the randomness of occurrence of different types of water years and the effects of drought.

2.2.3 Water yield and hydropower simulation

The estimation of potential water yield is based on the annual water balance, $Q = P - ET - \Delta S$, where Q is runoff, P is precipitation, ET is evapotranspiration and ΔS is change in subsurface storage (R. C. Bales et al., 2018). Since we were mapping a multi-year average water yield, the ΔS was omitted. Precipitation came from PRISM (Daly et al.,1994), and ET came from the high correlation between annual ET and the annual average of the Landsat satellite - derived normalized differenced vegetation index (NDVI) (Goulden and Bales, 2019), based on the observation that patterns in ET are driven largely by vegetation (Goulden et al., 2012, Figure S2.1). The NDVI value came from the complete collection of U.S. Geological Survey Landsat™ Surface Reflectance data for the water years of interest (1985-2021) (Roche et al., 2020).

For hydropower generation, to estimate the potential revenue and the benefits of forest restoration, we followed methods by Guo et al. (2021) and developed hydropower-simulation models that incorporate energy-price information. We calculated the annual power generation (E) and the potential annual power generation revenue (R) using the following equations:

$$E = \sum_{i=1}^{t} \sum_{j=1}^{n} \eta_j \rho g Q_{ij} H_{ij} \qquad \text{(Eq1)}$$

$$R = \sum_{i=1}^{t} \sum_{j=1}^{n} \eta_j \rho g Q_{ij} H_{ij} \times P_i \qquad \text{(Eq2)}$$

where i is the time, j is the powerhouse, P_i is the energy price at time i, η_j is the overall efficiency, ρ is the water density, Q_{ij} is the water release for powerhouse j at time i, H_{ij} is the average water head for powerhouse j at time i.

The inputs of the hydropower model are hourly inflows of corresponding reservoirs and hourly energy prices. We obtained inflow data from the United States Geological Survey's National Water Information System, and future energy prices from Seel et al. (2018), which predicts hourly energy prices based on historical prices. These values consider the increasing penetrations of variable renewable energy, and show a pattern similar to those reported by the California Independent System Operator (Guo et al., 2021).

Given the temporal imbalances between peak demand for electricity and renewable-energy production, energy prices are typically higher during high-demand periods. We use energy prices as indicators to guide the operation of the hydroelectric system to determine the timing of water releases, which can maintain a smooth grid on the one hand while simultaneously driving power-generation revenue. We used such a process to estimate potential power-generation revenue.

Simulations were performed in Systems Thinking, Experimental Learning Laboratory with Animation (STELLA 2.0.1), a visual programming language for system-dynamics modeling (ISEE Systems). The hydropower system owned by the YWA includes two reservoirs and three powerhouses, which are New Bullards Bar Reservoir, Englebright Reservoir, Colgate Powerhouse, and Narrows 1&2 Powerhouses. The hydropower system owned by PCWA includes two reservoirs and four powerhouses, which are French Meadows Reservoir, Hell Hole Reservoir, French Meadows Powerhouse, Middle Fork Powerhouse, Ralston Powerhouse and Oxbow Powerhouse. The attributes of these hydropower facilities, including the maximum and minimum reservoir storage capacity over time, the efficiency of the power plants, and the flood-control and environmental-flow requirements were obtained from the statement-documents from Federal Energy Regulatory Commission (FERC/EIS-0281F, FERC/EIS-F-0242) and confirmed with associated water agencies (See Figures S2.2-S2.3 for the configuration, parameters, input and output of the hydropower simulation model). We simulated the hydropower generation for a 15-year study period under analysis for both systems and evaluated the simulation results with historical generation data recorded by the California Energy Commission. We used the Mean Square Error skill scores demonstrated by Harrison and Bales (2016) to assess simulation skill.

Mapping hydropower generation and potential power-generation revenue of upstream areas provides an intuitive perception of the water-related ecosystem services in the regions. The geographic distribution of annual water yield in a watershed is heterogeneous, and the value of each unit of water varies due to the heterogeneous geographic distribution. The value was determined by a combination of the annual water yield, the characteristics of the hydropower system, and the relative locations of powerhouses in the hydropower system. For mapping, we compiled data on water yield, recorded hydropower generation, and simulated power-generation revenue for 15 years (2004-2018) across the two watersheds. We mapped each powerhouse to the reservoir that supplies it, and then use the 'Watershed' function inside ArcGIS Pro (2.9.3) to map the sub-basins that supply the reservoirs. The power-generation and the potential revenue maps for each sub-basin were determined by the average value of the power generation and potential revenue of each powerhouse over the 15 years and the water yield maps for each sub-basin, and the overall maps were generated by stacking the individual sub-basin maps (Table S2.1 for data sources).

2.2.4 Effects of forest treatment

Forest treatment aims at removing dead fuels and small trees that serve as ladder fuels and reducing the tree density, which has similar effects on biomass as do wildfires. Therefore, the effects of wildfires of different severity on the magnitude of biomass removed were used as proxies for forest treatments. Our method followed that described in Roche et al. (2020), who found that medium-severity wildfires (25-50% basal-area removal) resulted in average decline in ET of 200 mm in the first year, with recovery to pre-disturbance values within 20 years post fire. They analyzed ET changes for 33 past wildfires in the Yuba and American basins using ET from a top-down statistical model (Goulden et al., 2012; Goulden and Bales, 2019). That model used correlations of measured annual ET from eddy-covariance towers across California with NDVI measured by satellite to predict ET across the Sierra Nevada. The wildfires span the period 1985–2015 and were categorized by different levels of forest basal-area loss. Because restoration treatments in these areas are more recent, using wildfire disturbance as a proxy for fuels treatments provides a longer record over varying interannual climate conditions. We used wildfires characterized by 25%-75% basal area loss as a proxy for medium-intensity forest treatments, which represents a more-realistic management action for public land; and we used and wildfires characterized by 75%-100% basal area loss as a proxy of high-intensity forest treatments, which is achievable in private land and used for estimation of the maximum possible benefit. We labeled polygons of different levels of basal area loss with the year in which they occurred and used “Raster” package (Hijmans, 2021) in R language (Version 3.6.3) to extract and calculate their subsequent 15-year average ET from the ET data layers of different years. In this, we also considered the uncertainty of treatment effects under medium-intensity treatment due to variation in stand, precipitation, subsurface water storage, and pre-fire density at different elevations and interannual variation in climate (Roche et al., 2020).

2.2.5 Analysis of economic benefits

The economic benefits of additional water yield can be measured by increased hydropower generation and the market value of water. To assess the benefits of hydropower generation, we used the increase in total water yield due to possible annual ET reductions within the proposed treatment areas to adjust the inflow data for the hydropower model. The adjustment was based on the principle that the increased flows follow the original flow pattern. With the same simulation process for hydropower generation, we derived the post-treatment time series of hydropower generation as well as the revenue from power generation after treatment. The economic benefits of water sales were determined by the amount of additional potential water yield multiplied by the marginal price of water sales. The marginal water prices were based on recent sales by the two water agencies and varied by the water-year type (personal communication with YWA and PCWA, see acknowledgements). Not unexpectedly, critical and dry water years have higher marginal prices, which are $500 and $200 per acre-foot (AF, $617 and $247 per thousand m^3), respectively, while other water-year types have marginal prices of $50 per AF ($62 per thousand m^3). Note that these recent year-by-year sales are to downstream agencies, not sales to customers within their service areas. We considered both high-intensity and medium-intensity treatments, and the uncertainty around the treatment effect. These treatments were equivalent to medium and high severity fire, respectively ((25-75% vs >75% basal area removal). Our time-series data were from the period 2004-2018. We assumed that the year 2004 is the first year after the completion of forest treatments, with the following fifteen years being the analysis period. The net present value (NPV) represents the overall economic benefit, calculated by the following equation:

$$NPV = \sum_{i=1}^{n} \frac{Value\_Power_i + Value\_Water_i}{(1+Discount)^i} \qquad \text{(Eq3)}$$

where *NPV* is the net present value, *n* is the total analysis period (15 years), *i* is year, *Value_Power* is the benefit of hydropower generation, *Value_Water* is the benefit of water sales, *Discount* is the annual discount rate, which is 3% in this study. *NPV* represents benefits from additional runoff, and does not include the cost of forest treatment.

We considered the effect of the randomness of the order of occurrence of the different water years on the overall economic benefits over the project period. We randomly ranked the fifteen years, repeated 10,000 times, and derived values for the mean and plus and minus one standard deviation. There were five water-year types in the 15 years analyzed, including three wet years, one above-normal year, five below-normal years, three dry years and three critical years. As found by Diffenbaugh et al. (2015), climate change appears to be increasing the likelihood of a large-scale atmospheric pattern that yields warm, dry weather in California. In the face of climate change, we thus considered a drought scenario by randomly removing one wet year and randomly selecting a critical year from the original 15-year scenario to replace it.

2.3 Results

2.3.1 Water-yield and hydropower simulation

The model showed good simulation skill for both the YWA and PCWA hydropower systems for the study period (Figure 2.2), with Mean Square Error skill scores of 0.97 and 0.88 respectively (R-squared of 0.97 and 0.91). Generally, wet years generate more power, while dry years or critical years generate less. In these simulations the YWA hydropower system generates an average of 1.30 million MWh annually, 45% more than the 0.89 million MWh simulated for the PCWA system.

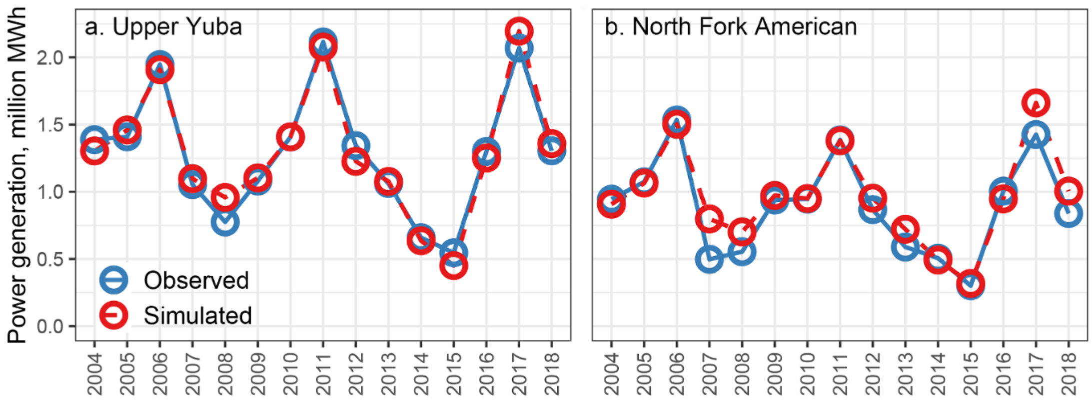

Figure 2.2. Simulated versus observed power generation of the two hydropower systems.

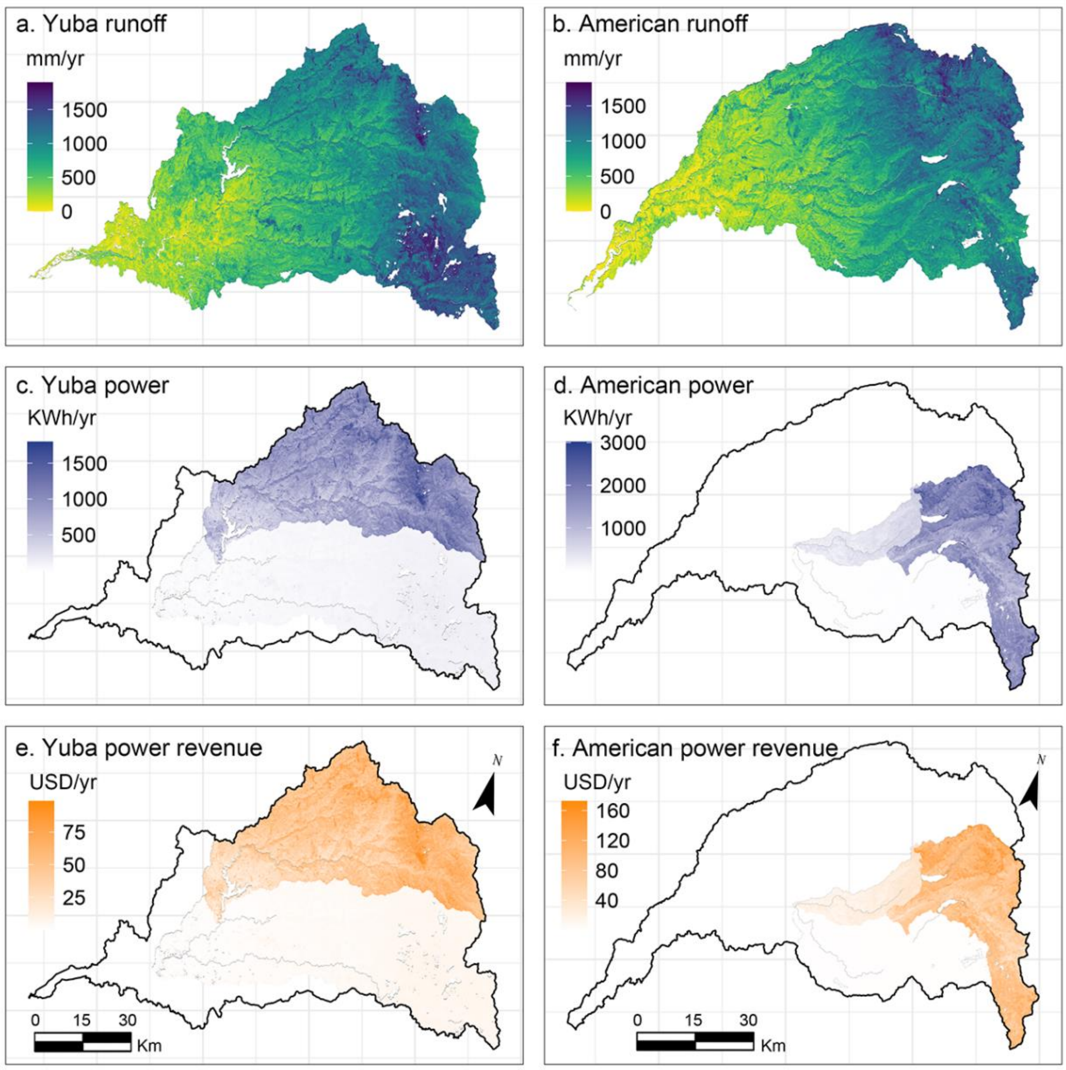

Figure 2.3. Average annual water yield (a,b), average annual power generation (c,d) and average annual potential power generation revenue(e,f) for 15 years analyzed of the two watersheds.

The average annual water yields of the two watersheds over the 15-year period were 846 mm for the Upper Yuba and 752 mm for the North Fork American. In both watersheds, from west to east, water yield increases with elevation (Figure 2.3, a-b). We also mapped the hydropower generation and potential power-generation revenue based on the water-yield map (Figure 2.3, c-f). Spatially, the 15-year average annual power generation per hectare are 0-19.5 MWh/ha across the Upper Yuba and 0-33.3 MWh/ha across the North Fork American, and the 15-year average annual potential revenue are $0-1070/ha across the Upper Yuba, and $0-1907/ha across the North Fork American. Within the watersheds, some areas had water yield that is more important for local hydropower generation, as reflected in significantly higher values for power generation per unit volume of water (Figure S2.4). As shown in the maps, for the Upper Yuba watershed, the sub-basins that supply the New Bullards Bar reservoir had the highest value for hydropower generation per unit volume of water, since the water from those sub-basins goes through a high-capacity powerhouse, while lower values are associated with area whose water passes through only the two smaller downstream powerhouses. Likewise, only a portion of the North Fork American watershed's water yield was of value for PCWA power generation, and the areas with highest power-generation value per unit volume of water were the sub-basins supplying the French Meadows reservoir, since the water from this basin passes through all four powerhouses. Comparing the two watersheds, the American had a smaller tributary area with hydropower value, but could generate more power per unit volume of water and thus potential revenue. Temporally, the annual power generation per unit volume of water varied for different water-year types, with the wet year having the lowest value per unit of volume water (Figure S2.5).

2.3.2 Effects of forest treatment

We extracted how the ET changes post wildfire for 15 years in the two watersheds. For the first year, the mean ET dropped by 361 mm and 371 mm for high-severity wildfires (>75% basal area removal), and 277±78 mm (mean ± standard deviation, same for all the following) and 269±118 mm for medium-severity wildfires (25-75% basal area removal), for the Upper Yuba and the North Fork American study areas respectively; and ET gradually recovers to the pre-fire level over the following 15 years (Figure 2.4). Referring to near the above ET changes, under the medium-intensity treatment scenario, for the Yuba Project the mean projected volume of increased water yield over 15 years was 38.5±26.3 million m^3 (31.2±21.3 thousand AF), with 6.4±1.8 million m^3 in the first year after treatment. For the French Meadows Project, the total volume of increased water yield was 32.5±16.4 million m^3, with 4.1±1.8 million m^3 in the first year. In the high-intensity treatment scenario, the respective mean values were 56.7 and 8.4 million m^3 for the Yuba Project, and 42.2 and 5.6 million m^3 for the French Meadows Project.

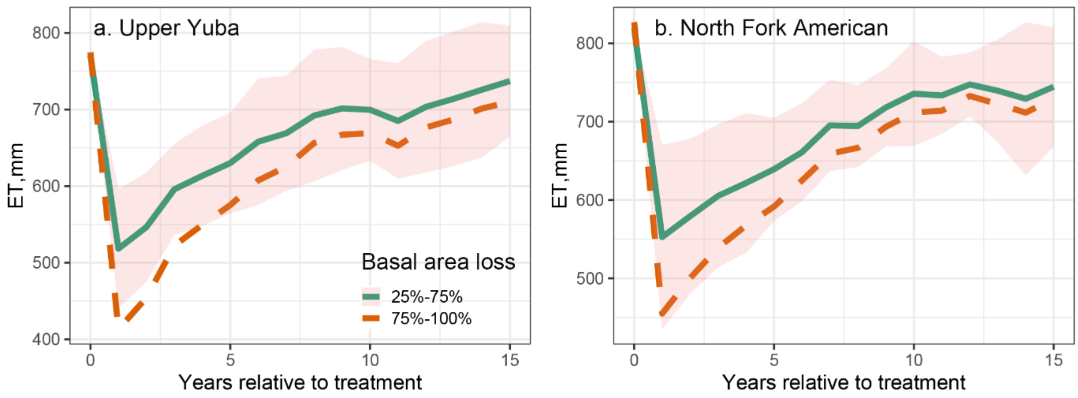

Figure 2.4. ET reduction and recovery after wildfires of high and medium severity for the Upper Yuba and North Fork American watersheds. Plus and minus one standard deviation is shown for the 25%-75% basal area loss class.

2.3.3 Analysis of economic benefits

The potential annual revenue increase and NPVs of the two projects over the 15 years post treatment showed high-intensity treatment generating more benefits than medium-intensity treatments due to more water yield (Figure 2.5). Using the mean annual ET reductions post-treatment as estimates of the potential changes in water yield, the NPV for the Yuba Project was $9.0 million, with $3.1 million in hydropower and $5.9 million in water sales under high-intensity treatment, versus $6.5 million, with $2.3 million in hydropower and $4.2 million in water sales under medium-intensity treatment. The potential annual revenue increases for the Yuba Project were $0.08-$2.5 million, and $0.05-$2.2 million for high and medium intensity, respectively. For the French Meadows project, the potential NPV for high-intensity treatment was $7.1 million, with $2.8 million in hydropower and $4.3 million in water sales; and the annual revenue increase ranged from $0.08 to $2.2 million. For the medium-intensity treatment the potential NPV was $5.4 million, with $2.1 million in hydropower and $3.3 million in water sales; and the annual revenue increase ranged from $0.07 to $1.7 million. For both projects, the maximum annual revenue increase occurred in year 5, a critically dry year, and the minimum value occurred in year 14, a very wet year. The uncertainty of ET reduction post-wildfire gave a standard deviation of 47% of the mean NPV for the Yuba Project and 39% of the French Meadows Project.

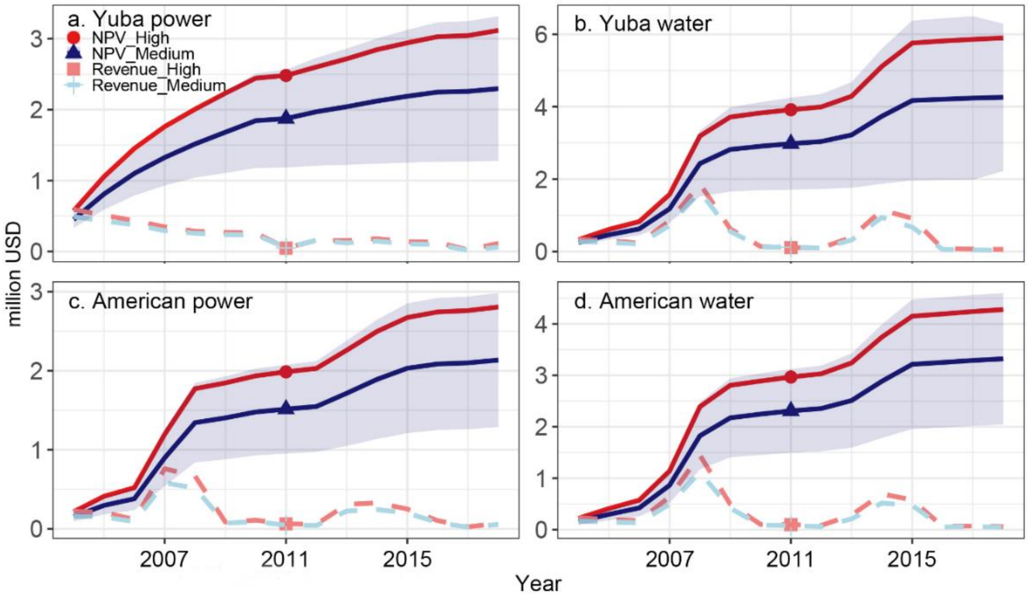

Figure 2.5. The annual revenue increase and the accumulated net present value under different treatment intensity for 15 years analyzed (2004-2018) for the Upper Yuba watershed (a for hydropower and b for water sales) and the North Fork American watershed (c for hydropower and d for waters sales). Plus and minus one standard deviation is shown for NPV under medium treatment intensity.

From the stochastic analysis, under the medium-intensity treatment scenario, the NPVs were \$7.0±3.3 million for the Yuba Project and \$6.1±2.5 million for the French Meadows Project; and more than half of their NPVs were accumulated in the first five years after treatment, with 62% and 57% respectively (Figure 2.6). Moreover, in a drier scenario, which has one more critically dry year, the mean NPVs were higher than those under a normal scenario. The overall combined mean NPV per ha for hydropower and water sales for the drier scenario were higher by \$396/ha (\$160/ac), or 13% for the Yuba Project, and \$627/ha (\$254/ac), or %16 for the French Meadows Project, under the medium-intensity scenario (Table 2.1).

Table 2.1. Mean value (± SD) of net present value per ha for two projects under different scenarios after stochastic analysis

	Project benefit, $ per ha (± SD)							
	Yuba				French Meadows			
	High		Medium		High		Medium	
Scenario	Power	Water	Power	Water	Power	Water	Power	Water
Normal	1248	2874	919 (403)	2105 (1008)	1972	3242	1525 (635)	2506 (1035)
Drought	1287	3370	949 (413)	2471 (1171)	2167	3803	1720 (704)	2938 (1198)

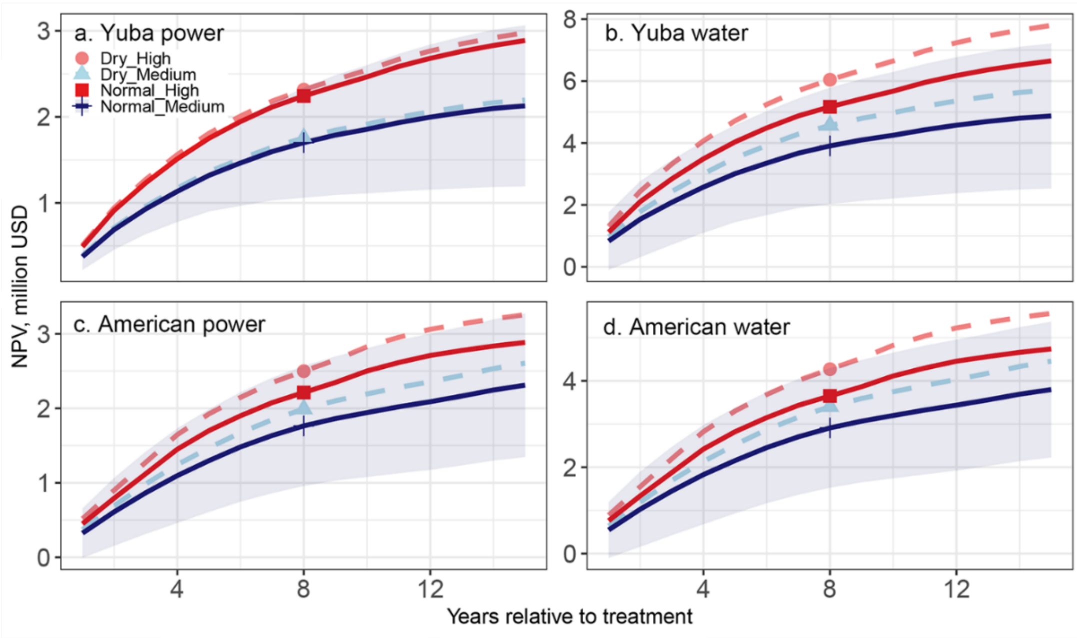

Figure 2.6. The mean accumulated net present value under different treatment intensity scenarios (high, medium) and different climate scenarios (normal, dry) after stochastic analysis. Plus and minus one standard deviation is shown for the benefits under normal and medium-intensity treatment scenario. Panel a and b show the hydropower and water sales for the Upper Yuba watershed, and panel c and d show the hydropower and water sales for the North Fork American watershed.

2.4 Discussion

2.4.1. Findings in context

Our findings reflect previous studies showing increases in water yield from Sierra Nevada watersheds with fuels treatments. Saksa et al. (2020) estimated that a relatively light vegetation decrease leads to an average 12% runoff increase in the central Sierra Nevada, but does not track vegetation recovery after disturbance. They also reported that additional water yield is proportional to the original flow, averaging over wet and dry years. Our findings showed a similar proportionality (Figure S2.6). After analyzing the corresponding decrease of ET following wildfires of different severity in the Yuba and American River watersheds, Roche et al. (2020) inferred that potential runoff may increase by about 200 mm in the first year after removing trees through management actions equivalent to a medium-severity wildfire. They reported that historically, some areas recover to pre-disturbance ET levels within 15 years, with others not fully recovered after 20 years. Bart et al. (2021) found that on average, in three sub-basins in the Southern Sierra Nevada, following 20% and 50% forest biomass-reduction, 102 and 263 mm of water (8.0% and 20.6% of mean annual precipitation), respectively were made available. However, they did not track vegetation recovery after disturbance.

Our study focused on the economic value of lower ET resulting from changes in forest biomass. We illustrated that using a top-down approach we can readily estimate the additional water yield and its benefits from forest restoration for any arbitrary polygon on the landscape. While our ET product has been evaluated at the watershed scale, and shown to provide a good water balance when compared with available precipitation and runoff data ($ET = P–Q$), it can be applied to any area by summing pixel-level values of $P–ET$ to estimate Q. Compared with previous studies that estimated the effects of forest treatment on water yield, either with distributed hydrologic models or process-based ecohydrological model (Khanal & Parajuli, 2013, Burke et al., 2021, Li et al., 2021, Bart et al., 2021), a top-down approach has advantages in supporting subsequent benefit analysis given its application to any polygon on the landscape and reliance on readily available data. Combined with local water-related information on hydropower-system attributes, water rights, and water storage, we can adapt and apply models that determine the value of water and analyze the economic feasibility of proposed forest-treatment projects. This approach can be scaled to different locations or applied to areas with different treatment methods.

We used NPV in referring to the benefits of hydropower and water sales, while the cost refers to the operational cost of forest restoration. We acknowledge that there are multiple other benefits associated with forest restoration, notably air-quality protection, provision of habitat, and carbon storage; and there are also multiple beneficiaries besides water and hydropower providers (Eriksson et al., 2022). Our analysis analyzed the water-related costs and benefits specific to partnerships investing in headwaters as natural infrastructure, and benefit streams that can be monetized to recover those costs. This is key information supporting the investment in forest-restoration projects by water-sector beneficiaries.

For the sake of simplicity and generalizability of the method, this study made several assumptions. First, as found by Roche et al. (2018), the changes in NDVI and thus ET of Sierra conifer forests following forest thinning or fire were observed to be consistent with changes in forest density indicated by basal area and canopy cover, and thus we used wildfires categorized by different basal area loss as a proxy of treatment (Roche et al., 2020). As in our study, their analysis of the recovery period focused on the Yuba and American watersheds, with similar findings across the Sierra Nevada (Ma et al., 2020). We used 15 years as a benefit period for the analysis; however, the recovery rate also depends on how dry or wet is the post-disturbance period.

Second, we neglected the interannual change of subsurface storage, ΔS, when estimating the change in potential water yield (P-ET). For dry years some ET will be satisfied by ΔS rather than by precipitation in that year ($ET>P$ for some pixels). However, since we do a pixel-by-pixel analysis, those negative values will not affect the positive values in other pixels. That is, for an estimate of basin-scale P-ET, our index of potential streamflow available for hydropower or water sales, we only sum positive values. For wetter years following dry years, some amount of precipitation will go toward refilling the carryover deficit in the subsurface in the pixels that had P-

ET<0 in the dry years, i.e. satisfying the carryover ΔS deficit from the previous year. So there is a potential overestimate of potential runoff in wetter years. However, this will have a relatively small effect on the water and hydropower sales estimate, as there are lower values for water sales in wetter years, and during very wet years some water bypasses the hydropower system. In addition, referring to Roche et al. (2020), the interannual change of subsurface storage is quite small within the two project areas during the study period. The effect will be more important in lower-precipitation areas such as the southern Sierra Nevada.

2.4.2. Variability of benefits

When determining contributions to financing forest treatments, attention should be given to which areas have higher versus lower potential water-related values. Comparing the two watersheds, it can be seen from the historical power-generation maps as well as the potential-revenue maps that the North Fork American watershed has a higher value per unit area compared to the Upper Yuba watershed. However, characteristics across both point to higher-elevation forested areas providing much greater value owing to higher water yield and potential for passage through multiple downstream power houses. This is determined by the different characteristics of the hydropower system of each watershed. The system operated by the PCWA has a cumulative elevation difference of 1168 m, more than twice the 535 m of the hydropower project owned by YWA, and therefore has a higher initial potential energy per unit of water that can be converted to electricity. This difference is also reflected in the effect of the forest-treatment project. For the French Meadows Project, in a medium-intensity treatment scenario, the NPV of the potential economic benefits of additional water yield for hydropower per km^2 is 1.7 times than that of the Yuba Project, despite the fact that the estimated 15-year total increase in water yield per km^2 of the French Meadows Project is only 1.25 times of that of the Yuba Project. For water sales, this difference does not exist because the economic benefit of water sales per unit of water is only influenced by the marginal price. These results show for different hydropower systems, the economic value per unit of water upstream of hydropower having greater elevation drop is greater, as well as the unit benefit of hydropower generation arising from forest treatments. Previous studies that mapped and valued annual hydropower ecosystem service used models such as Integrated Model of Land Surface Processes (Strand et al., 2018) or Integrated Valuation of Ecosystem Services and Tradeoffs (Zhu et al., 2022, Fu et al., 2014), combined with the configurations of local hydropower systems. In our study, we followed a similar approach to map the value of annual hydropower ecosystem service, with enhancement to the method with finer temporal resolution and richer configurations that enable better assessment of the marginal value of additional water yield for hydropower, given the ever-changing energy prices and water levels in reservoirs.

The economic value per unit of water increase varied across different water year types. Typically, in dry years, the value is higher. When considering the medium-intensity treatment scenario, the average economic value of water for hydropower generation is \$36/thousand m^3 (\$44/AF) in wet years, while for dry and critical years it averages \$63/thousand m^3. This trend is even more significant for the French Meadows Project, where the average economic value of water for hydropower generation is \$22/thousand m^3 in wet years, while for dry and critical years it averages \$159/thousand m^3. In wet years, the value is lower because there is already enough water yield for power generation, and thus the additional water is supplementing generation at times of lower electricity prices. For dry years, the value is higher because there is less water yield and most of the increased water can be used to generate power at times with higher electricity prices. As for the value of water sales, the marginal price of water sales also varies depending on water-year type. In dry years, particularly critical years, the price could be much higher due to high demand for water. After back-to-back drought years, some buyers even paid \$2000/AF for water to ensure their crop production (Henry, 2022). When doing the sensitivity analysis to the effects of marginal water prices on the overall benefits, doubling the dry and critical year marginal prices to\$494 and \$1234 per thousand m^3 would increase the NPV of benefits by \$1646/ha (\$666/ac) or 54% for the Yuba Project, and \$2056/ha or 51% for the French Meadows Project over 15 years under medium-intensity treatment. When we set the marginal price of water in the wet year to zero, the benefits dropped by \$116/ha or 4% for the Yuba Project and \$437/ha, or 11% for the French Meadows Project. Thus, price changes due to drought rather than wet years will affect overall benefits to a greater extent.

While benefits from water sales are relatively low in wet compared to dry years, California's aim of expanding water banking through diversion of high flows to groundwater recharge (State of California, 2021) could provide even greater value from forest restoration. To achieve this, it will be important to engage downstream users in partnerships for forest restoration.

2.4.3. Net benefits

Recent average costs of the forest treatment are estimated at \$2965/ha (\$1200/ac) for the Yuba Project and \$3635/ha for the French Meadows Project without considering the sales value of harvested products (personal communication with YWA and PCWA). Those values are near our estimate of the mean NPV of economic benefits of hydropower generation plus water sales in a medium-intensity treatment scenario, \$3024/ha for Yuba and \$4031/ha for French Meadows. The benefits per unit area associated with water alone in both projects exceeded the cost of forest treatment, not to mention other co-benefits coming from wildfire-risk mitigation through forest restoration (Eriksson et al., 2022). Our analysis suggests that in a drought scenario, in which more dry years are expected, the economic benefits from forest restoration will be greater than those under a normal scenario. This means that forest restoration is a favorable adaptive-management measure to deal with drought, since it can also reduce or mitigate drought-related stress by reducing stand density and adjusting species composition. It also highlights the opportunities for water-rights holders to pass on investment in source-water restoration to downstream beneficiaries of the runoff and hydroelectricity resulting from forest restoration.

Generally, the benefit of water sales estimated in this analysis can be expanded to other watersheds in the Sierra Nevada, given the similarity of treatment effects and marginal water prices. In addition, 19 watersheds associated with the Sierra Nevada own hydropower capacity over 100 MW (Figure S2.7), with mean value of 584 MW, while the two watersheds in this study have hydropower capacity of 415 MW and 314 MW, respectively. This means that in addition to being protected from wildfire, drought, and pests by forest restoration, these watersheds will provide great opportunities to enhance hydropower generation. Given the goal of providing 100% of retail electricity sales with carbon-free electricity by 2045 of California (Tarroja et al., 2019), the findings of this study further justified investments in forest-restoration projects in this area.

The scale of the Yuba and French Meadows projects used in this research is typical of the scale of current forest-restoration projects. Ongoing efforts across the state to expand the scale of projects, and build capacity for this scaling up, offer the potential to both lower treatment costs and enhance water-related and other benefits.

2.5 Conclusions

This study illustrates a pathway for planning, prioritizing, evaluating, and verifying the direct, monetizable water benefits of forest-restoration projects from the perspective of water and hydropower providers and downstream users. We offer two main conclusions. First, the benefits from hydropower and water sales arising from strategically placed forest restoration could be high enough to cover the costs. The strategy refers to projects placed upstream of as much of the hydropower system as feasible and within the watershed that supplies water to hydropower supply or regulating reservoirs. The elevation difference in the hydropower system is also important. Second, in a drier climate, the benefits for the systems studied will be even greater, as water shortages increase the value of water. These findings justify the investment in forest restoration, and can be extended to other watersheds in the Sierra Nevada, as well as to headwater watersheds that provide similar water-related ecosystem services. Our results reinforce the central role of water and hydropower providers in partnerships for management of source-water watersheds, and the importance of accurate, scalable data and tools from the hydrology and water-resources community.

Chapter 3: Valuing co-benefits of fire regulation through forest restoration in wildfire-vulnerable forests

3.1 Introduction

Wildfires are a major natural hazard that accounts for 23% of the deforestation across the global forests (Curtis et al., 2018, Shmuel & Heifetz, 2022). Trends in fuel moisture over recent decades indicate that global wildfire activity will increase with anthropogenic climate change (Ellis et al., 2022). The frequency and severity of wildfires have been increasing in forests across the western United States (Abatzoglou & Williams, 2016, Dennison et al., 2014, Burke et al., 2021), increasing calls for fire suppression when a wildfire does occur, and also for fuels treatments to reduce projected severity. In addition to a warming climate, excessive vegetation density and forests overstocked with small trees and brush caused by unsustainable timber harvesting and historical fire suppression are major reasons for the occurrence of more-severe wildfires (Collins et al., 2017). This is especially evident in California, which is roughly one-third forested (Taylor, 2018); and the state has recognized the importance of moving from a regime dominated by destructive wildfires to a more-sustainable condition with beneficial wildfires (California Natural Resources Agency, 2022). The sustainability of these forested landscapes could be defined as having three pillars: i) ecological resilience, defined as the degree to which the forest can absorb disturbances while still retaining ecological function, biodiversity, and other important attributes, ii) ecosystem services or benefits to humans, and iii) environmental justice, how the health of these forests impacts rural communities and future generations (R. Bales et al., 2023).

Forests provide critical provisioning, regulating and cultural ecosystem services, including carbon storage, timber provisioning, erosion regulation, air-quality regulation, recreation, provision of habitat, and more. High-severity, catastrophic wildfires not only cause loss of life, property, and infrastructure, but also destroy or damage associated forest ecosystem services. For example, there is growing evidence that the forested lands in California will be a net source of greenhouse gas emissions well into the future if action is not taken to enhance forest health and resilience to reduce the threat they face from wildfire (Forest Climate Action Team, 2018). More than 190,000 ha of timberland in California were burned in 2020 (California Department of Forestry and Fire Protection, 2020). Studies found that post-fire yields of eroded sediments across watersheds affected by the Thomas and Carr Fires were at least 4.8 times pre-fire yields (East et al., 2021, Jumps et al., 2022). In terms of air quality, the total health costs related to air pollution exposure caused by wildfires in California in 2018 alone were estimated to be as high as $32.2 billion US dollars (D. Wang et al., 2021). Additionally, the survival of species and the prosperity of rural communities depend on California's forests, given that high-severity wildfires cause loss of habitat and elimination of safe-movement corridors for wildlife, and many rural communities rely on these lands, which provide vital resources and services including timber, livestock grazing, water, wildlife habitat, recreational opportunities, and biomass fuels for their economic livelihood. Therefore, sustainable management of forests is centeral to the state's strategy to mitigate the wildfire risk and make communities, watersheds, and habitats resilient to ever growing climate threats.

Forest restoration through stewardship fuels-treatments, which basically means removing the less-fire-resistant smaller trees and returning to a forest with larger trees that are widely spaced, has been recognized as an effective way to regulate wildfire (North et al., 2022, S. L. Stephens et al., 2013). Forest restoration makes it less likely that fire will move from ground to crown and makes tree-to-tree fire less probable (Agee & Skinner, 2005). Waltz et al. (2014) found that fuel treatments can reduce burn severity, as it was observed that high-severity patches were significantly smaller in treated units compared to untreated units after a wildfire. A forest experiment in southeast Australia demonstrated that active management of fuels can reduce wildfire risk and fire severity (Weston et al., 2022). Loudermilk et al. (2014) found that strategically placed fuels treatments substantially reduced wildfire risk and increased fire resiliency of the forest in the Lake Tahoe basin, California. Other studies have reported similar findings (Stephens et al., 2012, Prichard et al., 2010, Keenan et al., 2021, O'Donnell et al., 2018).

To protect forest ecosystems and their services from catastrophic wildfires, there is an urgency to restore the health and resilience of forests in California and across the western United States, particularly in the face of climate change, as proposed by action plans issued by resource managers (e.g., CalFire, 2018, Forest Climate Action Team, 2018). The State of California and the USDA Forest Service have partnered to launch an initiative to manage forests in a way that reduces the risk of high-severity wildfires and droughts, and restores forest resilience (State of California & USDA, 2020). The California Forest Management Task Force created a comprehensive strategy to accelerate efforts to restore forest health and resilience in California's forests, grasslands, and other natural places (California Forest Management Task Force, 2021). However, the pace and scale of forest restoration are far behind the need to meet these goals, due to important gaps in capacity, resources, and funding (Quesnel Seipp et al., 2023). Although studies have analyzed the economic value of forest treatment in mitigating wildfire, particularly on how much fuels treatments reduced wildfire-suppression costs, benefits from any single category are not sufficient to offset treatment costs (Hunter & Taylor, 2022). A promising solution to bridging these gaps are multi-benefit partnerships aimed at restoring public and private lands, while providing an array of benefits to rural communities and the public as well as to holders of water and other property rights (Edelson & Hertslet, 2019, Eriksson et al., 2022). Failing to incorporate benefits into a multi-benefit framework is an obstacle to identifying the main beneficiaries, forming an effective organizational mechanism, and promoting the implementation of restoration projects in a cooperative manner. This multi-benefit analysis is complicated given that several factors must be considered and integrated, such as wildfire prediction, treatment effectiveness, ecosystem services and their values, which few studies have examined comprehensively.

To bridge this gap, this study focused on quantitatively estimating the economic benefits of forest restoration on enhancing fire regulation and associated ecosystem services within a multi-benefit framework. Using multiple datasets of terrestrial-ecosystem and wildfire attributes, coupled with market prices and cost-valuation models, we examined the following questions. First, how do projected benefits of fire regulation enhance ecosystem services threatened by high-severity wildfires compared to costs of those management actions? Second, how do these potential benefits vary across the landscape, and what conditions and characteristics dominate the benefits? We carried out an analysis at the project level and scaled the analysis to the entire Sierra Nevada study area to assess valuation and opportunities monetizing benefits of such projects at a larger scale.

3.2 Materials and Methods

3.2.1 Study area

We used two ongoing projects in California's Sierra Nevada, North Yuba and French Meadows, with respective areas of 23.1 km^2 and 28.6 km^2, to illustrate project-level benefits. The two project areas are dominated by mixed-conifer forests, with white fir (*Abies concolor*), ponderosa pine (*Pinus ponderosa*), Jeffrey pine (*Pinus jeffreyi),* sugar pine (*Pinus lambertiana*) and lodgepole pine (*Pinus contorta*) as the major tree species. The average elevation is 2087 m for North Yuba and 1778 m for French Meadows, with mean slopes of 24% and 19% respectively. The respective 30-year average annual precipitation (1991-2020) values are 1690 and 1739 mm, derived from the Parameter elevation Regression on Independent Slopes Model (PRISM). We extended the area of interest to the entire Sierra Nevada using the same algorithms for estimating benefits (Figure 3.1). The restoration activities include thinning and understory biomass treatment through mechanical thinning, hand thinning, and mastication. In this study we focused on the overall effects of the restoration, based on historical data, without distinguishing these specific methods.

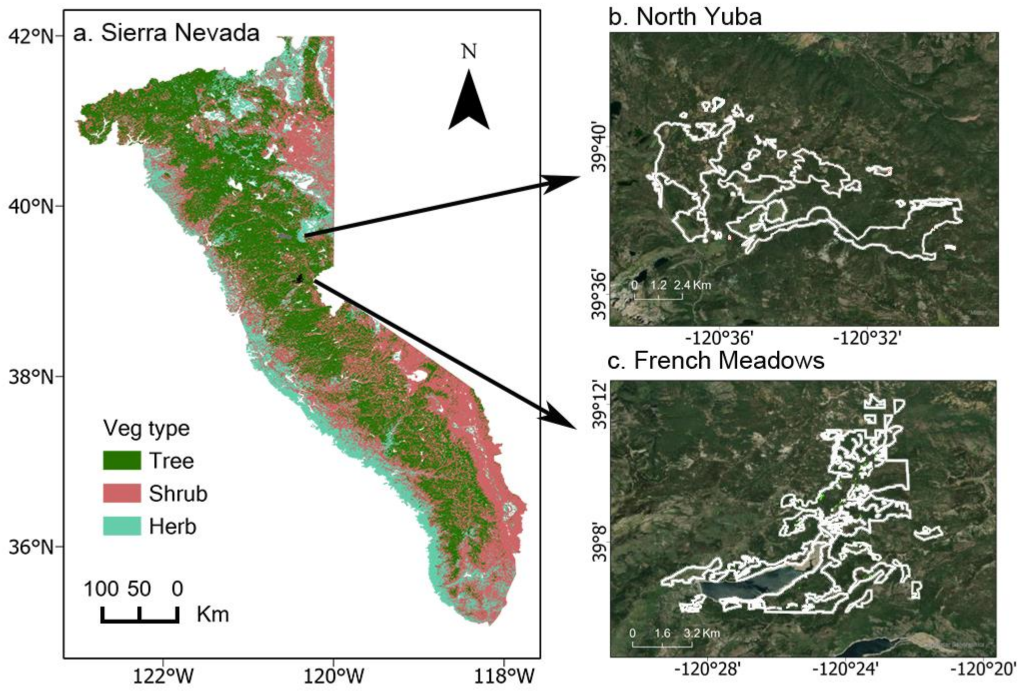

Figure 3.1. Maps of Sierra Nevada (panel a) and the treatment projects analyzed in this study, the Yuba Project (panel b) and the French Meadows Project (panel c).

3.2.2 Fire risk and overall benefits

The methods we used to estimate the benefits of fire regulation through forest restoration were adapted from Scott (2006). Fire risk is defined as loss of value in ecosystem services due to wildfire in a given landscape, and is measured by burn probability, burn severity, and the effects of a given severity on ecosystem services. Burn probability represents the likelihood of a given landscape burning. Burn severity is defined with reference to the Monitoring Trends in Burn Severity (MTBS) project, which is “the degree to which a site has been altered or disrupted by fire” and is categorized into four categories, namely high, moderate, low and unburned (Finco et al., 2012). We used flame length, a widely accepted metric, in determining the burn severity (Salis et al., 2019, Elliot et al., 2016). In this study, we analyzed four ecosystem services vulnerable to wildfire, namely carbon storage (climate regulation), timber provisioning, erosion regulation and air-quality regulation, i.e. three regulating services and one provisioning service, as defined by Millennium Ecosystem Assessment (Reid et al., 2005). Each ecosystem service will have a corresponding loss of value that depends on burn severity.

The overall benefits arising from forest restoration analyzed in this study come from the difference between the fire risk before and after fuels treatments. Our approach follows the equations below for quantitative estimation at landscape level:

$$Benefit = \sum_{i=1}^{4}\sum_{t=1}^{x}\sum_{j=1}^{n}\sum_{k=1}^{3}\frac{\left(P_{jt} \times S_{jtk} - \hat{P}_{jt} \times \hat{S}_{jtk}\right) \times NVC_{ikt}}{(1+r)^t} \quad (1)$$

where i is the i^{th} ecosystem service, four in total. t is the year after the treatment, and x is the total number of years we consider treatment bringing benefits, although the benefits also decline with vegetation regrowth and fuel accumulation. j refers to j^{th} pixel in a landscape, with the total number of pixels as n. k refers to the burn severity, where 1 for high severity, 2 for moderate severity and 3 for low severity. P_{jt} represents the burn probability at pixel j at year t, and S_{jtk} represents the probability of pixel j subject to high, moderate, or low burn severity at year t. $\hat{P}_{jt}$ and $\hat{S}_{jtk}$ are the corresponding variables post treatment. NVC_{ikt} represents the loss of value of ecosystem service i at burn severity k at year t. r is the discount rate and is set to be 3%.

To determine the fire-related variables above, we obtained spatially explicit data of burn probability and burn severity both before and after fuels treatments, and also estimated the duration of the benefit period. The extent to which fuels treatments reduce the predicted burn probability and the predicted flame length was assessed by examining how these two simulated fire-related indices change the first year after forest disturbance. We used the polygons for MTBS-defined low or moderate wildfires in the Sierra Nevada in 2020 to extract and track these two indices from the fire-simulation products of 2019 and 2021, downloaded from Pyrologix (Vogler et al., 2021).

To convert predicted flame length into predicted burn severity, we also examined how the simulated predicted flame length for 2019 corresponds to the wildfires that occurred in 2020 in high, moderate, and low severity across the Sierra Nevada. That is, by using millions of pixels and establishing this correspondence, we estimated the probability of fires occurring in each severity for a given predicted flame length. We accounted for the uncertainty of this probability by calculating its 95% confidence interval (95% CI) using the bootstrapping method, which means resampling with the number of pixels in each burn severity at each predicted flame length, iterating 10,000 times, and then computing the 95% CI with the bootstrap percentile method. To assess the benefit period, we used polygons in low or moderate severity wildfires from 2003 to 2008 across the Sierra Nevada to extract time-series predicted flame length for the corresponding subsequent years, using the data provided by the Natural Climate Solutions Data Atlas (M. Goulden et al., 2022). For this analysis, flame length was based on ground fuel, and did not include canopy fire. We derived the average time required for the predicted flame length to recover to its pre-disturbance level and regarded this as the benefit period. We assumed that the predicted burn probability and flame length will remain constant during this period without treatment; and assume that with treatment both indices will decrease in the first year to the extent we estimated, and then linearly return to their pre-disturbance levels.

We also compared the overall project benefits to the costs, which were \$2965/ha for the North Yuba Project and \$4712 for the French Meadows, as previously reported (Guo et al., 2023).

3.2.3 Carbon storage

The benefits of fuels treatments on carbon storage come from the carbon emissions avoided by regulating expected fire severity through treatments:

$$Benefit_{carbon} = \sum_{t=1}^{x}\sum_{j=1}^{n}\sum_{k=1}^{3}\frac{\left(P_{jt} \times S_{jtk} - \hat{P}_{jt} \times \hat{S}_{jtk}\right) \times Cl_k \times SCC_t}{(1+r)^t} \tag{2}$$

where Cl_k represents the loss of carbon storage per unit area following burn severity k, and SCC_t is the social cost of carbon as carbon emitted at year t. Cl_k was estimated by tracking how carbon storage was altered by wildfire. We examined the mean value of the loss of carbon storage due to historical wildfires of high, moderate, and low severity (Figure S3.1) directly through burning, although wildfires can also lead to slow decay of dead carbon and carbon sequestration due to forest regrowth, which offset each other, for one or two decades after fire. The time-series carbon-storage data were derived from time-series biomass data from the Natural Climate Solutions Data Atlas, which includes total live and dead biomass (J. A. Wang et al., 2022). The total live biomass includes both above and belowground biomass and is calculated as total biomass plus net primary productivity and minus total biomass that died each year. The total dead biomass includes standing snags, coarse and fine woody detritus (M. Goulden et al., 2022). We examined the changes in live and dead biomass one year after the wildfires and summed them as the change in total biomass. The biomass was converted to carbon storage with a scaling factor of 0.47 (Coffield et al., 2022). We also estimated the 95% CI of these changes in carbon stocks.

The social cost of carbon (SCC) is an estimate of the economic loss, in US dollars, of one additional ton of carbon dioxide emitted into the atmosphere (Tol, 2011, Nordhaus, 2017). Its value depends on the specific trajectory of emissions, economic production, and climate change over time (Binder et al., 2017). We used the estimates from Rennert et al., (2022), including a mean value of \$185 per ton of CO_2 emitted in 2020, and values for each of the subsequent years, and used a 5-95% quantile range (\$44-413 in 2020, Table S2.1) to reflect uncertainty.

3.2.4 Timber provisioning

The benefits of fuels treatments on timber provisioning were calculated as the loss of potential timber value due to high-severity wildfires avoided by treatment:

$$Benefit_{timber} = \sum_{t=1}^{x}\sum_{j=1}^{n}\left(P_{jt} \times S_{jt1} \times V_j - \hat{P}_{jt} \times \hat{S}_{jt1} \times \widehat{V_j}\right) \times P_{lumber} \times \frac{(1+inf)^t}{(1+r)^t} \tag{3}$$

$$V_j = f_{log}\left(Db_j, Sh_j\right) \times Ds_j \tag{4}$$

where V_j refers to the volume of lumber of pixel j, in thousand board feet (MBF, 1MBF=2.36 cubic meters), and $\widehat{V}_j$ is the volume of lumber of pixel j post treatment. S_{jt1} represents the probability of the pixel subject to high-severity wildfire. P_{lumber} is the price for lumber per MBF. inf is the inflation rate and was set to be 2% in this analysis.

To determine V_j and $\widehat{V}_j$, Db_j is the diameter at breast height (DBH), Sh_j is the stand height, and Ds_j is the density of trees (stems per ha). $\widehat{Ds}_j$ is the density of trees post treatment. f_{log} is the log rule. We assumed that wildfires of high severity deprive trees of their value as lumber (Figure S3.2). The volume of lumber contained in a standing tree is the sum of the volume of logs that would be obtained if the tree were cut, bucked, and scaled, usually considering only the central stem and ignoring branch wood (Löwe et al., 2019). To determine this volume, foresters have developed log rules (Table S2.2), which need measurements of DBH and the number of 16-foot logs (The Pennsylvania State University, 2020). The number of 16-foot logs per tree is determined by the merchantable stand height, which was set at 0.4 of the total stand height in this analysis. Combining the Ds_j with the volume of lumber per standing tree, we can obtain the V_j. The $\widehat{Ds}_j$ was adjusted based on Ds_j by reducing excessive tree density to 400 trees/ha for forest resilience (Keifer et al., 2000).

The associated forest attributes were obtained from gradient-nearest-neighbor (GNN) data, which are multivariate, imputed maps of forest attributes based on 30-m Landsat imagery, Forest Inventory and Analysis data, and other geospatial data products, such as climate and topography (https://lemmadownload.forestry.oregonstate.edu).

To obtain P_{lumber}, we extracted the 50-day moving-average lumber prices from Markets Insider (https://markets.businessinsider.com, downloaded in 2022) from 2019 to 2021, and used a 5%-95% quantile range to account for the uncertainty of the prices.

3.2.5 Erosion regulation

The benefits of fuels treatment on erosion regulation were calculated as the costs of dredging wildfire-induced sediment accumulation in reservoirs avoided by fuels treatment:

$$Benefit_{erosion} = \sum_{t=1}^{x}\sum_{l=1}^{f}\sum_{j=1}^{n}\sum_{k=1}^{3}\left(P_{jt} \times A_{jtlk} - \hat{P}_{jt} \times \hat{A}_{jtlk}\right) \times W_j \times SDR_j \times Cv \times Cd \times \frac{(1+inf)^{t+l}}{(1+r)^{t+l}} \quad (5)$$

$$A_{jtlk} = \left(R_j \times K_{ktj} \times LS_j \times C_{ktj} \times P_j\right) \times \frac{f-l}{f} \qquad (6)$$

where A_{jtlk} is the predicted soil loss at pixel j at year l after fire-year t at burn severity k without fuels treatments. Given that the effects of wildfire on soil loss can last for years, l is the year showing the effect of wildfire on increasing soil loss following year t, with f in total. A_{jtlk} was estimated by the Revised Universal Soil Loss Equation (RUSLE), where R_j is the rainfall/runoff erosivity factor at pixel j, K_{ktj} is the soil erodibility factor at pixel j, which varies at different burn severity k at different year t. The adjustment of the soil erodibility factor follows Terranova et al. (2009), multiplying the original data by 2, 1.8 and 1.6 according to the high, medium and low severity, respectively. LS_j is the slope length and steepness factor at pixel j. C_{ktj} is the cover factor at pixel j, year t, under burn severity k, which was estimated from the normalized difference vegetation index (NDVI) referring to Ayalew et al. (2020). We examined the NDVI values by extracting and calculating the mean NDVI the first year after a wildfire using associated polygons of wildfires in each burn severity from historical wildfires across the Sierra Nevada and thus determined C_{ktj}. We also examined how long on average it takes for the cover factor to recover to the pre-disturbance level by using polygons of wildfires from 2003 to 2008 to extract the NDVI values in the following years from time-series NDVI data, and regard this period as f, namely the total period during which wildfire increases soil loss. P_j refers to support practice factor, we assumed it to be 1 in this analysis. As for $\hat{A}_{jtlk}$, the corresponding soil loss after treatment, its difference from A_{jtlk} arises from the condition that the fuels treatments are expected to alter the predicted burn severity during the period we analyzed, and thus the corresponding $\widehat{K}_{ktj}$ and $\hat{C}_{ktj}$. The original data of R, K, LS were acquired from the State Water Resources Control Board (www.waterboards.ca.gov), and the annual NDVI time-series data were generated with reference to Roche et al., (2018).

W_j refers to whether a pixel j is subject to the erosion-regulation benefits. We considered the area where the sediment will accumulate in a reservoir that supplies water to at least one major hydroelectric powerhouse. To do this, we selected all major powerhouses (with capacity over 30 MW) within California and mapped the reservoirs that supply each using the 'watershed' function of ArcGIS Pro 2.9.3 to determine the contributing area of each reservoir. The list of hydroelectric powerhouses was obtained from California Energy Commission (https://www.energy.ca.gov).

SDR_j is the sediment delivery ratio and is derived from slope, following the equation $SDR = 0.627\ slope^{0.403}$ (J. R. Williams & Berndt, 1972). The slope is in percent rise generated from the digital elevation model and was obtained from the Natural Climate Solutions Data Atlas.

Cv refers to a ratio of converting weight to volume of sediment, which is 1.13 m^3/ton based on the research conducted by Snyder et al., (2004) on the sediment properties of Yuba River. Cd is the cost for dredging sediment, with reference to Denver Water's cost of dredging Strontia Springs Reservoir following the Buffalo Creek and Hayman fires, which was \$120/m^3 adjusted for inflation (Jones et al., 2017). To consider the uncertainty of this price, we used a range of \$55-\$179/m^3 (QEA, 2020) for high and low values.

3.2.6 Air-quality regulation

The benefits of fuels treatments on air-quality regulation were calculated from the avoided health costs related to air pollution exposure caused by wildfires with versus without treatment:

$$Benefit_{air} = \sum_{h=1}^{m}\sum_{t=1}^{x} Y_{0h}\left(1 - e^{-\beta_h \Delta PM_t}\right) \times Pop \times Ch_h \times \frac{(1+inf)^t}{(1+r)^t} \tag{7}$$

where h refers to the h_{th} health impact, and m is the total kinds of health impacts we considered. In this study we considered two impacts, namely hospital admission of all respiratory illness and hospital admission of all cardiovascular illness.

$Y_{0h}\left(1 - e^{-\beta_h \Delta PM_t}\right) \times Pop$, as part of this equation, is often referred to as the health impact function or the concentration-response function. ΔPM_t is the expected change of air quality ($PM_{2.5}$) from fire mitigation in year t after fuels treatments; β_h is a parameter that estimates the incidence change of h_{th} health impact of a unit change in ambient air pollution; Pop is the number of people affected by the air pollution reduction; Y_{0h} is the health incidence rate of h_{th} health impact, an estimate of the average number of people who suffer from some adverse health impact in a given population over a given period of time. Ch_h is the monetized value of the incidence change of the h_{th} health impact for a given year (See Table S2.3, Table S2.4).

This analysis was performed by BenMAP-CE (version 1.5.8.17), open-source software developed by the US Environmental Protection Agency that is widely used in measuring the economic health cost of wildfires (D. Wang et al., 2021). Y_{0h}, β_h, Pop and Ch_h are embedded in BenMAP-CE. ΔPM_t reflects the extent to which fuels treatments can reduce the concentration of $PM_{2.5}$ attributed to wildfire. To determine ΔPM_t, we first estimated the difference in annual $PM_{2.5}$ emissions due to wildfires between the treated and untreated situation, following the methods proposed by Xu et al., (2022). Emissions were calculated as a function of area burned, fuel loading, the fraction of vegetation burned based on burn severity, and an emissions factor specific to each vegetation type:

$$\Delta E_t = \sum_{k=1}^{3}\sum_{j=1}^{n}\sum_{v=1}^{5} V_{jv} \times \left(S_{jtk} \times F_{tv} - \widehat{S_{jtk}} \times \widehat{F_{tv}}\right) \times cr_{vk} \times ef_v \tag{8}$$

where ΔE_t is the difference of the annual mass of $PM_{2.5}$ emissions between treated and untreated cases. V_{jv} is whether pixel j is subject to vegetation type v, and five types in total were included in this study, namely grass, shrub, forest < 5500 ft, forest 5500-7500 ft and forest > 7500 ft. F_{tv} is the fuel loading of vegetation class v at year t without treatment, and $\widehat{F_{tv}}$ is the corresponding value with treatment. cr_{vk} is fuel consumption rate of vegetation type v under severity class k, and ef_v is the emission factor of emission for vegetation v. The vegetation-type data were obtained from the LANDFIRE program. F_{tv}, cr_{vk} and ef_v were obtained from Xu et al., (2022), and $\widehat{F_{tv}}$ was adjusted based on F_{tv} with its fuel load reduced after a moderate wildfire as a proxy of treatment.

After determining the difference in total annual $PM_{2.5}$ emission, we made assumptions to allocate the emission to estimate the annual change of $PM_{2.5}$ concentration. We assumed vertically, emissions decrease with height up to 2 km as the upper limit of the distribution, referring to Chen et al., (2022). They studied the vertical distribution of $PM_{2.5}$ in northern China and found that concentration decreases with height and when altitude reached 2 km, the correlation coefficient between aerosol optical depth and $PM_{2.5}$ decreased to zero. Horizontally, referring to buffer zones created by studies examining the effects of wildfire on $PM_{2.5}$ (Moeltner et al., 2013, Aguilera et al., 2021), we assumed a 200-mile (322-km) radius region centered on the study area, within which the distribution of $PM_{2.5}$ decreases linearly with distance from the center. Thus, we can convert the ΔE_t to ΔPM_t and calculate the benefits of air-quality improvement using BenMAP-CE.

3.3 Results

3.3.1 Effects of fuels treatments on wildfire

After the evaluation of how low- and moderate-severity wildfire, as a proxy for fuels treatments, impacted the wildfire predictions, we found that they are projected to reduce the predicted burn probability and flame length by 81% and 71% on average, respectively, in the first year after the treatment based on examining over 0.8 million pixels (Figure 3.2a).

Above about 1 m, the probability of high-severity wildfire increases with predicted flame length and that for low-severity wildfire decreases (Figure 3.2b). Moderate-severity wildfire probability is about the same as for low severity. Below 1-m flame length, the probability of low-severity wildfire is higher and that for medium and high severity is lower. At 0.3 m it is 0.46±0.01 (±95% CI) for low severity, 0.29±0.01 for high severity and 0.25±0.01 for moderate severity. Uncertainty in the probability of low and moderate severity wildfire increases with predicted flame length, especially after 20 m, owing to few data, i.e., limited occurrence.

We used the 10 years following forest disturbance as the benefit period, during which predicted flame length returned to pre-disturbance levels, based on observing the time-series data normalizing fire-occurrence year and predicted flame length (Figure 3.2c). The annual predicted burn probability was thus developed from mapped flame length (burn severity) data, namely $P_{jt}, S_{jtk}, \hat{P}_{jt}, \hat{S}_{jtk}$ in equation1, and spatial data generated (see Figure S3.3).

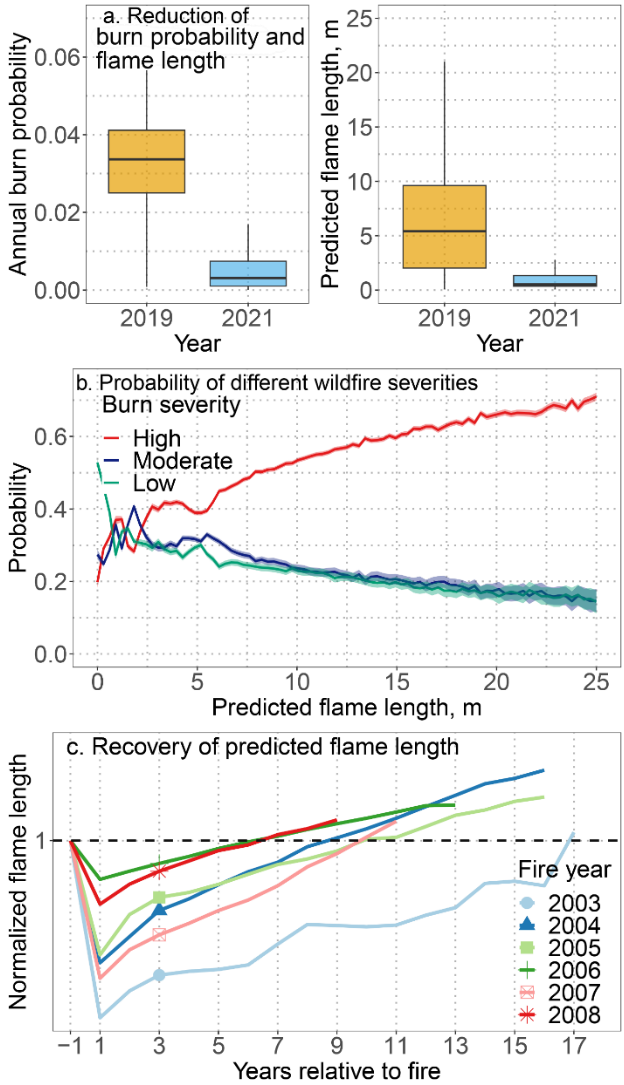

Figure 3.2. a) Reduction of wildfire prediction parameters, the annual burn probability and flame length. b) Probability of wildfires of different severity as a function of predicted flame length, based on historical data (shading shows 95% confidence intervals). c) Years required for the predicted flame length to return to pre-disturbance level given the wildfires occurring from 2003 to 2008 across the Sierra Nevada.

3.3.2 Valuation of project benefits

Landscape values used in calculating individual benefits for carbon storage, potential timber provisioning, erosion avoidance, and health for the two study areas, using equations 2-8, are shown on Figures 3.3-3.6, with valuation estimates on Figure 3.7.

The average net carbon losses in past wildfires in each severity (Cl_k, eq. 2) averaged 3.3 (±0.01), 2.0 (±0.01), and 0.7 (±0.01) kg/m^2 for high, moderate, and low severity, respectively (Figure 3.3a). The increase in dead carbon was about 60% of the loss in live carbon, across all three severities. Figure 3.3b shows the King Fire as an example to illustrate different burn severity, and changes in live carbon, dead carbon, and net carbon stock due to wildfires. The current (2021) mean carbon stock of the two project areas is 18 kg/m^2 for North Yuba and 19 kg/m^2 for French Meadows (Figure 3.3c). Using equation 2, we derived the carbon-storage benefits for fuels treatments for the two projects, with mean values of \$1.26 million for North Yuba and \$2.52 million for French Meadows in total, equivalent to \$544/ha (low/high values of \$128/\$1171, Table S3.1) and \$880/ha (\$208/1893), respectively (Figure 3.7a). These values represent the benefit, or change in expected value of carbon storage, from lowering projected wildfire severity.

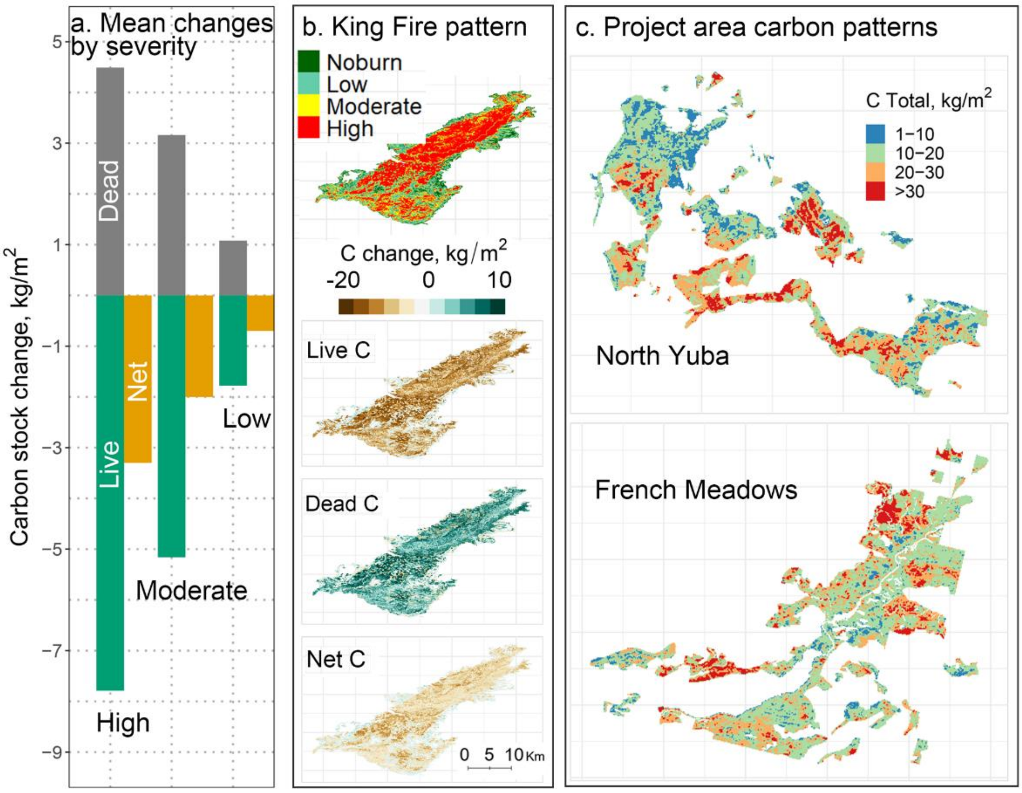

Figure 3.3. Carbon stock and its change after different severity of wildfire: a) changes in live (losses), dead (gains) and net carbon stocks, averaged across all 27 fires analyzed; b) changes due to King Fire, as an example; and c) current (2021) carbon stock (live plus dead) for the two project areas. See Figure S3.4 for all fires analyzed.

For timber provisioning, the average DBH (Db_j), stand height (Sh_j), and tree density (Ds_j) are 50 cm, 14 m, and 755 trees/ha for the North Yuba area, and 57 cm, 18 m and 682 trees/ha, for the French Meadow (Figure S3.5), resulting in respective potential lumber volumes before (V_j) treatment being 305 and 462 m^3/ha (Figure 3.4). After treatment the respective lumber volumes ($\widehat{V_j}$) are 117 and 204 m^3/ha. Using equation 3, we derived timber-provisioning benefits for the two projects, with mean values of \$3.82 million for North Yuba and \$12.54 million for French Meadows, equivalent to \$1651/ha and \$4384/ha. Respective 5/95% quantile values across pixels are \$1115/2716 and \$2960/7208 (Figure 3.7b).

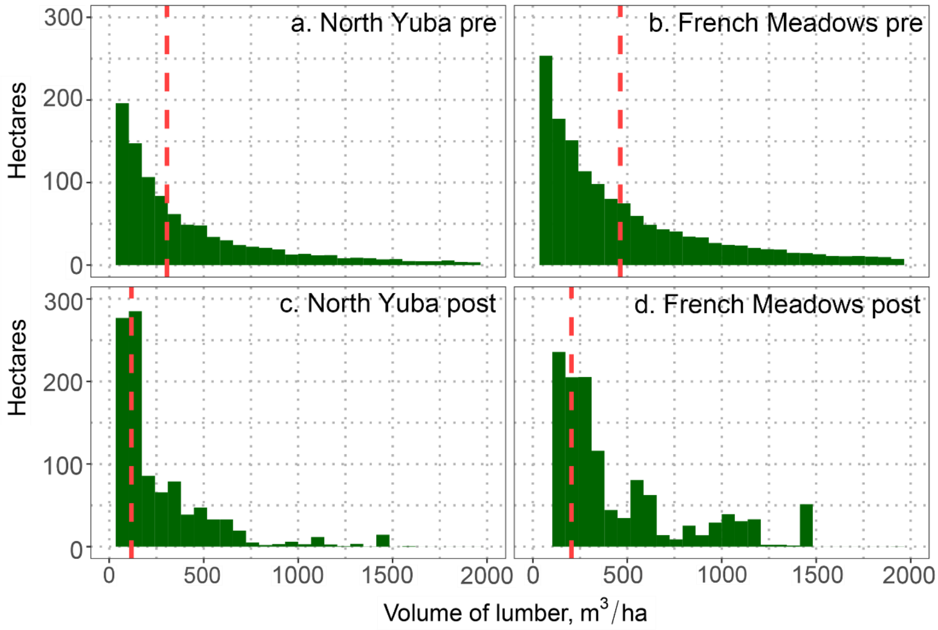

Figure 3.4. Volume of lumber before and after forest treatment for the two project areas, with the dash lines showing the mean values of lumber volume. See Figure S5 for other parameters of trees used in calculation.

For erosion regulation, the expected sediment avoided from the two project areas through fuels treatments during the period analyzed averaged 6.7 and 8.9 tons/ha for North Yuba area and French Meadows, respectively, with 86% being avoided within the first ten years after treatment (Figure 3.5). Mean NDVI values for areas burned at high, moderate, and low severity were 0.28, 0.36, and 0.46 one year after the wildfire, resulting in corresponding cover-factor values of 0.5, 0.3, and 0.2 (Figure S3.7). It took around 10 years for the NDVI to recover to the pre-disturbance level, so f, the total years that wildfire would contribute to increasing soil loss, was estimated to be 10 (Figure S3.7). Other variables used in calculating the soil loss (R, K, LS) are shown in Figure S3.8. W_j, whether a place is subject to erosion regulation benefits and SDR_j, the sediment delivery ratio, are shown in Figure S3.9. There are reservoirs operated by the Yuba Water and Placer County Water downstream of the two project areas, resulting in W_j of 1, and respective mean sediment-delivery rates of 0.13 and 0.12. Using equation 5, we derived the respective benefits of erosion regulation for the two projects, with mean values of $2.01 million and $3.47 for North Yuba and French Meadows in total, equivalent to $870/ha and $1213/ha. Respective low/high pixel values were estimated to be $435/1416 and $588/1920 (Figure 3.7c).

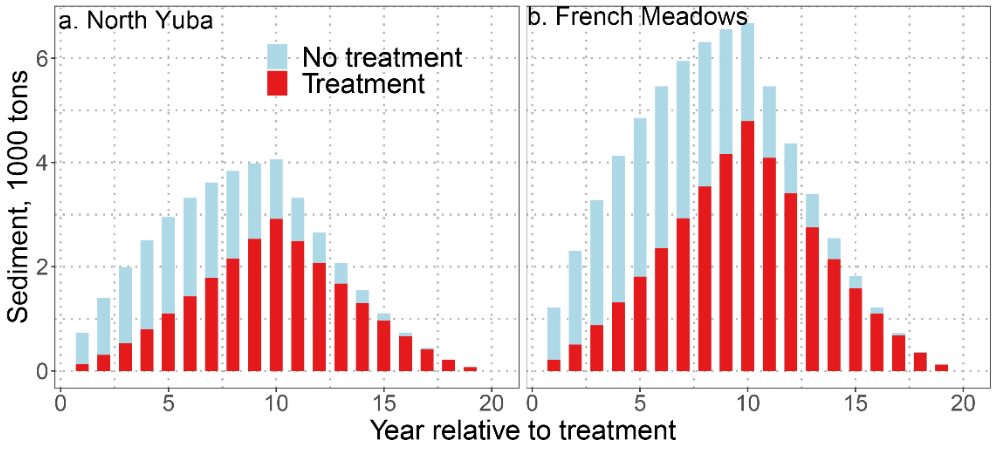

Figure 3.5. Expected differences of sediment due to wildfire between the treatment and no-treatment scenarios of each year. See Figure S3.7-S3.10 for the factors used in calculating the sediment delivery and the resulting map of the sediment avoided.

For air-quality regulation, the difference in expected mass of $PM_{2.5}$ emissions due to wildfire before and after treatment was 23.4 and 60.0 tons for North Yuba and French Meadows, respectively (Figure 3.6). Using equation 7 with BenMap-CE, we derived respective mean air-quality benefits of $1.04 million and $2.77, equivalent to $450/ha and $969/ha (Figure 3.7d). Respective low/high values, representing the uncertainty in health impact function and health cost, were $297/583 and $647/1255.

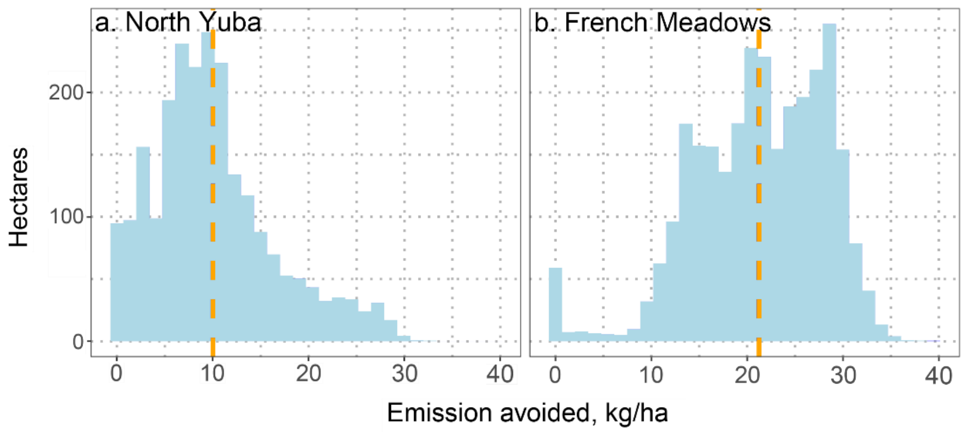

Figure 3.6. Histogram of $PM_{2.5}$ emissions from wildfire avoided through forest treatment across the two project areas during the benefit period. See Figure S3.11 for the PM2.5 emissions avoided across the two project.

The overall mean fire-related benefits up the sum of the four individual benefits, reach $3513/ha for North Yuba and $7445/ha for French Meadows, which exceed recent average costs of performing forest restoration in these two areas (Figure 3.8). Adding in previously estimated water-related benefits, hydropower generation and water sales, further increases the value proposition for fuels treatments.

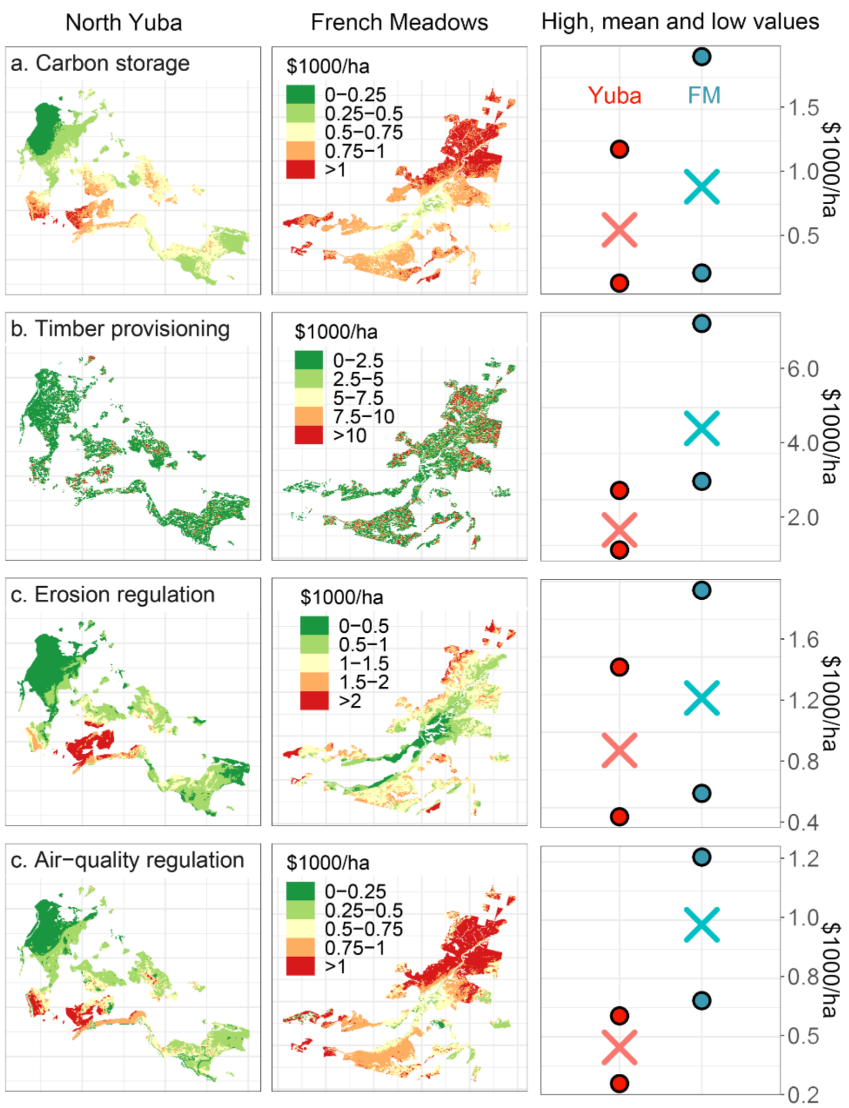

Figure 3.7. The spatially explicit benefits of the two project areas, with panel a showing the benefits of carbon storage, panel b showing the benefits of timber provisioning, panel c showing the benefits of erosion regulation and panel d showing the air quality regulation. Right side is the benefit per unit area of the project area, and the points represent the high and low values of the benefit while the cross represents the mean values.

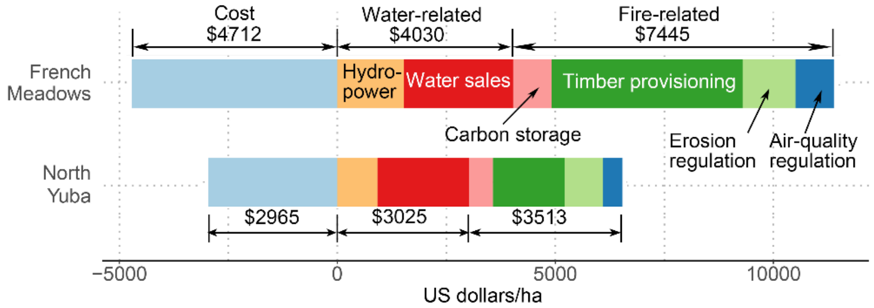

Figure 3.8. Aggregate benefits and costs of forest restoration for the two project areas. Water-related benefits adapted from Guo et al., 2023.

3.3.3 Scaling of benefits

Using values developed for the North Yuba and French Meadows projects, we examine potential benefits of fuels treatments across the 10.9-million-ha Sierra Nevada (Figure 3.9). Over 85% of the land has the potential for fuels treatment to enhance potential carbon storage through reducing expected wildfire severity (over $50/ha), with 67% of the land in the high-benefit category (over $250/ha). For timber provisioning, 36% of the Sierra Nevada region would benefit from fuels treatments, with 25% in the high-benefit category. Respective values are similar for erosion regulation, 35% and 25%, and higher for air-quality regulation, 64% and 40%. Although the land area with benefits for timber provisioning and erosion regulation is smaller than that of carbon storage and air-quality regulation, the mean benefits per unit area within the benefit area are larger, with $2126/ha and $1731/ha versus $834/ha and $696/ha. If we overlay the four benefit-maps for the overall benefits, 48% of the land in the Sierra Nevada has potential benefits over $1000/ha, while the mean benefit per unit area for these areas is $4909/ha.

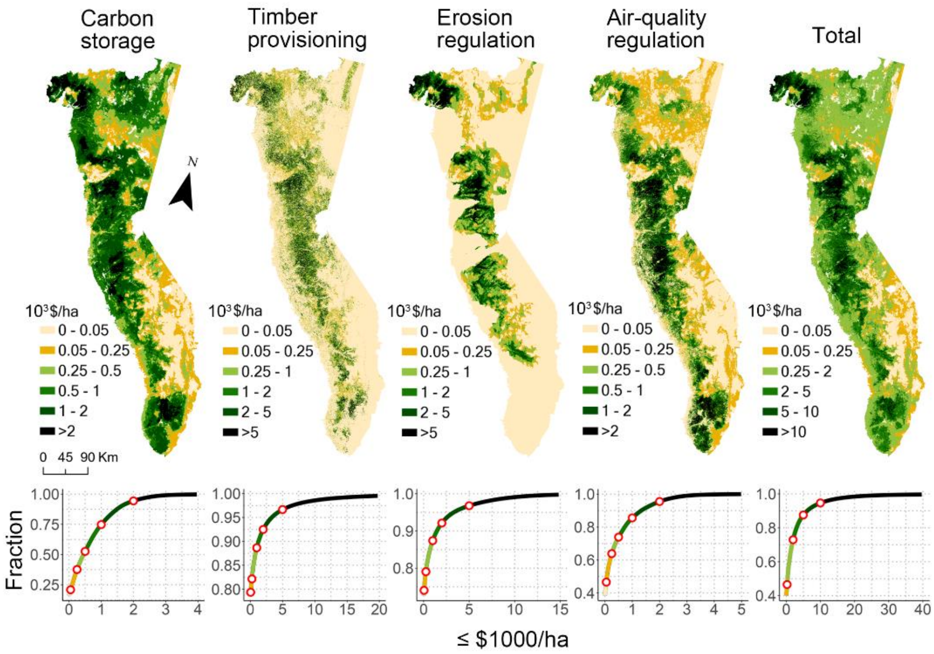

Figure 3.9. Aggregate benefits across the Sierra Nevada, and the cumulative histogram of benefits per hectare, with the open circles representing the thresholds for different levels of benefit.

3.4 Discussion

3.4.1 Benefits and implication

Benefits per unit area, and thus for any specific fuels-treatment project that is proposed, depend on location, surroundings, and the natural characteristics of the project area. In particular, benefits depend both on projected wildfire occurrence and on characteristics affecting the apparent value of each ecosystem service. In our mapping of four co-benefits across the Sierra Nevada, 32% of cumulative benefits are above $2000/ha and 23% above $3000/ha, with 13% above $5000/ha. These numbers reflect the potential of co-benefits, when monetized, in contributing to the costs of fuels treatments for forest restoration. In addition, removing trees makes more water available for downstream hydropower generation and water supply, and the. water-related benefits could reach additional several thousand dollars per hectare if the project area is strategically planned. Thus, while the protection of built infrastructure remains a primary driver for investments in reducing wildfire severity in California (Eriksson et al., 2022), co-benefits are central to bridging the huge funding gap between the urgent need to increase the pace and scale of forest restoration, and the public funds available to meet that need.

Comparing the benefits of the two prototype projects as examples, the overall benefit for French Meadows is greater than that of the North Yuba Project, as well as for each ecosystem service. The mean burn probability of the North Yuba area is 0.0095 and the mean predicted flame length is 1.9 m, while respective values for the French Meadows Project are 0.015 and 4.5 m. This means that on average, fire is predicted to have a higher chance of occurring and with a higher severity across French Meadows than over the North Yuba area. For carbon storage, the difference in fire predictions leads directly to a higher benefit of carbon storage per hectare for French Meadows than that of North Yuba, with a mean of $336/ha, given that the carbon loss is coupled with wildfire severity. While for timber provisioning, this difference is magnified by the trees within the French Meadows Project area being taller and thicker, resulting in more lumber volume available and potentially more benefits. The mean DBH is 7 cm more and the stand height is 4 m more in French Meadow versus North Yuba. One caveat is that the benefit to timber provisioning represents the available timber and does not reflect planned or proposed harvesting. For erosion regulation, the annual soil loss per hectare first year post wildfire for French Meadows is projected to be 14.8 tons/ha or 7% greater than that of North Yuba. Although the mean sediment-delivery ratio for the French Meadows area is lower by 0.012, considering the greater burn probability of the area, the mean benefit is higher in French Meadows compared to North Yuba, with a value of $343/ha. For air quality, the mean emission avoided per hectare for North Yuba is 10 kg/ha, versus 23 kg/ha for French Meadows. In addition to the avoided emissions, the higher benefit of air regulation for the French Meadows area reflects larger the population and higher baseline incidence rate, leading to greater benefits.

In addition to the several ecosystem services mentioned in this study, recreation and provision of habitat are vulnerable to catastrophic wildfires (McMorrow et al., 2008, Bawa, 2017). Recreation in the Sierra Nevada provides diverse experiences, psychosocial value, and public-health benefits to people (Halofsky et al., 2021). Nyelele et al. (2023) estimated that the travel costs, as a proxy of the value of recreational ecosystem services, could reach $1.35 to $1.84 billion per year in the Tahoe Central Sierra Initiative project area, a 9700 km^2 area across the junction of the

North and Central Sierra Nevada. That represents an average recreational benefit of $1400-1900/ha, representing a wide range intensity of recreational use. Moreover, the provision of habitat is key to providing living spaces for plants or animals and maintaining a diversity of those that can support multiple ecosystem services that benefit human well-being (Brockerhoff et al., 2017). Wildfires and other disturbances will disrupt the structure and composition of forests and compromise the recreational ecosystem services, and those disturbances were estimated to generate a $93 million annual loss in recreational services from 2005 to 2016 in U.S. national forests (Sánchez et al., 2021). Also, Stephens et al. (2016) found that over 80,000 ha of California spotted owls potential nesting habitat was burned by wildfire during 2000 to 2014, as an illustration that fires damage habitats. Therefore, reducing the risk of wildfire would also benefit these two ecosystem services in terms of avoiding the associated damage.

Monetizing co-benefits of fuels treatments can be challenging given the often-siloed nature of resource management. Poor alignment across levels and sectors of government, environmental and social heterogeneity and lack of enabling conditions and implementation capacity are major challenges facing forest restoration (Chazdon et al., 2021, Potts, 2020). Overcoming barriers to cooperation can be done through partnerships such as were formed for the French Meadows (Edelson & Hertslet, 2019) and North Yuba (Quesnel Seipp et al., 2023) projects, partnerships that bring together multiple interests who recognize the power of integrating resource-management objectives. These partnerships can also help overcome some of the constraints in the planning and selection of forest-restoration projects, such as the accessibility of machinery and labor, limited resources for implementation, and the preference for specific communities and regions (Lydersen et al., 2019, Jones et al., 2017).

Aiming to overcome the historical funding and other resource limits to increasing the pace and scale of forest restoration, Quesnel Seipp et al. (2023) outlined the sort of innovative cooperation mechanism that enables private-public partnerships and cost-sharing opportunities. The public-private partnership enables private capital to finance much-needed fuels treatments, and beneficiaries of forest restoration make cost-share and projected-benefit payments over time to provide investors with competitive returns based on a project's expected outcomes. It should be emphasized that benefits are projected based on best-available science, and given the variability of climate as well as markets, the return over any multi-year period may be more or less than projected. Quantified economic benefits arising from avoided wildfire risk, as shown in this study, demonstrate direct benefits to the public as well as property-rights holders, and justify their investment with projected net benefits over a ten-year period, which has the potential to strengthen cooperation through partnerships and facilitate the implementation of restoration projects. The methods and maps we developed in the current analyses enable extracting the potential economic benefits under any given spatial polygon, thus providing comparisons of proposed projects in the planning phase. In addition, with spatial-optimization tools, we can find the area with the highest benefits under given constraints, and thus further supporting the decision making of such projects. That is, the analyses developed here are an essential step in the overall adaptive-management cycle.

The direct beneficiaries of the four ecosystem-service benefits assessed in this study include the people of California and downwind areas (air quality), carbon-credit developers, wood-products companies (timber provision), infrastructure owners such as counties, the state, and water agencies (erosion regulation), and the U.S. Forest Service, who is the land manager. Benefits also help the California Department of Forestry and Fire Protection, Air Resources Board, and other state agencies to realize their legislatively mandated responsibilities for fire protection, protecting public health, providing habitat and biodiversity, providing water security, supporting underserved communities, and other public benefits.

Given that the Sierra Nevada stores over 420 million tons of carbon, provides over 75% of the drinking water for California, and is home to vulnerable communities where 440,000 people belong to systemically underserved populations, including people of color, the disabled community, indigenous people, and people living in poverty (Kocher & Beckwitt, 2012, Sierra Business Council, 2022), it is essential to restore the sustainability of forests in the Sierra Nevada by increasing the pace and scale of forest restoration. The restoration can help achieve: 1) carbon-neutrality goals, by avoiding emissions from wildfire and channeling carbon into large fire-resistant trees, 2) increased job opportunities, through implementing management activities that provide related services such as sawmills, biomass energy production, and transportation, and 3) improvement of the well-being of local communities by enhancing economic prospects for their residents and reducing the risk of wildfires moving into communities (Mccann et al., 2020, Quesnel Seipp et al., 2023).

3.4.2 Assumptions and limitations

In terms of the effect of forest treatment on lowering the burn probability, we only considered this effect within the treatment area. However, this effect may extend beyond the treated area (A. A. Ager et al., 2010; Chiono et al., 2017), given that treatment will slow or stop the spread of wildfire. Thus, the benefits from wildfire mitigation we analyzed in this study provide a conservative estimate. In addition, we used a percentage of reduction to represent this effect, and when we applied a sensitivity analysis around these two percentages, which are 81% for burn probability and 71% for predicted flame length, it showed that the benefits are much more sensitive to burn probability than the flame length. When we increase and decrease the reduction of burn probability by 10%, namely 91% and 71%, while keeping the reduction of predicted flame length unchanged, the overall benefits increased and decreased by 4.4% and 5% respectively. On the contrary, if we increase and decrease the percentage of reduction of predicted flame length by 10%, the overall benefits increased and decreased by 0.4% and 0.2%. Therefore, a more-accurate simulation of fire behavior and treatment effects, especially the prediction of burn probability, is key to the estimation of fire risk. In addition, we examined the sensitivity of discount rate, and when the discount rate was set to 0% instead of 3% used originally, the overall benefits increased by 14%. This implies that a lower discount rate leads to higher benefits, and the choice of discount rate should be treated cautiously as it will have a significant impact on the overall benefits.

During the treatment process, a portion of the carbon stock is expected to be removed through tree harvesting and dead biomass removal. We assumed the mean value of consumption of live carbon due to moderate- and low-severity wildfires as a proxy for the effect of tree harvesting on carbon stock, which is estimated to be 3.5 kg/m^2, similar to the value of 3.4 kg/m^2 estimated by Chung, et al. (2023, review) for carbon removed by commercial thinning. For the dead biomass, we assumed half of the dead biomass, primarily coarse and fine woody detritus, will be removed through treatment, and used the aforementioned scaling factor to estimate the carbon mass. It is estimated that the mean carbon removed through treatment for the two project areas could reach 6 kg/m^2, of which 2.5 kg/m^2 comes from dead-carbon removal. The fate of wood and biomass removed from forest treatment depends on how they will be utilized and was not included in this study. Typically, large trees that are harvested for wood products are not considered carbon emissions. Innovative use of wood residues such as hydrogen production with carbon capture and storage, glue-laminated timber, and oriented strand board can minimize the carbon emissions of the small trees and residues (Cabiyo et al., 2021).

3.5 Conclusions

This study valued the benefits of forest restoration aimed at enhancing fire regulation, showing that together the sum of four fire-related co-benefits can exceed several thousand dollars per hectare, with a net present value that is greater than the cost of implementing the fuels treatments. Second, the benefits vary spatially based on the location, surroundings, and the attributes where the restoration is implemented, and are highly related to the likelihood and severity of potential wildfire. If projects are strategically planned, the benefits can be several times the average historical costs of restoration treatments. We also demonstrated that by using our state-of-the-science data and tools with locally relevant parameters for valuing benefits across a region, in this case the Sierra Nevada, multi-benefit data can help inform planning and evaluating on-the-ground forest-restoration projects, and later verifying outcomes. They can assist multi-benefit partnerships in developing the value proposition needed to bring about investments in fuels treatments, and to develop means to monetize the benefits. Our analysis thus emphasizes the importance of timely, credible, and salient spatial data, and demonstrates a scalable pathway for valuation of the ecosystem-service benefits of management actions.

Chapter 4: Evaluating and optimizing forest restoration for healthier and more resilient forests

4.1 Introduction

Forests provide wide range of ecosystem services that are essential to humans' continued existence and wellbeing (Taye et al., 2021). The Sierra Nevada accounts for approximately 25% of California's total land area and are 62% forested (North et al., 2017). The ecosystem services provided by the forests of the Sierra Nevada encompass the full spectrum of provisioning, regulating and cultural services, that range from tangible direct uses such as the timber provisioning, to indirect tangible uses such as air-quality and erosion regulation, and intangible services, such as cultural and spiritual wellbeing.

Disturbances, such as wildfires, are an integral part of forest ecosystem dynamics while climate change is altering the extent, frequency and intensity of these disturbances (Lecina-Diaz et al., 2021). Wildfires can consume large amounts of biomass, alter soil properties, substantially impact key ecosystem processes, influencing hydrological and biochemical cycles, and are often considered has negative impacts on ecosystem services of forest land (Roces-Díaz et al., 2022). These negative impacts include increased soil erosion (Cole et al., 2020) (East et al., 2021, Jumps et al., 2022), loss of soil functioning (Raiesi & Pejman, 2021), food provisioning (Taboada et al., 2021) and recreation opportunities (Gellman et al., 2022). Although there are many studies on the impact of fire on ecosystem services, these findings mostly come from analysis of specific wildfires or experiments. The drivers of wildfire occurrence include climate, landscape and human (Lan et al., 2021), and these factors determine the location, size and severity of wildfires. For California’s Sierra Nevada, with a large increase in wildfire activities over recent decades, climate factors such as vapor pressure deficit and burning index dominate the fire probability in higher elevation forest, while population density was comparatively more important in the lower elevation forest regions. As wildfires are widely distributed in space, evaluating the impact of wildfires with different burning severities on ecosystem services at larger temporal and spatial scales will help to understand the impact of wildfire more comprehensively on ecosystem services.

To protect the forests ecosystem services from catastrophic wildfires, forest restoration, which refers to forest thinning, prescribed burning, and other management activities, has been recognized as an effective way to mitigate the wildfire risk. Understanding the relationships among ecosystem services can facilitate efficiently managing multiple ecosystem services and integrating them into landscape management, decision-making and policy development (Schirpke et al., 2019). Knowledge of the relationship among ecosystem services and attributes of forests could provide not only how each ecosystem services interacts with each other, but also the insight into the foundations of how forests support ecosystem services. The synergy between two ecosystem services indicates both services either increase or decrease simultaneously, while the tradeoff is the opposite (Zhang et al., 2020). Furthermore, the relationship between the tree biomass and flame length partially reveals how the accumulation of biomass impacts the risk of wildfire, and the correlations between the tree biomass and evapotranspiration reveals how changes of tree biomass can impact the ability of forests to provide water.

Many studies analyzed the effects of forest restoration (Salis et al., 2016)(Vaillant et al., 2009). On the one hand, these analysis focused on its effects only on fire behavior, on the other hand, only a handful studies assessed the effects in spatial and temporal contexts and incorporated them into the optimization framework (Chung, 2015). Forest restoration, while mitigating the severity of wildfires, will also generate other co-benefits simultaneously (Eriksson et al., 2022). Monetizing these benefits provides a quantitative indicator that can be used to value the benefits of restoration project, thus promoting the financing and implementation of such projects. Guo et al., (2023) and Guo et al., (2024, paper in preparation) presented the methods to monetize the benefits from six ecosystem services enhanced by forest restoration, using two projects in the Sierra Nevada for demonstration. Scaling these approaches to the Sierra Nevada has the potential to quantitatively guide forest restoration to a larger spatial scale.

To bridge the aforementioned research gaps, this study focuses on research questions as following: 1) across the Sierra Nevada, to what extent did the historical wildfires alter these ecosystem services provided by the forests, 2) what are the synergies and tradeoffs among ecosystem services and major characteristics of the forests, and 3) how could the implementation of forest restoration be evaluated and optimized to maximize its ecological benefits in mitigating the risk of wildfire and droughts?

4.2 Materials and Methods

4.2.1 Study area

The Sierra Nevada is a mountain range in the Western United States, with vast majority of the range lies in the state of California and an area over 100,000 km^2. From West to East, the Sierra Nevada's elevation increases gradually from 150 m to more than 4,300 m. The major trees species across the Sierra include Douglas-fir, ponderosa pine, lodgepole pine, western hemlock, grand fir, western juniper, Jeffrey pine, canyon live oak (lemma.forestry.oregonstate.edu). The 30-year average annual precipitation (1991-2020) values range from 110 mm to 3015 mm, derived from the Parameter elevation Regression on Independent Slopes Model (PRISM). The Sierra Nevada stores nearly half of the forest carbon stocks and provides over 60% of the drinking water of California (https://wildfiretaskforce.org, Rhoades et al., 2018). We divide the Sierra Nevada region into six sub-regions for analysis, defined by Sierra Nevada Conservancy (https://gis.data.ca.gov), namely North Sierra, Central North Sierra, Central Sierra, South Central Sierra, South Sierra and East Sierra (Figure 4.1).

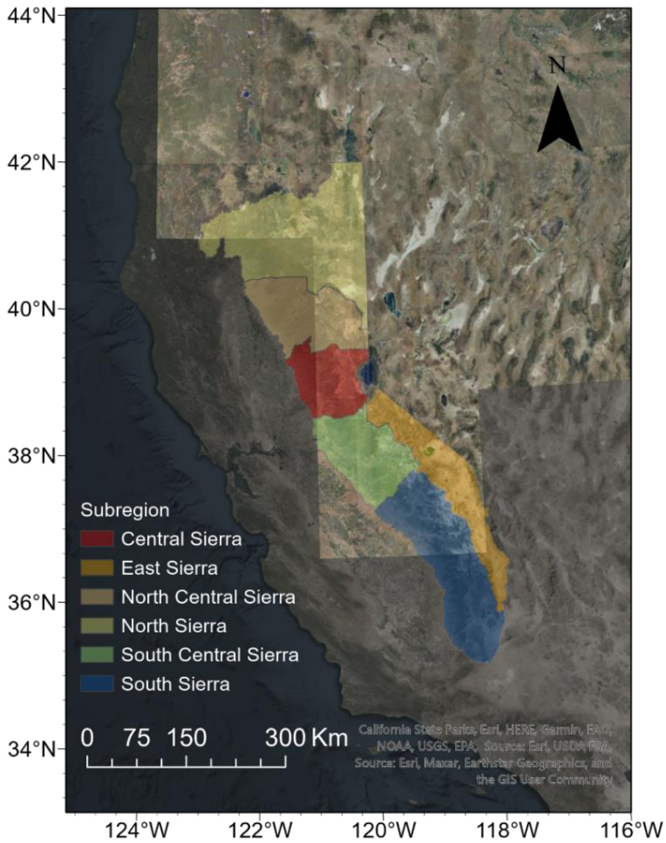

Figure 4.1. The map of Sierra Nevada and the subregions

4.2.2 Historical wildfires and their impacts on ecosystem services

We collected the data of historical wildfires across the Sierra Nevada from 2000 to 2021 from Monitoring Trends in Burn Severity (MTBS) program, which provides 30-m resolution fire occurrence data with distinguished burn severity labeled as high, moderate and low. We aggregated the total area burned at each severity each year and within six sub-regions.

We examined the impact of wildfires on five ecosystem services, namely carbon storage, timber provisioning, erosion regulation, hydropower and water supply. The impact here is defined as the difference in annual ecosystem services in the year before and the first year after a wildfire within the area where the wildfire occurred, assuming these changes are caused by wildfire completely. In addition to erosion regulation, these estimates were conducted by extracting time-series ecosystem services data layers using aforementioned wildfire polygons. The change of erosion-regulation (ton/ha) was examined following the methods proposed by Guo et.al., (2023 paper in preparation). Regarding the time-series ecosystem services data layers across the Sierra Nevada, carbon storage (kg/m^2) were derived from the Natural Climate Solutions Data Atlas, which considered both total live and dead biomass (J. A. Wang et al., 2022). Timber provisioning (million m^3/ha) were estimated following Guo et.al., (2023 paper in preparation) with the time-series forest attributes data, including diameter at the breast height (DBH), stand height and tree density acquired from the LEMMA team.

The estimation of hydropower (MWh/ha) and water supply (million m^3/ha) were adapted and extended from the analysis done by Guo et al., (2023). The time-series water yield data across the Sierra Nevada were derived from the Natural Climate Solutions Data Atlas (M. Goulden et al., 2022). Hydropower, as an ecosystem service, here refers to the potential hydropower generation from the water yield on a landscape, while water supply refers to the water yield on a landscape that could be utilized by water rights holders that supply water to downstream users. For the sake of feasibility, we excluded water rights (power, domestic, irrigation, industrial or municipal) with limited face amount (<100000 af/yr), and obtained the names of the remaining water rights holders, coordinates of the diversion points and the reservoirs associated with them. We used the 'whitebox' package in R to delineate the watersheds that supply water to certain reservoirs and assigned the holders' names to the watersheds. The potential hydropower generation was calculated as $e=mgh\eta=\rho vgh\eta$, where ρ is density of water, g is the gravitational acceleration, h is the hydraulic head of the powerhouse, v is the volume of the water yield and η the efficiency of the power system.

4.2.3 Synergies and tradeoffs

To examine the synergies and tradeoffs among ecosystem services and other attributes of the forests, we used Spearman's rank correlation coefficients to measure the relationship between different pairs of mean values of ecosystem services and attributes at watersheds level, given that the Kolmogorov-Smirnov test indicated that not all data were subject to a normal distribution. The watersheds level refers to 1445 huc12 watersheds within the Sierra Nevada. We used the layers of the five ecosystem services aforementioned and attributes such as tree biomass (kg/m^2), evapotranspiration (ET) and predicted flame length (m). Significantly correlated ($p < 0.01$) pairs were regarded as trade-offs or synergies, respectively, whereas non-significant correlations indicated no or very weak interactions.

4.2.4 Evaluating and optimizing forest restoration

Monetizing the benefits of forest restoration on multiple ecosystem services provides a single metrics for evaluating or prioritizing restoration projects. Using the four benefit-maps (30-m resolution) across the Sierra Nevada generated by Guo et.al., (2024 paper in preparation), as well as the benefit-map for hydropower and water supply adapted and extended from (Guo et al., 2023), we evaluated the monetized benefits of a proposed forest restoration project, namely the Trapper Project. The Trapper Project is in the Upper Yuba watershed with an area of over 12,000 ha. We clipped the six benefit-layers using the polygon of the Trapper project with 'Raster' package in R to extract their values at pixel and project level.

The optimizing of forest restoration projects refers to finding the project area with the greatest benefits based on preferred weights on each benefit. This study demonstrated such a path in two steps. First, given the weights of benefits, we calculated the mean value of the aggregated six benefits of each huc12 watershed and ranked the 1445 watersheds by this value. We devised three scenarios, of which the weight between water-related benefits (hydropower, water supply) and fire-regulation-related benefits (carbon, timber, erosion, air-quality) being 1:0, 0:1 and 1:1. Second, we used ForSysX to generate practical restoration projects within a watershed by specifying number and area of possible projects. ForSysX is a spatially explicit model that uses multi-criteria prioritization and optimization created to rapidly design fuel treatment and restoration scenarios developed by USFS (Alan A. Ager et al., 2021).

4.3 Results

4.3.1 Historical wildfires and their impacts on ecosystem services

The total area burned over 2000 to 2021 across the Sierra Nevada reaches 22,920 km^2, with 5,273 km^2 (23%) in high severity, 7,327 km^2 (32%) in moderate severity, and 10,320 km^2 (45%) in low severity. Year 2021 witnessed the largest burned area (5970 km^2), followed by year 2020 (4117 km^2) and 2018 (1825 km^2), all occurring in the past five years. In terms of sub-region, nearly three-quarters of the area of wildfires occurred in these three areas, South Sierra (26%), North Central Sierra (25%) and North Sierra (23%) (Figure 4.2).

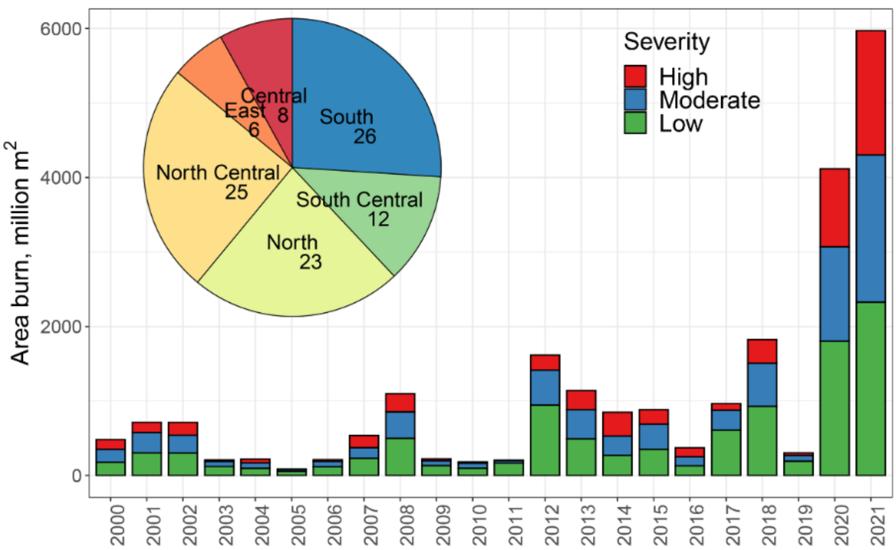

Figure 4.2. Historical wildfires across the Sierra Nevada and the proportion of each sub-region.

Wildfires had significant impacts historically on the five ecosystem services incorporated in this study. In terms of carbon storage, within areas where wildfires occur across the Sierra Nevada, wildfires consumed an average of 25% (by 357 g/m^2, 404,000 tons in total) of live carbon storage, of which 6% is due to high-severity wildfires, and 12% and 7% due to moderate and low-severity wildfires. From a sub-regional perspective, the Central Sierra has the highest value of mean carbon storage loss within the wildfire area at 558 g/m^2 (1,181 g/m^2 due to high-severity wildfire, same for the followings in the parentheses), while the East Sierra has the lowest value at 163 g/m^2 (451 g/m^2). The North Central Sierra has the highest value of annual total carbon storage loss at 110,000 tons (26,200 tons) while the East Sierra has the lowest value at

10,100 tons (2,200 tons) (Figure 4.3a).

For timber provisioning, in areas where wildfires occur, wildfires destroyed an average of 32% (by 52 m^3/ha, 5.9 million m^3 in total) of timber volume, of which 10% is due to high-severity wildfires, and 14% and 8% due to moderate and low-severity wildfires. From a sub-regional perspective, the Central Sierra has the highest value of mean timber volume loss within the wildfire area at 103 m^3/ha (218 m^3/ha), while the East Sierra has the lowest value at 7 m^3/ha (21 m^3/ha). The North Central Sierra has the highest value of total timber volume loss annually at 3.0 million m^3 (0.9 million m^3) while the East Sierra has the lowest value at 11,900 m^3 (5,730 m^3) (Figure 4.3b).

Wildfires increase the soil loss where wildfire occurred. It is estimated that historical wildfires will increase soil loss by 211% (by 55 tons/ha, 4.8 million tons in total) in the first year after a wildfire, with 61% coming from high-severity wildfires, 91% and 59% from moderate and low-severity wildfires. From a sub-regional perspective, the Central Sierra has the highest value of mean soil loss increase within the wildfire area at 85 tons/ha (382 tons/ha), while the North Central Sierra has the lowest value at 25 tons/ha (107 tons/ha). The North Central Sierra has the highest value of total increase of soil loss annually at 1.3 million tons (343,000 tons) while the East Sierra has the lowest value at 119,000 tons (35,000 tons) (Figure 4.3c).

For hydropower and water supply, wildfires enhanced these two ecosystem services due to reduction of water consumption by vegetation. The potential hydropower generation and water supply increased by 57% (by 0.7 MWh/ha, 80 GWh in total) and 60% (by 1878 m^3/ha, 182 million m^3 in total) within the wildfire area respectively, of which 14% and 15% were respectively due to high-severity wildfires. The Central Sierra provides the highest mean values of both increased potential hydropower generation and water supply within the wildfire area, at 1.5 MWh/ha (2.8 MWh/ha) and 2700 m^3/ha (5700 m^3/ha) respectively, while the East Sierra has the lowest values, at 0.2 MWh/ha (1.3 MWh/ha) and 700 m^3/ha (1700 m^3/ha). For the total value of increased power generation and water supply, the wildfire within the North Central Sierra provides additional 33 GWh (9.2 GWh) and 49.5 million m^3 (13.6 million m^3), while the East Sierra has the lowest values at 700 MWh (100 MWh) and 4.7 million m^3 (0.7 million m^3) respectively (Figure 4.3d and 4.3e).

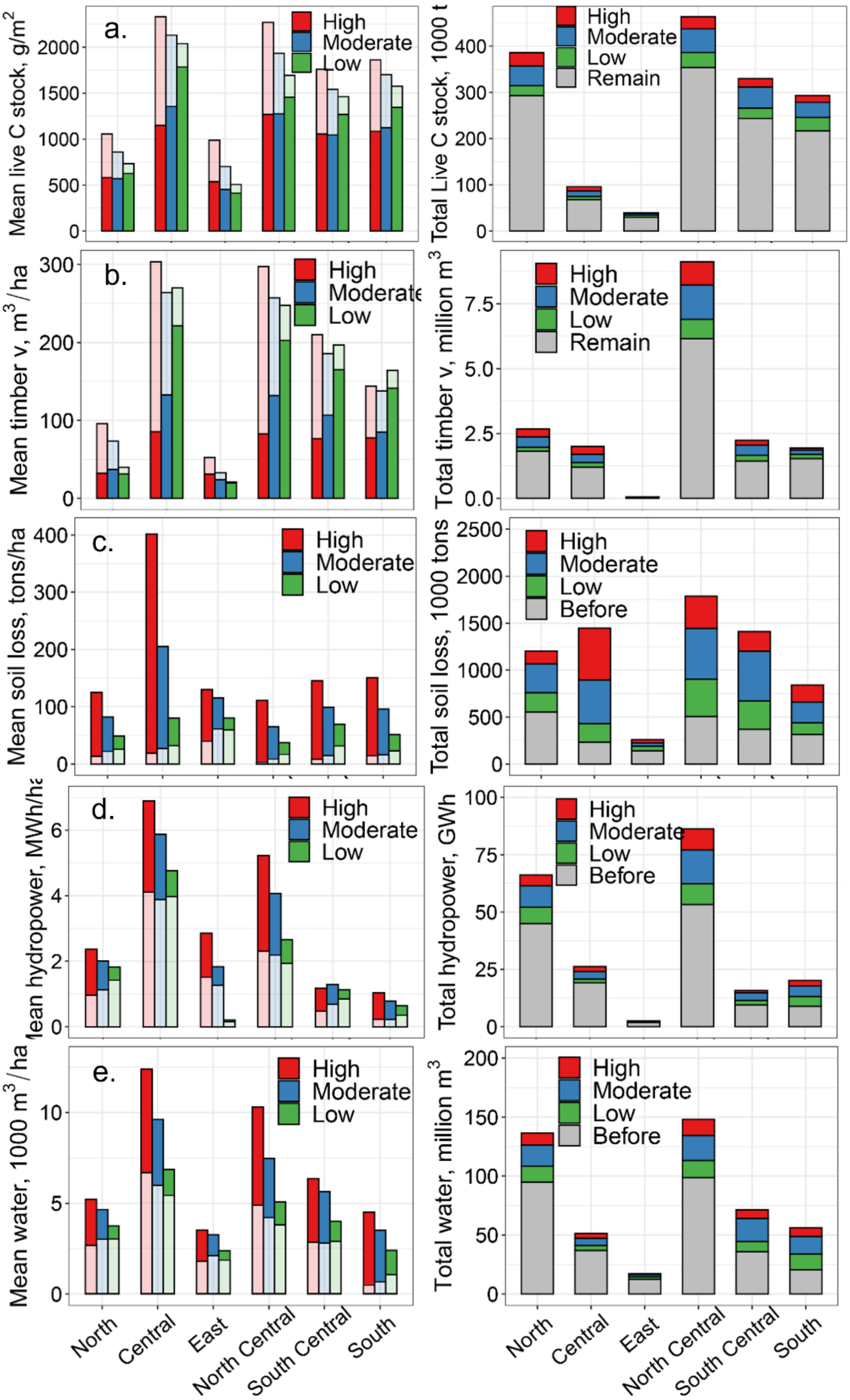

Figure 4.3. The impacts of historical wildfires on five ecosystem services within the area of wildfires at each subregion, with the left panels showing the mean change of ecosystem services at each severity per unit area, and the right panels showing the total change of ecosystem services at each severity.

4.3.2 Synergies and tradeoffs

The Spearman's rank correlation analysis reveals that synergy (coefficient > 0.85 and P value < 0.01) exists between tree biomass and multiple forest attributes and ecosystem services, such as evapotranspiration (ET), flame length, carbon storage and timber provisioning, which indicates that, on one hand, the accumulation of tree biomass sequesters more carbon and provides more timber, and on the other hand, it increases the risk of wildfire and drought. Hydropower also shows modest synergies with tree biomass and water supply (coefficient > 0.4 and P value < 0.01), and there are no strong tradeoffs exist between the variables we analyzed (Figure 4.4).

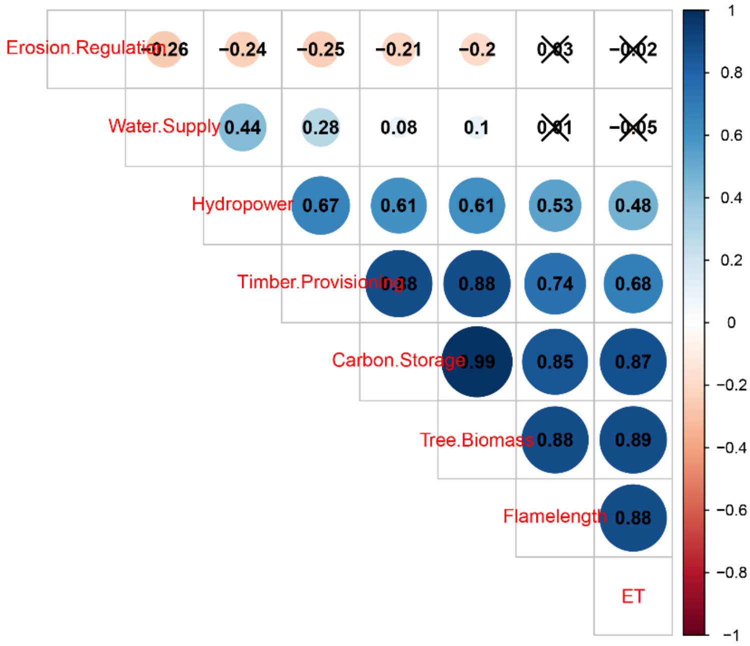

Figure 4.4. The Spearman's rank correlation coefficients of ecosystem services and forest attributes. See Figure S4.1 for more attributes.

4.3.3 Evaluating and optimizing forest restoration

Considering the benefits from forest restoration on the forested land, and the watersheds with clear beneficiaries, we mapped the benefit-map for hydropower and water supply, as well as the map of the beneficiaries. Due to the characteristics of hydropower, the benefits of hydropower vary in different regions, ranging from \$64/ha to \$4134/ha, and the benefit of water supply is uniformly at \$2115/ha. We also calculated the mean values of the six benefits in the huc12 watershed as the basic unit. We identified 16 major beneficiaries of each of the two ecosystem services (Figure 4.5). Combining the previous four benefit maps, we evaluated the benefits of the Trapper project. The total benefits reach \$21910/ha, of which \$2440 is carbon storage, \$9825 is timber provisioning, \$4427 is erosion regulation, \$2432 is air-quality regulation, \$671 is hydropower and \$2115 is water supply (Figure 4.6).

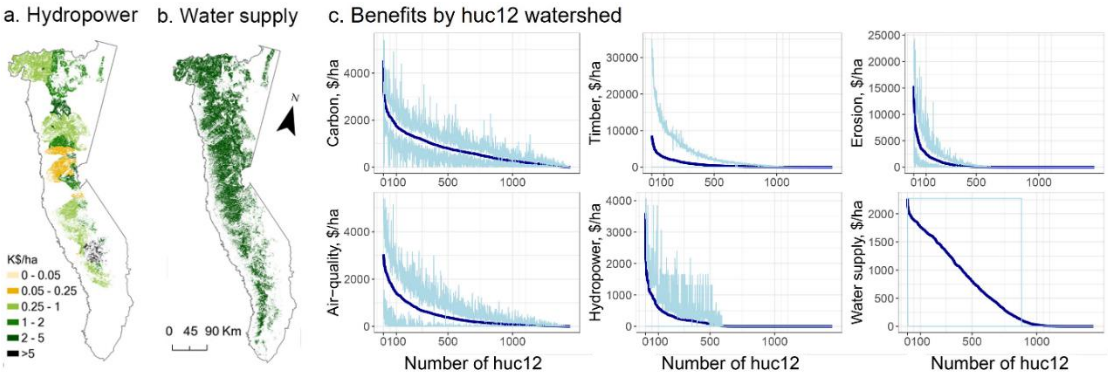

Figure 4.5. Maps of benefits forest restoration for hydropower and water supply (panel a and b), and (panel c) the mean benefits of each ecosystem service of 1445 huc12 (dark blue line), arranged in descending order on the x-axis, and values within each watershed that are at 5 and 95 percentiles (light blue line). See Figure S2 for water-related beneficiaries' map.

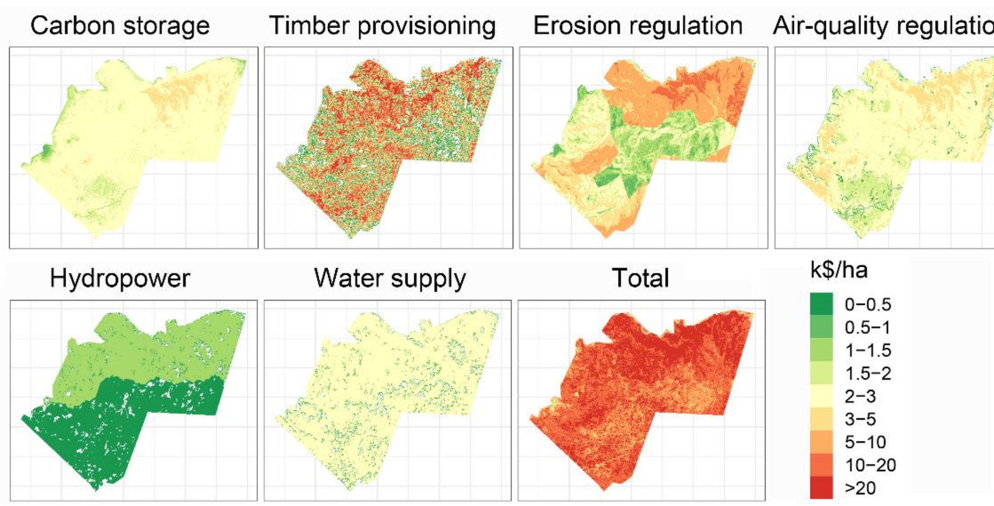

Figure 4.6. Evaluation of the benefits of Trapper Project with respective and total benefits.

In order to optimize the restoration project, we ranked the top 100 huc12 watersheds under the three scenarios by their mean overall benefit, considering all six ecosystem services. We selected the median watersheds, namely Bonta Creek-Cold Stream, Kanaka Creek and Soda Creek-East Branch North Fork Feather River. To find practical areas for implementation, we selected forested and public land areas in each watershed and excluded steep slope areas. Then, using ForSysX, we identified 20 potential projects of 40 ha each with maximized benefits, based on preferred weights. The average overall benefit of these projects could reach \$4,861, \$27,423 and \$17,114 respectively (Figure 4.7).

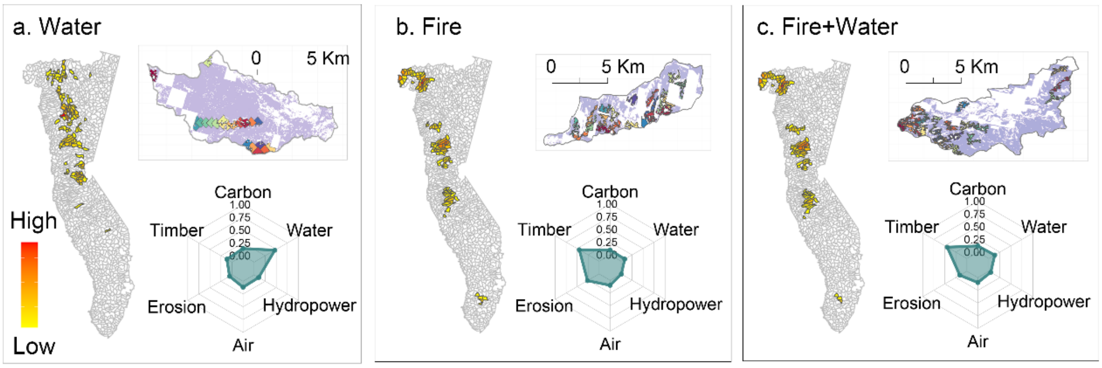

Figure 4.7. Optimization of forest restoration by three weight scenarios and its benefits. Shown are the huc12 watersheds of top 100 mean values, the watershed of median value and the relative value of each benefit of the prioritized projects within each watershed.

4.4 Discussion

4.4.1 Monetized benefits

Although wildfires increase water yield and thus hydropower generation to some extent, they reduce ecosystem services such as carbon storage, timber provisioning and erosion-regulation. In addition, wildfires also have negative impacts on other ecosystem services such as air-quality regulation, habitat provisioning and recreation (Eriksson et al., 2022, Guo et al., 2024, paper in preparation). Through the review of historical wildfires, we can find that spatial distribution of wildfires was not uniform. Wildfires occurred more frequently and cover larger areas in some subregions than in others. Furthermore, the impact of wildfire on ecosystem services in different regions varies due to the different characteristics of ecosystems. For instance, comparing Central Sierra and East Sierra, under high-severity wildfires, the average reduction in carbon storage in the Central Sierra is 730 g/m^2, or 162 %, more than that in East Sierra. In terms of erosion regulation, high-severity wildfires have more significantly weakened the erosion regulation capacity of the Central Sierra than the East Sierra, indicated by more soil loss at over 200 ton/ha first year after wildfires. Therefore, in order to restore forests to reduce the risk of wildfires, we need to consider both the severity of wildfires and the characteristics of the ecosystem. Monetized benefits of forest restoration provide a single indicator for this.

This study provides case studies on the use of monetized benefits to promote the implementation of forest restoration. The benefits of the Trapper project far outweigh the costs of adjacent North Yuba project, which was $2965/ha (Guo et al., 2023). In addition, through the corresponding beneficiary maps, we identified the potential water-related beneficiaries, namely the Yuba Water Agency, which could receive the benefits of hydropower, water supply, and erosion regulation. Applying the same method, we can evaluate the benefits of any planned project within the range of the Sierra Nevada, and identify certain beneficiaries with their expected benefits. The path of optimizing restoration project that we demonstrated provides promising potential for forest restoration. The watersheds we selected with overall benefits that are median among the 100 huc12 watersheds already have significant benefits. In addition, ForSysX provides practical project areas that capture the greatest benefits within the watershed, which could be used as reference for the places of implementation. The parameters of the optimizing process are adjustable, including the weight of benefits, watershed of interest, land ownership, and number of projects and area of each. The maps of benefits and beneficiaries that we generated, combined with appropriate optimization parameters, serve as a quantitative tool for informing the decision-making of forest restoration.

4.4.2 Assumptions and limitations

In assessing the impact of wildfires on ecosystem services, we considered only the first-year post wildfires. However, since these effects of wildfires on ecosystems typically persist for several years (Ma et al., 2020, Guo et al. 2023), our estimates are conservative in terms of the values. Nevertheless, these values still provide sufficient insights for comparing the conditions between different subregions. Regarding the synergies and trade-offs analysis, the results did not reveal any significant relationships between water supply, erosion regulation, and tree biomass. This may be because water supply is largely affected by precipitation, and in the estimation of soil loss using the Revised Universal Soil Loss Equation (RUSLE), the rainfall-runoff erosivity factor (R), slope length factor (L) and slope steepness factor (S) also play a major roles in determining the soil loss, in addition to soil erodibility factor (K) and cover-management factor (C), which are largely affected by vegetation cover and wildfire.

The beneficiaries map we generated included only water-related benefits. Other beneficiaries, such as carbon-credit developers, wood-products companies, infrastructure owners, land manager and the public have not been mapped and may need site-specific analysis. In addition to identifying beneficiaries, a successful forest restoration investment program requires collaboration among a variety of stakeholders and experts, as well as the emergence of advocates within the stakeholder community to move the program forward (Todd et al., 2013).

4.5 Conclusions

Wildfires in the Sierra Nevada Mountains have been increasing in recent years, but their distribution is not uniform across different subregions. Wildfires can reduce ecosystem services such as carbon storage, timber provisioning, and erosion regulation, but also increase hydropower and water supply to some extent. The impact of wildfires on these ecosystems varies in different subregions. Tree biomass is highly correlated with the severity of wildfires and evapotranspiration, and thus reducing biomass through forest restoration can reduce the risk of wildfires and droughts. To find suitable areas for forest restoration, this study uses multi-benefit maps to provide a way to evaluate and optimize restoration, with monetized benefits as the indicator. The case study shows that there is great potential for forest restoration within the

Sierra Nevada to achieve significant benefits and demonstrate a quantitative tool for informing the decision-making of forest restoration.

Chapter 5: Conclusions

In this dissertation work, we have explored the possibility of expanding the funding sources for forest restoration for increasing its pace and scale. We valued benefits of forest restoration on enhancing multiple ecosystem services across the wildfire-vulnerable forests, including hydropower, water supply, carbon storage, timber provisioning, erosion-regulation and air-quality regulation, using the state-of-the-science data and algorithm. Two water-related benefits come from lower forest water use and greater potential runoff following forest thinning, while the four fire-regulation-related benefits come from the reduced projected burn probability and severity after treatment.

The results demonstrate the great potential for forest restoration in the wildfire-vulnerable forests. Across the Sierra Nevada, the area with mean overall monetized benefits exceeding \$5,000/ha reaches 23,000 km^2, accounting for over 21% of the total area of the Sierra Nevada. In addition, there are more than 2,000 km^2 of land with benefits of more than \$20,000/ha, which is almost four times the cost we have been told, benefiting both the private and public sectors.

The benefits vary spatially based on the location, surroundings, and the attributes where the restoration is implemented. Benefits from fire-regulation, namely costs avoided from mitigating wildfire risk, are highly related to the likelihood and severity of potential wildfire, while water-related benefits are heavily influenced by the amount of reduced ET and water rights. Potential burn severity and ET are highly correlated to tree biomass.

The evaluation and optimization of projects using these monetized benefits as indicator, combined with optimization algorithms, can inform the decision of restoration activities by incorporating a suite of stakeholders in sharing project costs and repaying investors when environmental and social benefits are realized. Restoring the sustainability by increasing the pace and scale of forest restoration not only brings benefits by enhancing multiple ecosystem services, but also has the potential to create job opportunities and economic prosperity, thereby improving the well-being of local communities.

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Supplementary materials

Tables:

Table S2.1 Data sources

Data	Type	Period	Resolution	Source
Precipitation	Raster	2004-2018	Annual, 30m	Parameter elevation Regression on Independent Slopes Model
ET	Raster	2004-2018	Annual, 30m	Center for Ecosystem Climate Solutions
Inflow	Numeric	2004-2018	Hourly	United States Geological Survey
Power generation	Numeric	2004-2018	Annual	California Energy Commission
Energy price	Numeric		Hourly	Lawrence Berkeley National Laboratory

Table S3.1. Social cost of carbon (SCC) from 2020 to 2030, referring to Rennert et al., (2022)

Emission Year	Mean ($/ton)	Low ($/ton)	High ($/ton)
2020	185	44	413
2021	190	45	419
2022	195	46	424
2023	199	47	430
2024	204	48	436
2025	209	49	442
2026	214	50	447
2027	219	51	453
2028	223	52	459
2029	228	53	464
2030	233	54	470

Table S3.2. Doyle log rule, lumber volume (board feet) determined by DBH and number of usable 16-foot logs (the Pennsylvania State University, 2020).

16 ft logs\ DBH\Volume	1	1.5	2	2.5	3	3.5	4	4.5	5
10	14	17	20	21	22	0	0	0	0
11	22	27	32	35	38	0	0	0	0
12	29	36	43	48	53	54	56	0	0
13	38	48	59	66	73	76	80	0	0
14	48	62	75	84	93	98	103	0	0
15	60	78	96	108	121	128	136	0	0
16	72	94	116	132	149	160	170	0	0

17	86	113	140	161	182	196	209	0	0
18	100	132	164	190	215	232	248	0	0
19	118	156	194	225	256	276	297	0	0
20	135	180	225	261	297	322	346	364	383
21	154	207	260	302	344	374	404	428	452
22	174	234	295	344	392	427	462	492	521
23	195	264	332	388	444	483	522	558	594
24	216	293	370	433	496	539	582	625	668
25	241	328	414	486	558	609	660	709	758
26	266	362	459	539	619	678	737	793	849
27	292	398	505	594	684	749	814	877	940
28	317	434	551	650	750	820	890	961	1,032
29	346	475	604	714	824	902	980	1,061	1,142
30	376	517	658	778	898	984	1,069	1,160	1,251
31	408	562	717	850	983	1,080	1,176	1,273	1,370
32	441	608	776	922	1,068	1,176	1,283	1,386	1,488
33	474	654	835	994	1,152	1,268	1,385	1,497	1,609
34	506	700	894	1,064	1,235	1,361	1,487	1,608	1,730
35	544	754	964	1,149	1,334	1,472	1,610	1,743	1,876
36	581	808	1,035	1,234	1,434	1,583	1,732	1,787	2,023
37	618	860	1,102	1,318	1,534	1,694	1,854	2,013	2,172
38	655	912	1,170	1,402	1,635	1,805	1,975	2,148	2,322
39	698	974	1,250	1,498	1,746	1,932	2,118	2,298	2,479
40	740	1,035	1,330	1,594	1,858	2,059	2,260	2,448	2,636

Table S3.3. Health impact function

Endpoint	Study Location	Reference	Age	Function	Baseline Function	Beta	Distribution Beta	Parameter 1 Beta
Hospital Admission, all respiratory	26 U.S. Communities	Zanobetti, A., M. Franklin and J. Schwartz. 2009.	65-99	(1-EXP(-Beta*DELTAQ))*Incidence*POP	Incidence*POP	0.00207	Normal	0.000446
Hospital Admission, all cardiovascular	202 US Counties	Bell, M. L., K. Ebisu, R. D. Peng, J. Walker, J. Samet, S. L.	65-99	(1-EXP(-Beta*DELTAQ))*Incidence*POP	Incidence*POP	0.0008	Normal	0.000107143

	Zeger and F. Dominici. 2008.				

Table S3.4. Valuation function

Endpoint	Function	A	Name A	B	Name B
Hospital Admission, all respiratory	A*MedicalCostIndex+B*((median_income)/(52*5))*WageIndex	32563	mean hospital charge, in 2015$	5.346959	mean length of stay
Hospital Admission, all cardiovascular	A*MedicalCostIndex+B*((median_income)/(52*5))*WageIndex	42642	mean hospital charge, in 2015$	4.882744	mean length of stay

* The 'median_income' is embedded in the EPA Standard Variables, and the dollar values were adjusted in 2020 US dollars based on the 'MedicalCostIndex', 'WageIndex' and 'AllGoodsIndex' embedded in the EPA Standard Inflators.

Figures:

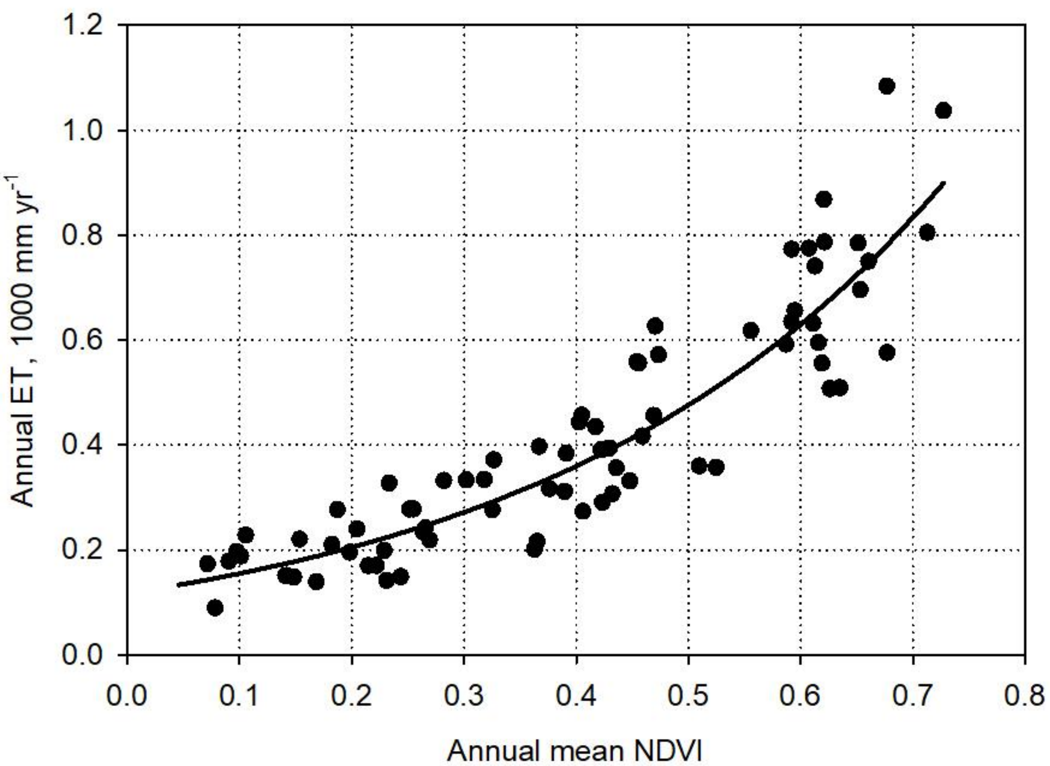
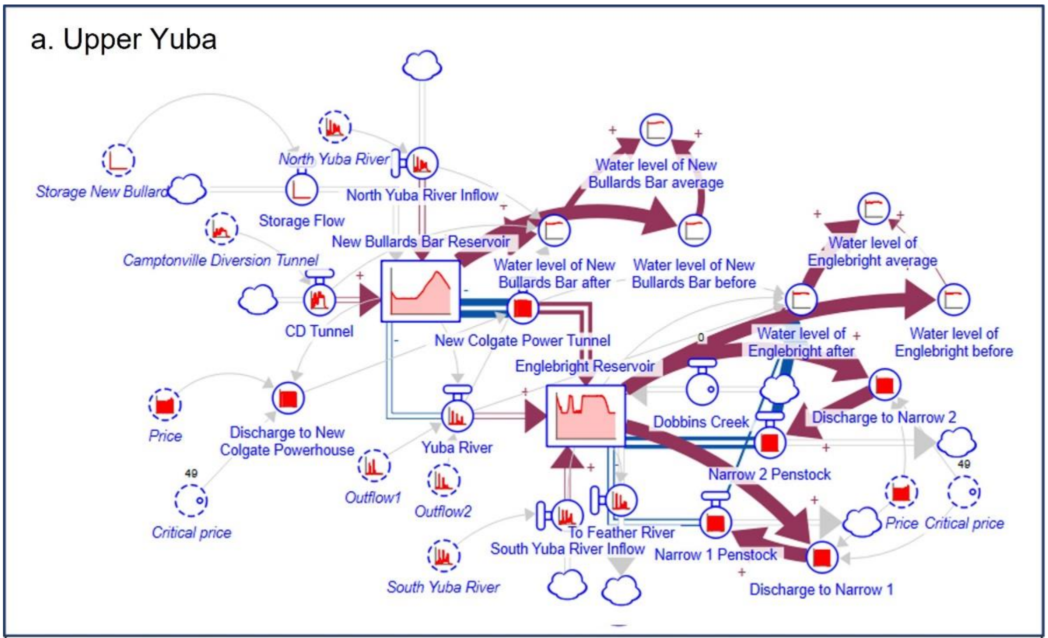
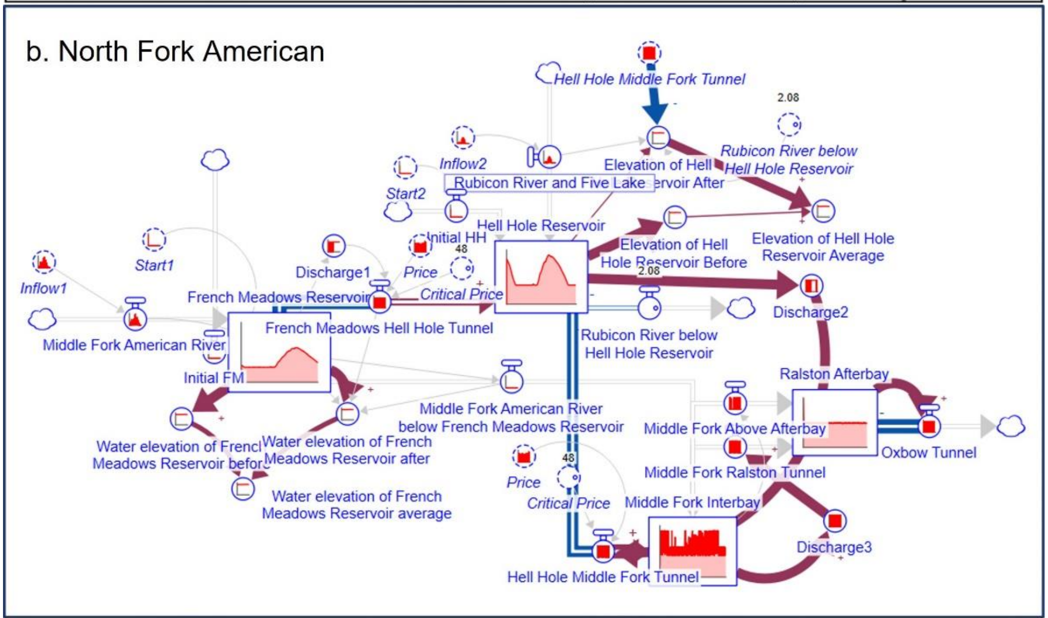


Figure S2.1. Annual water year ET by integrated eddy covariance against annual NDVI from

Landsat for 9 nearest upwind pixels across multiple years at 10 California flux towers. Solid black line shows the best fit regression through all sites and for all years was ET (mm) = 117.16 × exp(2.8025×NDVI) (R2 = 0.8386). Adapted from Goulden and Bales (2019).



Facility	Parameters
New Bullards Bar Reservoir	Max: 1955 feet, 966000 AF; Min: 1730 feet, 270000 AF;
Englebright Reservoir	Max: 525 feet, 44700 AF; Min: 517 feet, 37200 AF;
New Colgate Powerhouse	Max flow: 3430 cfs; Elevation: 591 feet;
Narrow 1 Powerhouse	Max flow: 730 cfs; Elevation: 308 feet;
Narrow 2 Powerhouse	Max flow 3400 cfs; Elevation 326 feet;



Facility	Parameters
French Meadows Reservoir	Max: 5263 feet; Min: 5160 feet;
Hell Hole Reservoir	Max: 4630 feet; Min: 4510 feet;
French Meadows Powerhouse	Max flow: 400 cfs; Elevation: 4630 feet;
Middle Fork Powerhouse	Max flow: 920 cfs ; Elevation: 2529 feet;
Ralston Powerhouse	Max flow: 836 cfs ; Elevation: 1175 feet;
Oxbow Powerhouse	Max flow: 1088 cfs; Elevation: 1089 feet;

Figure S2.2. Configuration and parameters of the two hydropower systems built in the simulation model using STELLA.

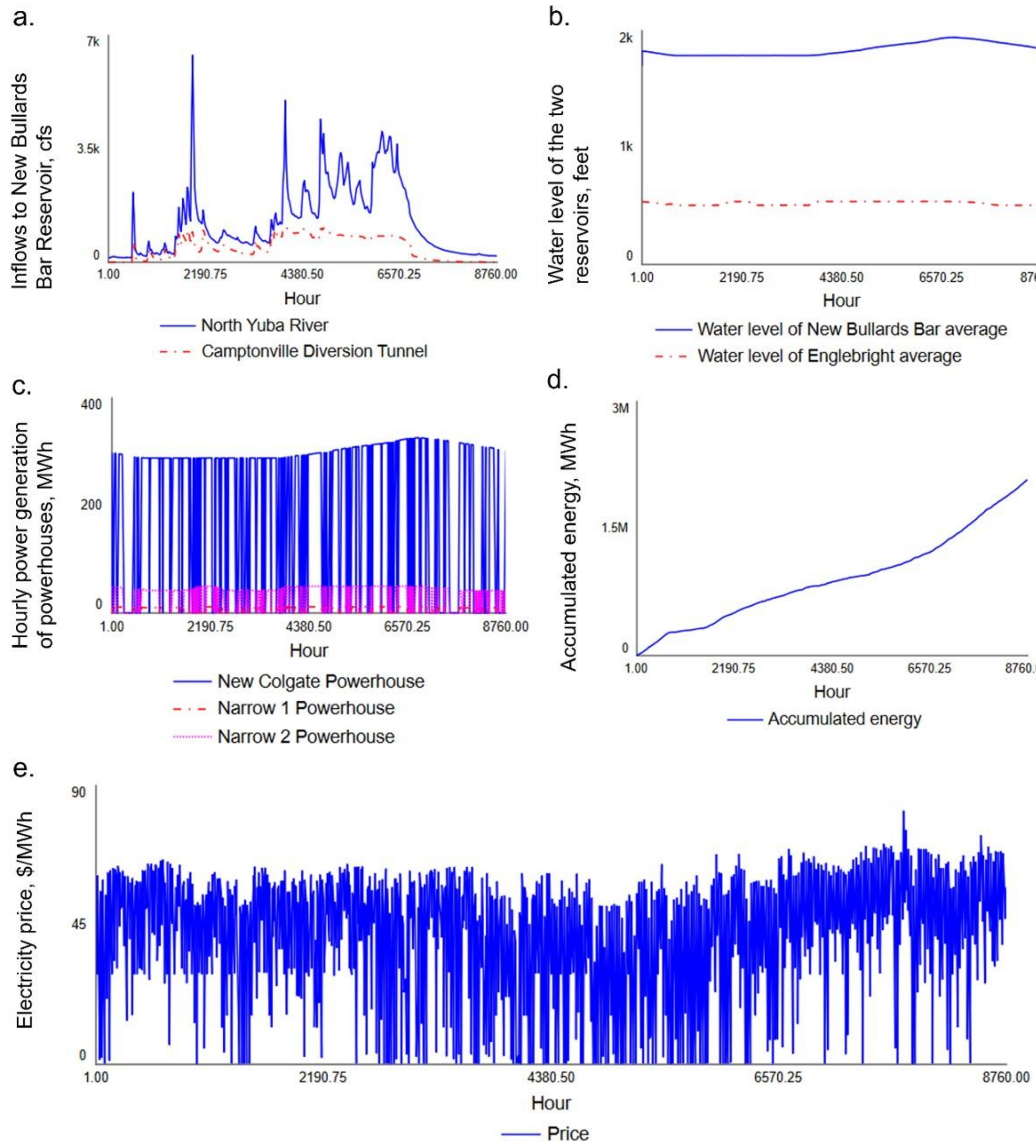


Figure S2.3. Some input and output values for the simulation of the hydropower project of YWA, taking water year 2011 as example for demonstration. Panel a shows the inflows to the New Bullards Bar reservoir. Panel b shows the variation of water level of the two reservoirs over the year. Panel c shows the hourly power generation of each powerhouse. Panel d shows the accumulated energy for the system over the year and panel e shows the hourly electricity price.

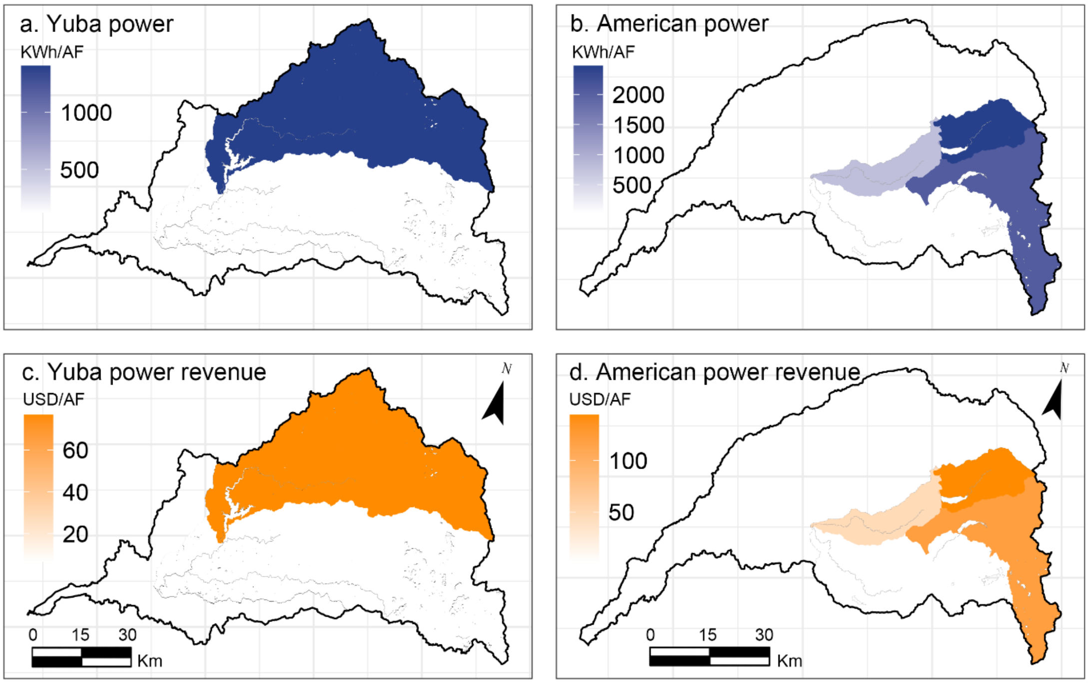


Figure S2.4. Average annual power generation and potential power-generation revenue per acre-foot of water in different areas of the two basins over a 15-year period.

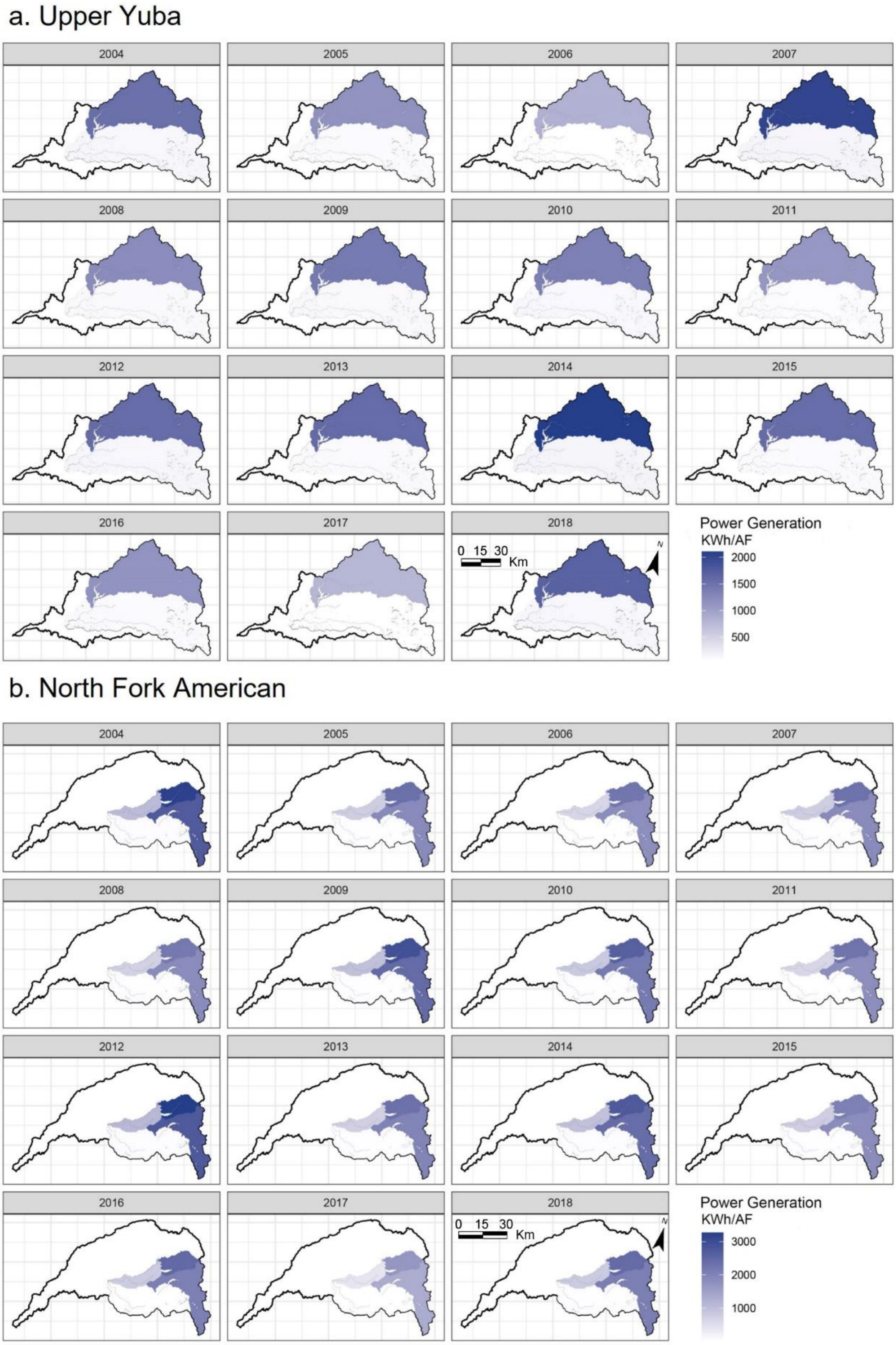


Figure S2.5. Annual power generation per acre-foot of water in different areas of the two basins for each year in the 15 years (2004-2018)

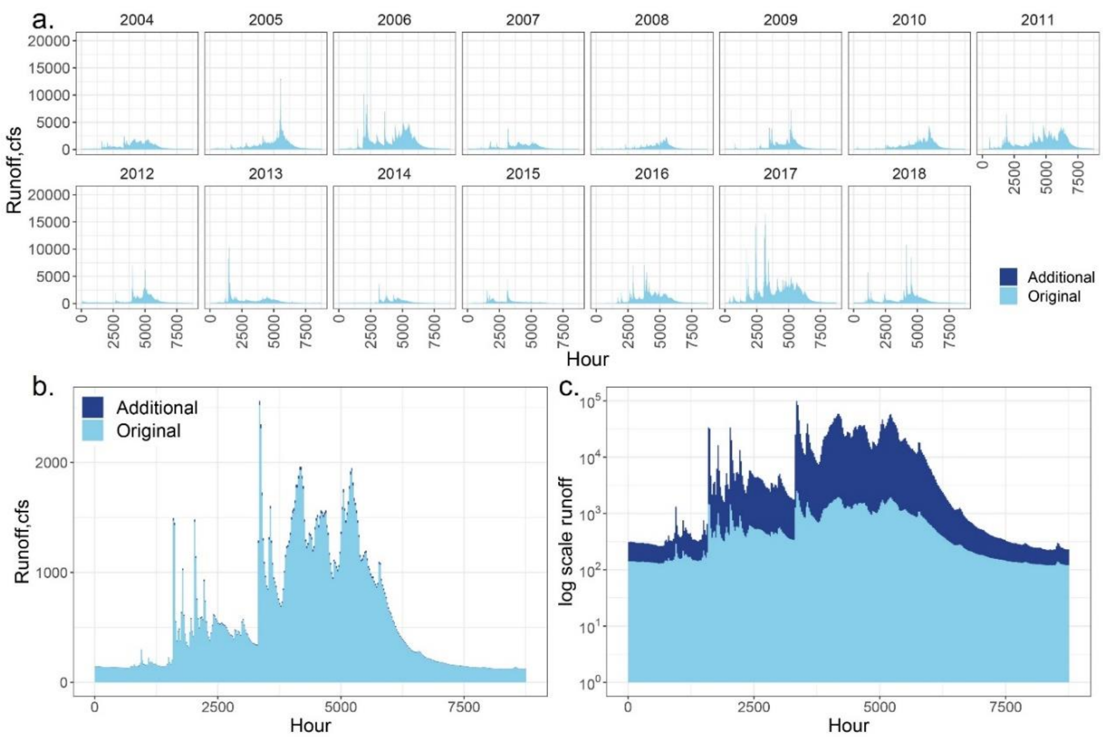


Figure S2.6. Original and additional runoff into the hydropower system in the Upper Yuba watershed. Panel a. original and additional runoff from 2004 to 2018; Panel b. original and additional runoff for 2004 with linear-scale values; Panel c. original and additional runoff of 2004 with log-scale values.

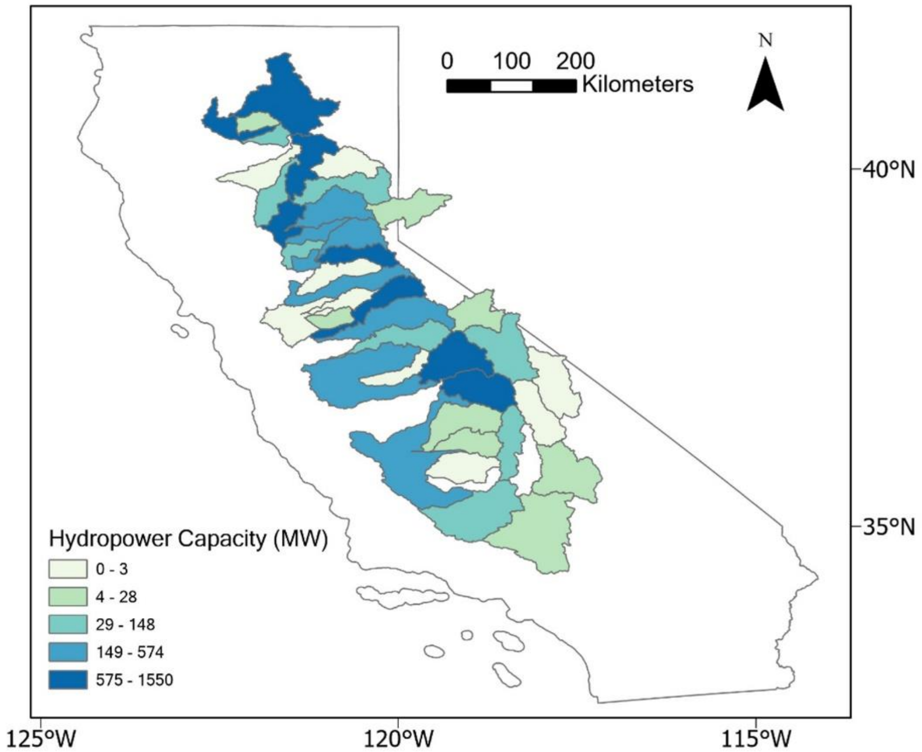


Figure S2.7. Hydropower capacity of watersheds associated with the Sierra Nevada.

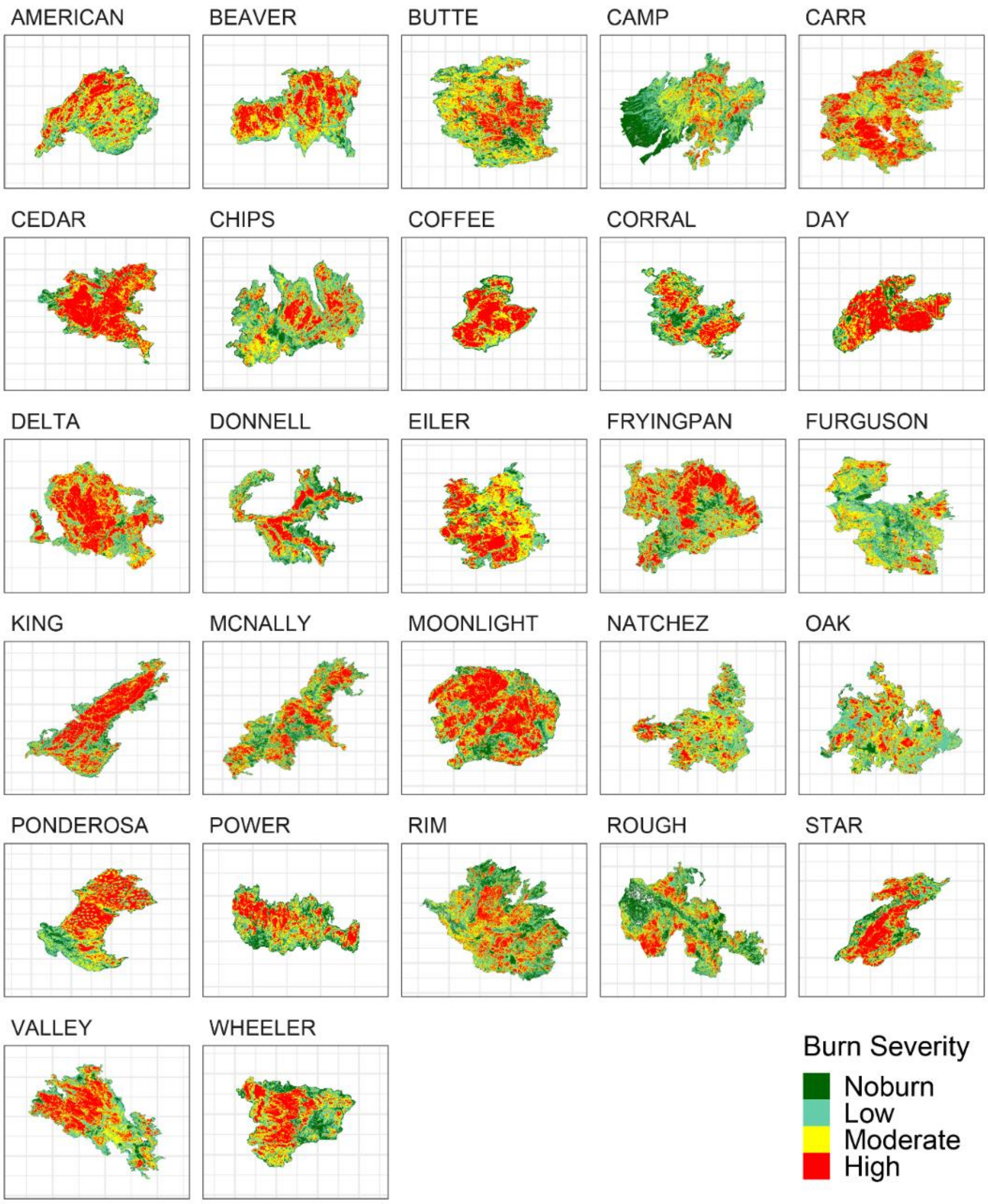


Figure S3.1. 27 wildfires used to examine carbon loss with burn severity categorized by MTBS

Figure S3.2. Trees endured high-severity wildfire (King Fire). Photo taken in the Sierra Nevada.

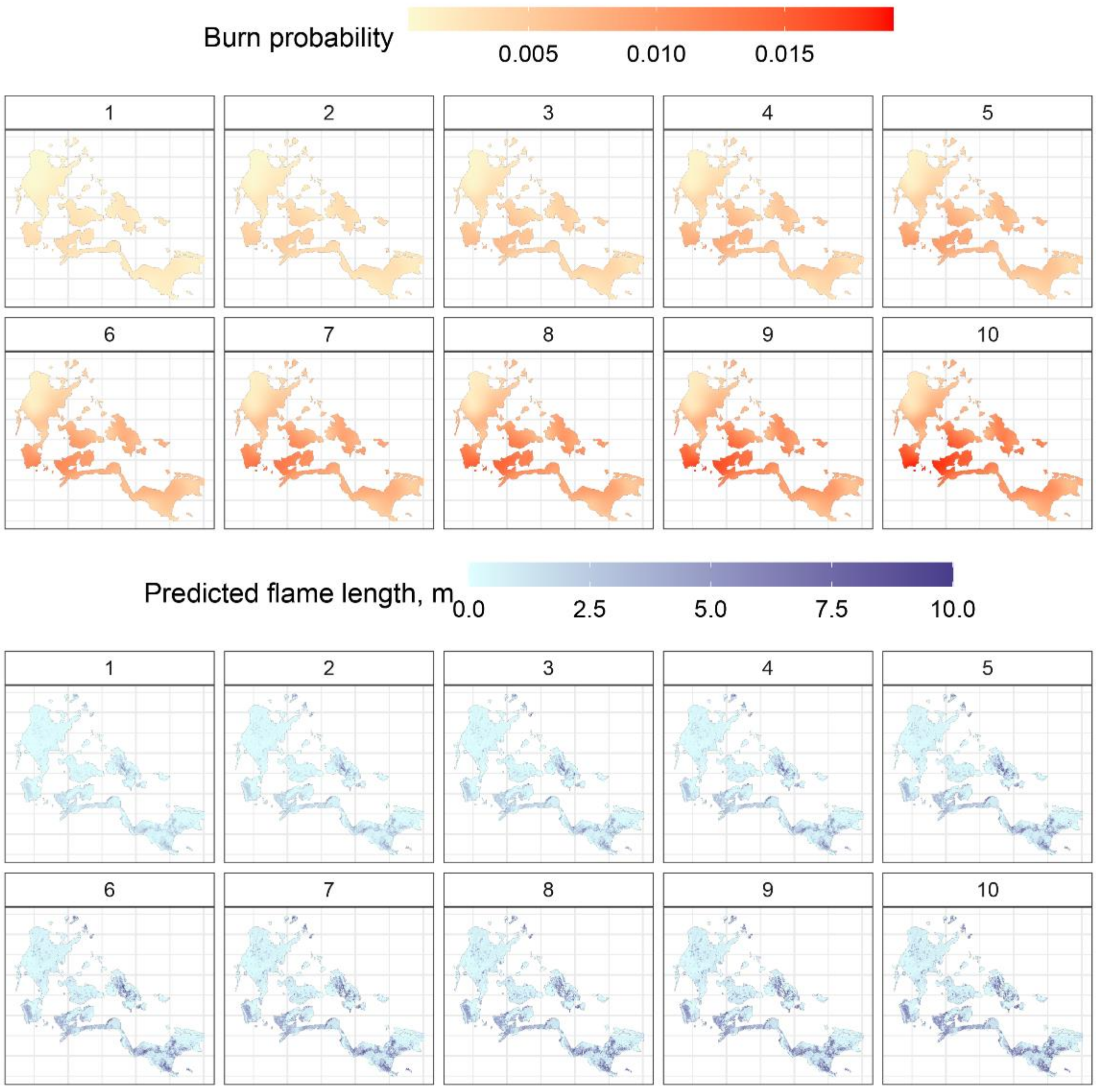


Figure S3.3. Burn probability and predicted flame length post treatment during the 10-year benefit period, taking the North Yuba Project area as an illustration.

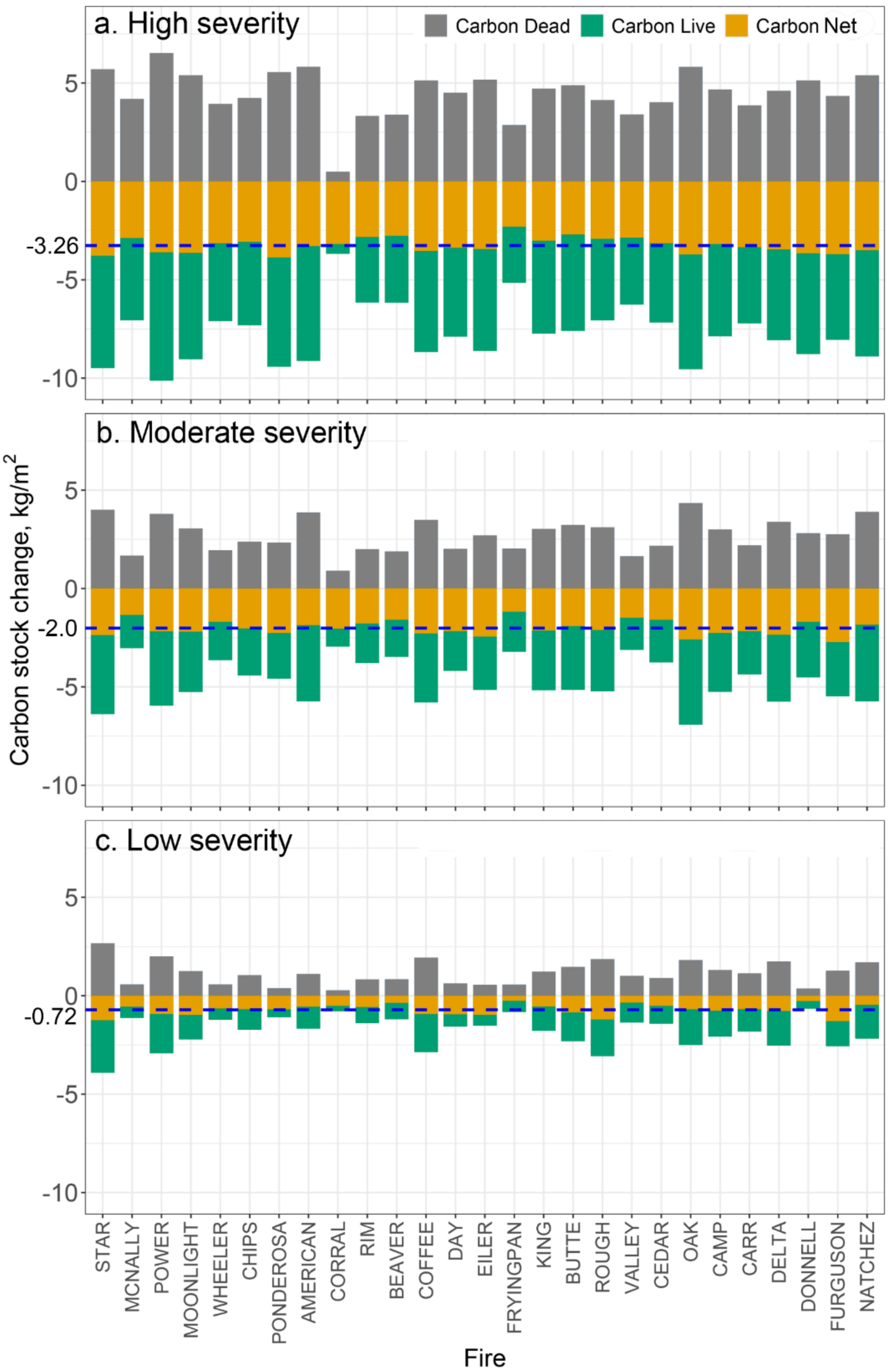


Figure S3.4. Carbon loss due to different burn severity for all analyzed fires.

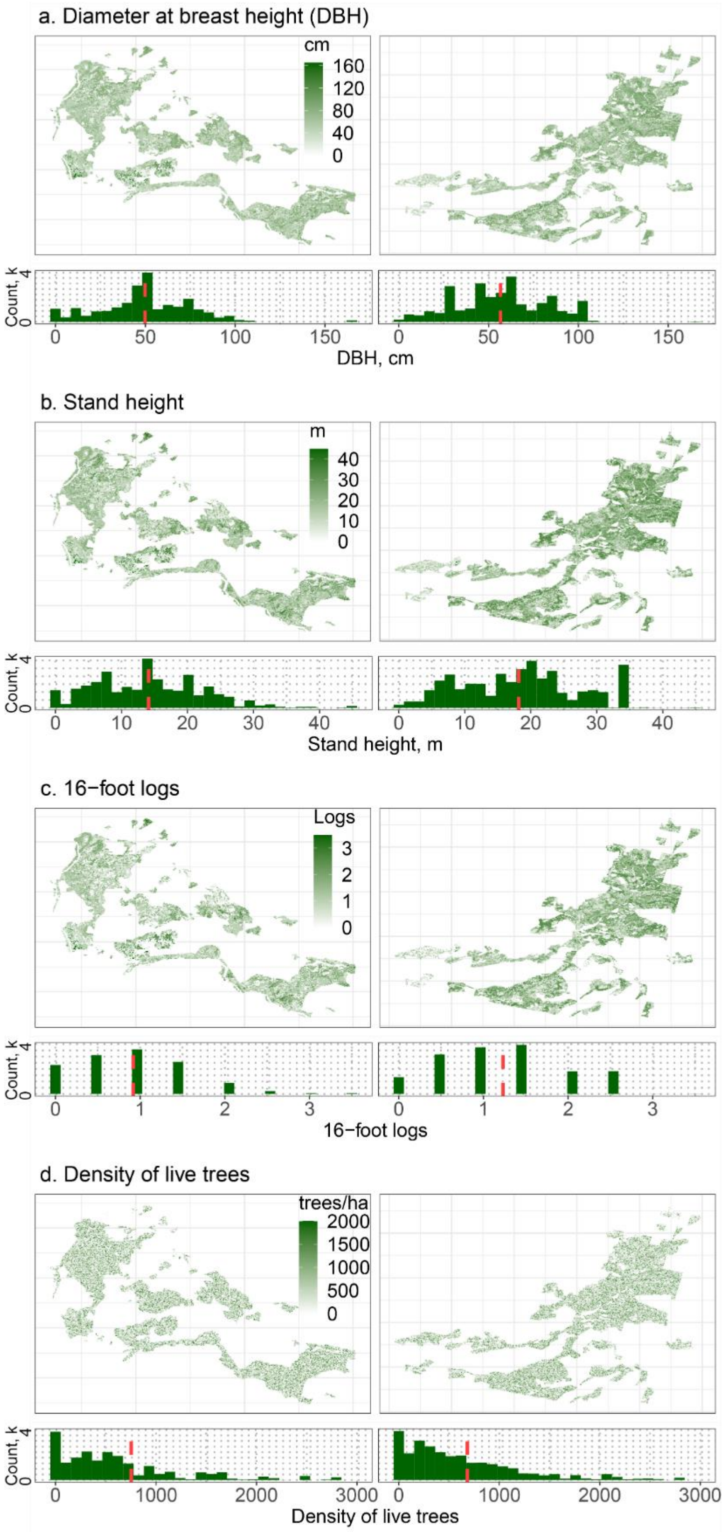


Figure S3.5. The parameters of trees with panel a, diameter at breast height; panel b, stand height; panel c, number of 16-foot logs and panel d, density of live trees within the two project area.

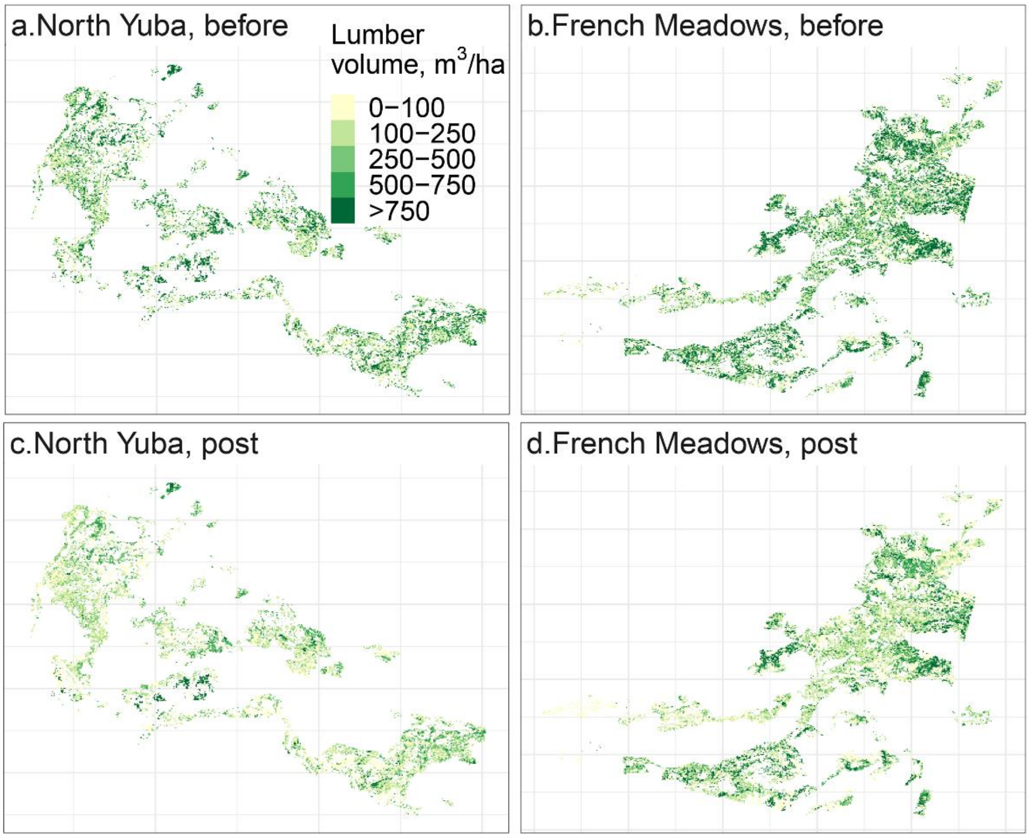


Figure S3.6. Volume of lumber before and after forest treatment across the two project areas

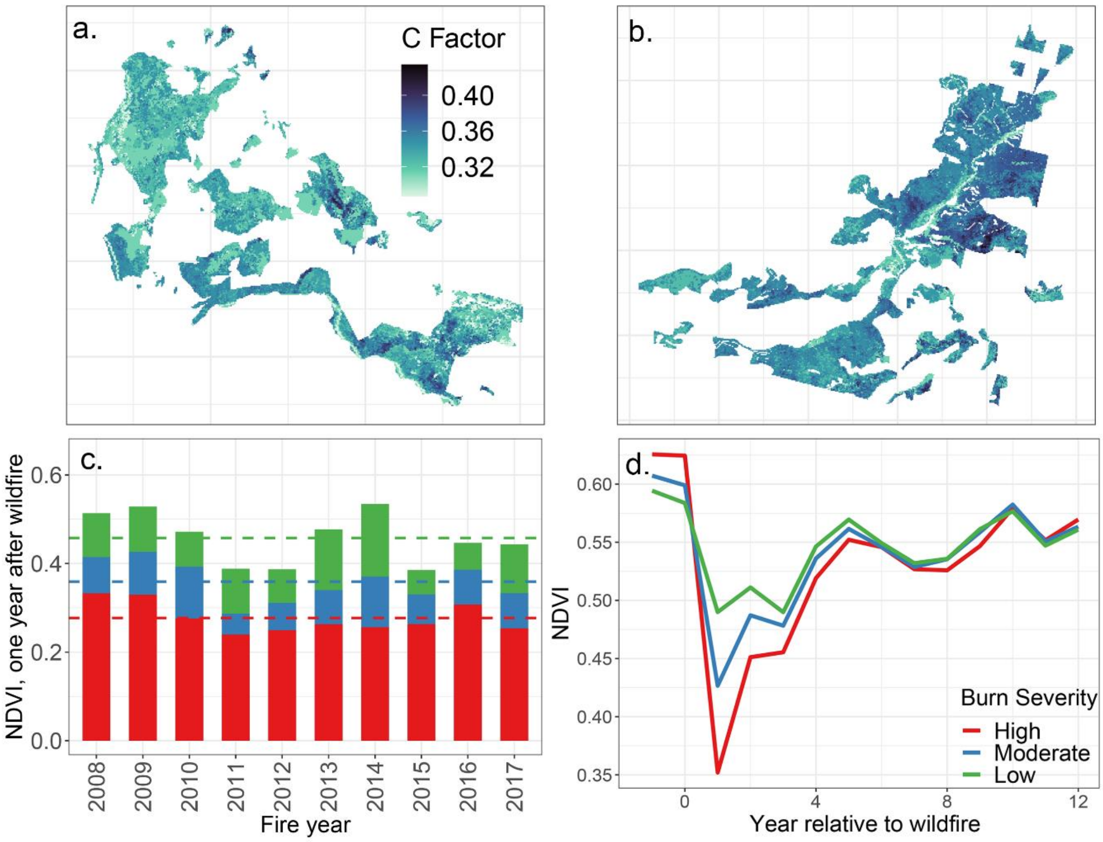


Figure S3.7. Estimation of C factor and the total period during which wildfire increases soil loss. Panel a and b show the original estimation of C factor for the two project areas. Panel c shows the mean NDVI values for high, moderate, and low severity wildfire burning areas one year after the wildfire, which are 0.28, 0.36, and 0.46. Panel d shows the period for the NDVI to return to the pre-disturbance level.

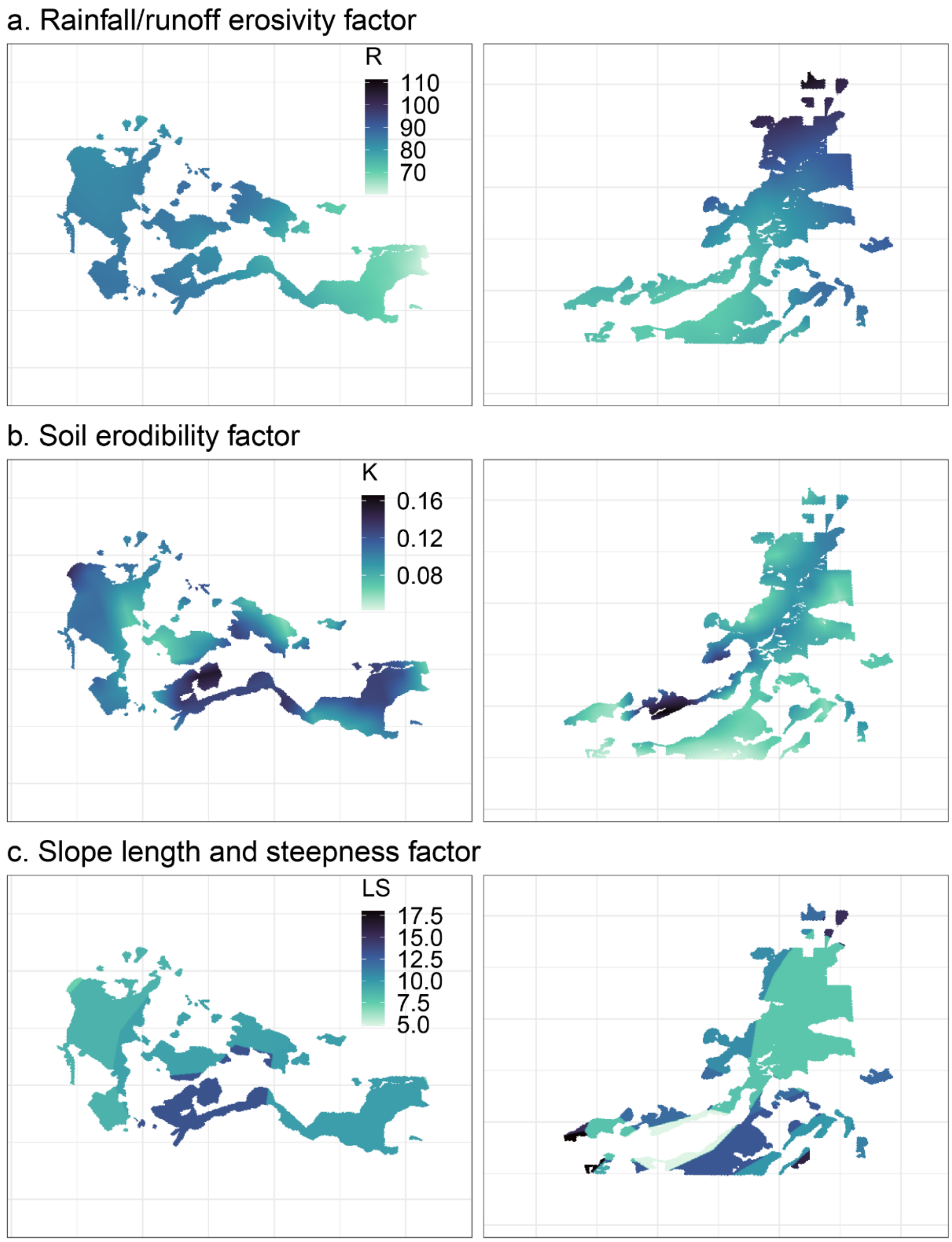


Figure S3.8. Factors calculating the soil loss through RUSLE, with panel a showing the rainfall/runoff erosivity factor, panel b showing the soil erodibility factor and panel c showing the slope length and steepness factor. All in standard US units.

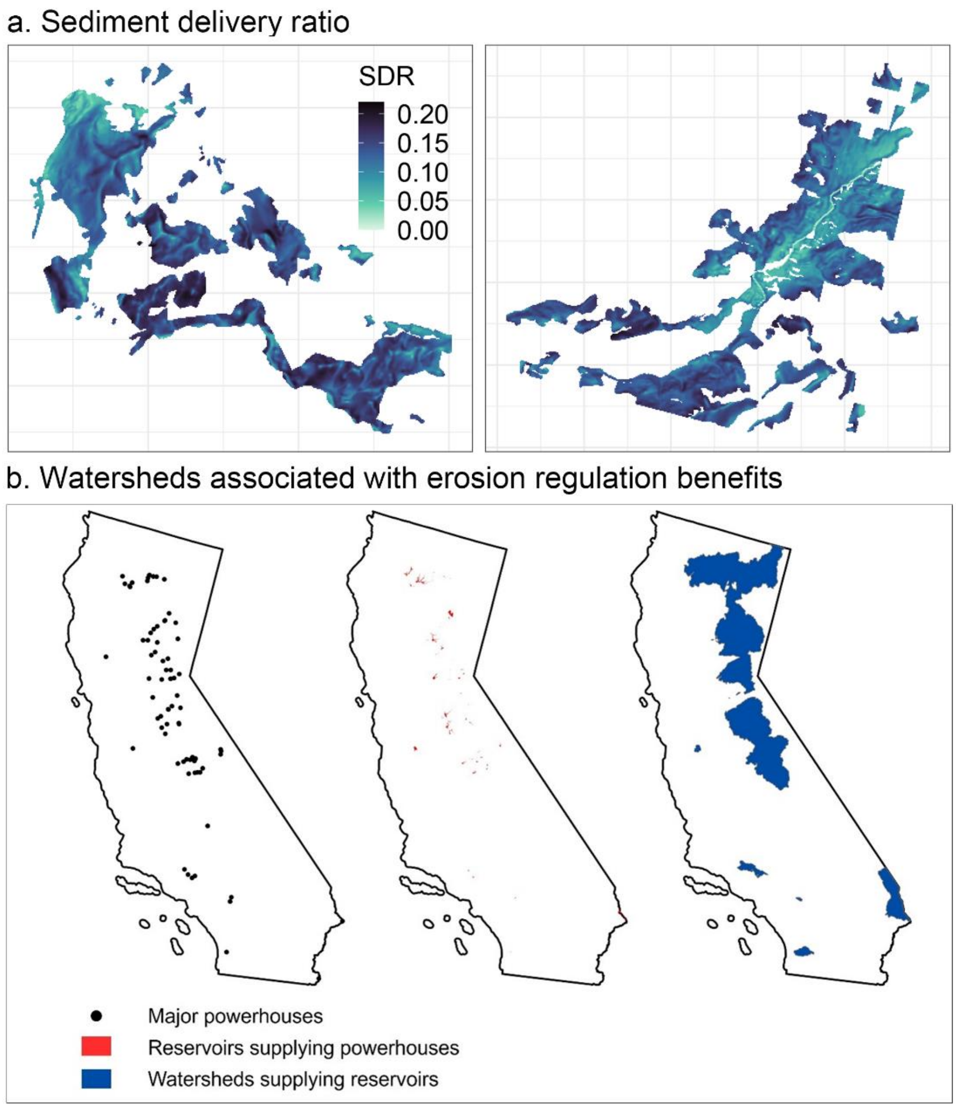


Figure S3.9. Sediment delivery ratio (panel a) and watersheds associated with the erosion regulation benefits (panel b).

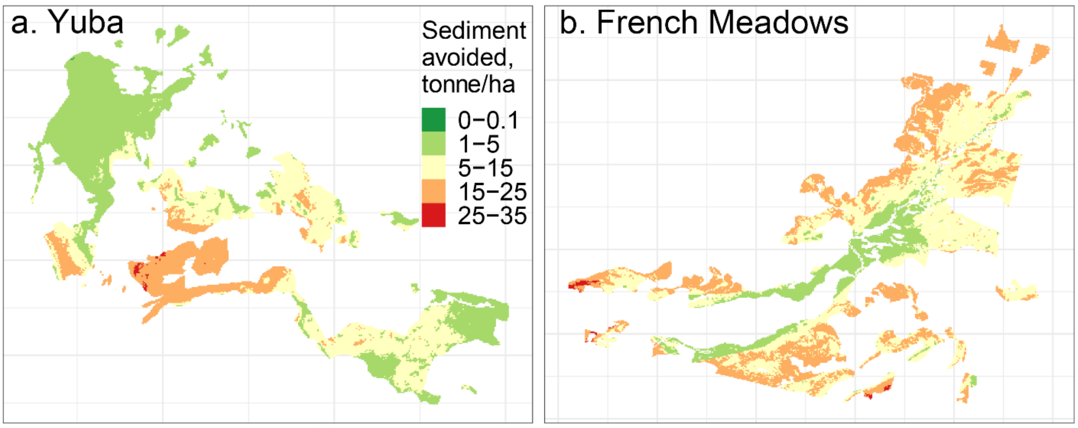


Figure S3.10. Expected sediment avoided through fuels treatments across the two project areas during the benefits period,

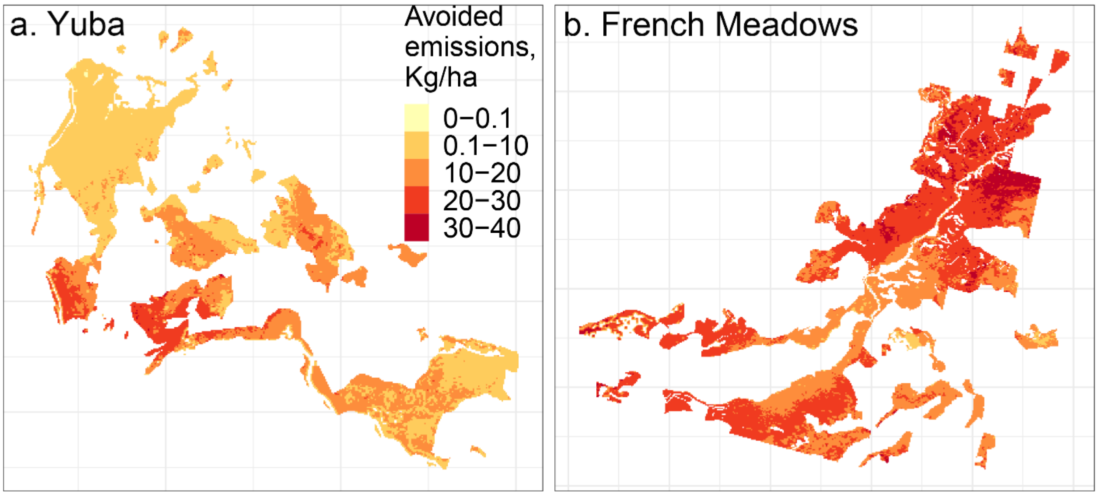


Figure S3.11. PM2.5 emissions from wildfire avoided through forest treatment across the two project areas during the benefit period.

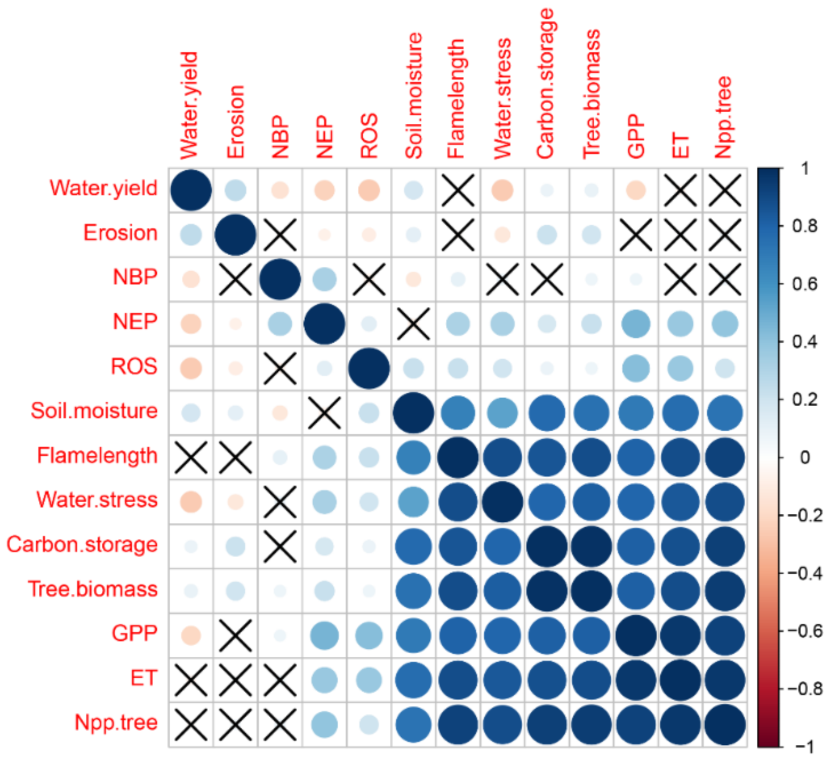


Figure S4.1 The Spearman’s rank correlation coefficients of ES and forest attributes.

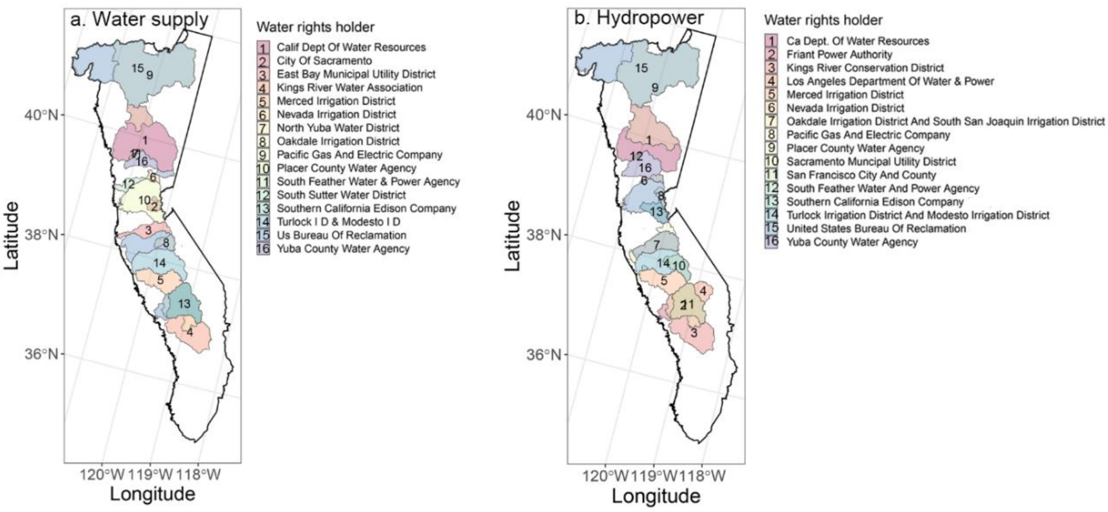


Figure S4.2. Maps of major beneficiaries of water supply and hydropower

Appendix

Guo, H.; Conklin, M.; Maurer, T.; Avanzi, F.; Richards, K.; Bales, R. Valuing Enhanced Hydrologic Data and Forecasting for Informing Hydropower Operations. Water 2021, 13, 2260. https://doi.org/10.3390/w13162260. (https://www.mdpi.com/2073-4441/13/16/2260?utm_campaign=releaseissue_waterutm_medium=emailutm_source=releaseissueutm_term=titlelink14