Science of the Total Environment 1001 (2025) 180487

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Valuing co-benefits of forest fuels treatment for reducing wildfire risk in California's Sierra Nevada

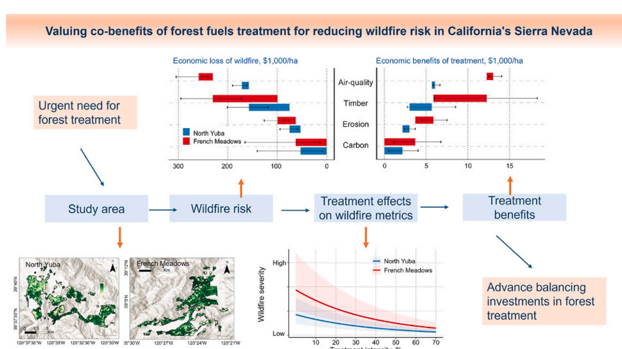
Han Guo [a,*], Michael Goulden [b], Min Gon Chung [a], Qingqing Xu [a], Charity Nyelele [b,c], Weichao Guo [a], Benis Egoh [b], Martha Conklin [a], Catherine Keske [d], Mohammad Safeeq [a,e], Roger Bales [a,d]

[a] *Sierra Nevada Research Institute, University of California Merced, Merced, CA, USA*
[b] *Department of Earth System Science, University of California Irvine, Irvine, CA, USA*
[c] *Department of Environmental Sciences, University of Virginia, Charlottesville, VA, USA*
[d] *Department of Management of Complex Systems, University of California Merced, Merced, CA, USA*
[e] *University of California Division of Agriculture and Natural Resources, Davis, CA, USA*

HIGHLIGHTS

- Developed a scalable method to quantify economic benefits of forest fuels treatment
- Treatments lower wildfire risk and avoid costs of thousands of dollars per hectare
- Results support data-informed forest management and innovative financing strategies

GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Wildfire risk
Forest fuels treatment
Economic valuation
Sierra Nevada

ABSTRACT

As wildfires in the western United States grow in frequency and severity, forest fuels treatment has been increasingly recognized as essential for enhancing forest resilience and mitigating wildfire risks. However, the economic valuation of the treatment's co-benefits remains underexplored, limiting integration into financial and policy decision making. Using highly forested land in California's Sierra Nevada as study areas, this study provides a methodology to quantify the economic benefits of forest fuels treatment in mitigating wildfire-induced losses across multiple ecosystem services, including carbon storage, timber provisioning, erosion regulation, and air-quality regulation. Integrating historical data on forest disturbances, ecological variables, and market-based ecosystem service valuation models, we demonstrate that treatment can substantially reduce wildfire risk and deliver measurable, significant economic benefits at a landscape level. The magnitude of these benefits is site specific and sensitive to burn probability, treatment intensity, and the baseline value of affected ecosystem

* Corresponding author at: 5200 Lake Rd, Merced, CA 95343, USA.
E-mail addresses: hguo6@ucmerced.edu (H. Guo), mgoulden@uci.edu (M. Goulden), mchung35@ucmerced.edu (M.G. Chung), qxu6@ucmerced.edu (Q. Xu), cnyelele@virginia.edu (C. Nyelele), wguo5@ucmerced.edu (W. Guo), begoh@uci.edu (B. Egoh), mconklin@ucmerced.edu (M. Conklin), ckeske@ucmerced.edu (C. Keske), msafeeq@ucmerced.edu (M. Safeeq), rbales@ucmerced.edu (R. Bales).

https://doi.org/10.1016/j.scitotenv.2025.180487
Received 29 March 2025; Received in revised form 17 August 2025; Accepted 10 September 2025
Available online 18 September 2025

services. This quantitative analysis provides a scalable approach to inform regional forest management strategies. It can also support innovative financing mechanisms such as public–private cost-sharing models, which can accelerate the pace and scale of forest fuels treatment efforts that enhance ecosystem sustainability and community resilience in wildfire-vulnerable landscapes.

1. Introduction

Forests in the western United States provide critical ecosystem services, such as carbon sequestration, water quantity and quality regulation, timber provisioning, air-quality regulation, recreation and habitat provisioning, all of which are fundamental to mitigating climate change and supporting human well-being (Taye et al., 2021; Müller et al., 2020; Nyelele et al., 2023). Among these, the Sierra Nevada, as the largest contiguous forested region in California, covers 25 % of the state's land area, supplies over 60 % of the state's developed water, supports hydropower generation, and sustains local economies through timber industries and recreation. However, decades of fire suppression and exclusion policies have homogenized forest structures, increasing their susceptibility to high-severity wildfires, drought, and pest outbreaks (Voelker et al., 2019). In recent years, wildfire frequency, extent, and severity have escalated dramatically, leading to severe ecological and economic consequences (Wasserman and Mueller, 2023; Burke et al., 2021; Daum et al., 2024). High-severity wildfires not only cause loss of life, property, and infrastructure but also disrupt or destroy ecosystem services. They consume biomass, shift forests from carbon sinks to carbon sources (Loehman, 2020; Liu et al., 2014), cause timber losses (Bousfield et al., 2023), and increase soil erosion through changes in vegetation and soil properties (East et al., 2021; Jumps et al., 2022). They degrade water quality by elevating sediment and contaminant loads for years post-fire (Rust et al., 2018), and disrupt recreation services by damaging landscapes, prompting park closures, and reducing tourism revenues (Duffield et al., 2013; Gellman et al., 2022). Smoke from these wildfires also degrades air quality, with severe implications for public health, such as increased respiratory and cardiovascular diseases (Wang et al., 2021; Schollaert et al., 2024).

Recognizing these growing threats and economic losses, efforts to restore forests through fuels treatment, such as mechanical thinning and prescribed burning, have been increasingly emphasized as effective strategies to mitigate wildfire risks and enhance forest resilience (Prichard et al., 2021; O'Donnell et al., 2018; Stephens et al., 2024; Weston et al., 2022). These treatments remove small trees and understory, creating a more open and diverse forest dominated by fewer but larger fire-resistant trees, thereby reducing the risk of crown fires and tree-to-tree fire spread (Agee and Skinner, 2005). In recognition of these beneficial effects, federal and state agencies have increasingly prioritized investments in forest fuels treatment (CalFire, 2018; Forest Climate Action Team, 2018; State of California and USDA, 2020). However, the high costs of forest fuels treatment—estimated at billions of dollars per year for the Sierra Nevada—far exceed available funding, resulting in an implementation pace and scale that are insufficient to meet the growing demands (Quesnel Seipp et al., 2023). A key challenge in raising funding for forest fuels treatment is the absence of a comprehensive methodology to economically quantify the ecosystem services losses associated with wildfire and the full range of benefits associated with treatment. Forest fuels treatment contributes to improved ecosystem services, including enhanced hydropower and water supply by reducing vegetation water competition, as well as improved timber provisioning, air-quality regulation, erosion control and habitat and biodiversity through wildfire regulation (Guo et al., 2023; Stephens et al., 2021; Stephens et al., 2020). These improvements can also generate significant economic benefits, including increased power generation revenue, avoided health expenditures, reduced sediment removal and water treatment costs, and potentially higher tourism and recreation revenue in treated landscapes. While previous research has evaluated timber revenues and fire suppression savings using context-specific methodologies (Sanderfoot et al., 2021; Rhoades et al., 2019; Otrachshenko and Nunes, 2022), the economic benefits of avoided costs resulting from wildfire regulation across multiple ecosystem services remain underexplored. Recent frameworks for quantifying market and non-market benefits (Yao et al., 2019) and addressing funding challenges through stakeholder engagement (Quesnel Seipp et al., 2023) provide valuable conceptual foundations for a comprehensive analysis incorporating multi-benefits, yet detailed economic valuation analyses grounded in credible biophysical data and ecosystem modeling process to effectively inform investment decisions are still lacking at both regional planning and project implementation scales.

To address these critical gaps in areas with a wide range of forest and landscape conditions, this study integrates historical data on forest disturbances, ecological variables, and market-based valuation models to achieve three key objectives: (1) develop credible algorithms to quantify the economic loss associated with wildfire and the benefits of forest fuels treatment; (2) assess the scale and key drivers of treatment benefits in mitigating wildfire risk, and (3) evaluate how benefit analyses can inform forest management strategies and financing mechanisms. To illustrate the approach, we apply it to two densely forested regions in the Sierra Nevada of California, representative of high fire-risk landscapes and diverse forest fuels treatment practices.

2. Methods

Our methods consist of three steps: first, analyzing the impacts of historical wildfires on ecosystem services and using data developed through ecological modeling to evaluate the potential effects of wildfires on the targeted landscapes; second, assessing how historical changes in vegetation cover and fuel load have influenced wildfire characteristics, including burn probability and predicted burn severity; and third, integrating ecosystem-service valuation to estimate the multiple benefits arising from forest fuels treatment applied for mitigating wildfire risk. In this study, four ecosystem services vulnerable to wildfire were included, namely carbon storage, timber provisioning, erosion regulation and air-quality regulation, as defined by the Millennium Ecosystem Assessment (Reid et al., 2005). All spatial datasets used in this study are summarized in Table 1 and Table S1. This includes detailed information on resolution, source, and temporal coverage for each variable.

2.1. Study area

The two areas analyzed in this study are in California's Sierra Nevada and are areas that recently received forest fuels treatment. We refer to them as the North Yuba and French Meadows projects. These regions are characterized by dense mixed-conifer forests, with areas of 23.1 km^2 and 28.6 km^2, respectively, and tree density estimated over 900 trees/ha. Due to increasing wildfire risks in recent years, these regions have been identified as priority sites for ongoing treatments. The average elevation is 2087 m for North Yuba and 1778 m for French Meadows, with mean slopes of 24 % and 19 %. The Parameter-elevation Regressions on Independent Slopes Model (PRISM) indicates 30-year (1991–2020) average annual precipitation of 1690 mm and 1739 mm for North Yuba and French Meadows respectively (Fig. 1).

2.2. Impacts of wildfires on ecosystem services

Burn severity and probability. We assessed the potential changes in

Table 1
Summary of data inputs.

Data	Unit	Spatial resolution	Temporal resolution
Burn probability	Unitless	30 m, statewide	Annual, 2019–2020
Predicted flame length	m	30 m, statewide	Annual, 2019–2020; Annual, 1985–2020
Wildfire perimeters	NA	Shapefile, statewide	Annual, 2001–2020
Burn severity	Unitless (categorical index)	30 m, statewide	Annual, 2001–2020
Carbon stock (Aboveground live)	kg/m^2	30 m, statewide	Annual, 2001–2021
Tree biomass	10 g/m^2	30 m, statewide	Annual, 2001–2021
Tree attributes (Tree species, DBH, Stand Height, Density)	species: NA, DBH: cm, Stand Height: m, Density: trees/ha	30 m, statewide	Current inventory (2017)
Precipitation	mm	30 m (resampled), project scale	30-year average
K, LS	K (tonnes·ha·hr / ha·MJ·mm), LS (unitless)	30 m (resampled), project scale	Current condition
Vegetation type	Categorical (LANDFIRE EVT)	30 m, project scale	2020
Vegetation cover loss (Tree, Shrub, Fuel)	%	30 m, statewide	Annual, 2001–2020

ecosystem services induced by wildfires under current conditions for the study areas. For each type of ecosystem service, these changes depend on the probability of wildfire occurrence at the site and the severity of the wildfire when it occurs. Burn severity, defined as “the degree to which a site has been altered or disrupted by fire,” is categorized into four levels: high, moderate, low, and unburned, based on criteria established by the Monitoring Trends in Burn Severity (MTBS) project (Finco et al., 2012).

Predicted flame length is widely recognized as a metric for wildfire severity. In previous analyses, thresholds have been established to convert predicted flame lengths from fire modeling into burn-severity levels (Salis et al., 2019; Elliot et al., 2016; Srivastava et al., 2018). For instance, flame lengths of 2.5 m and 1.2 m predicted by the FlamMap, a fire-mapping and analysis system describing potential fire behavior (Finney, 2006), were used as thresholds for high and moderate burn severity, respectively (Elliot et al., 2016).

For this study, we used predicted flame length and burn probability simulated based on vegetation conditions at the end of 2019 and 2020, prior to large-scale forest fuels treatment in the study areas. The data were produced by the USDA Forest Service (USFS), Rocky Mountain Research Station, and Pyrologix LLC, using FlamMap for the predicted flame length and FSim, a large-fire simulation system for burn probability (Finney et al., 2011)(Table 1). Inputs included local fuel, weather, topography, and past wildfire ignitions, with calibration runs aligning predictions to historical fire patterns (Vogler et al., 2021). The mean annual burn probability for French Meadows is about 50 % higher than for North Yuba (0.0148 versus 0.0096) and also has a much higher mean predicted flame length (4.5 vs 1.9 m). Few pixels in either area have annual burn probability as high as 0.020 or projected flame length as high as 10 m (details in Fig. S1). Instead of defining a fixed flame length threshold for burn severity, we employed a multinomial logistic regression model with polynomial terms to predict the probability distribution of burn severity levels, using predicted flame length as a continuous predictor. Pixel-level burn severity frequencies from the 2020 wildfires (MTBS data) were matched with predicted flame length from 2019 projections. Model accuracy was evaluated by comparing predicted and observed burn severity levels (Fig. S2).

Carbon storage. We assessed the impact of wildfires on carbon storage, defined in this study as aboveground live carbon storage, by analyzing changes across historical burn-severity levels. To achieve this, we used polygon and raster datasets from 2001 to 2020, including wildfire perimeters from the California Department of Forestry and Fire Protection (CAL FIRE), burn severity from MTBS, and carbon storage from Natural Climate Data Atlas (Goulden et al., 2022) (Table 1).

Wildfires were delineated into distinct shapefiles based on burn-severity levels—unburned, low, moderate, and high—by cropping the annual burn-severity raster to the wildfire extent and vectorizing the data. For each burn-severity polygon, the change in mean carbon storage was calculated as the difference between carbon storage one year before and one year after the wildfire. This analysis focuses on short-term, wildfire-year losses in live carbon only, as data limitations prevent accurate tracking of longer-term fluxes involving wildfire-induced dead biomass and decay. To evaluate the significance of these changes, we conducted a paired *t*-test. Further, linear regressions were used to examine the relationship between burn severity and changes in carbon storage. Post-fire carbon storage served as the dependent variable, while predictors included pre-fire carbon storage, burn-severity levels (high, moderate, and low) as dummy variables and potential interaction terms. We compared models with and without interactions between pre-fire carbon and burn severity, using criteria such as adjusted R^2, Akaike Information Criterion (AIC), and Variance Inflation Factor (VIF) to select the preferred specification. The same approach was applied to all wildfire-related regressions. Confidence intervals were generated to quantify the uncertainty associated with the estimated impacts.

By analyzing the impacts of past wildfires on carbon storage and incorporating burn-probability and flame-length estimates for the study site, we evaluated the potential effects of future wildfires on carbon storage. All regression models were fitted at the polygon level (wildfire burn-severity polygons) to reduce pixel-scale noise. Subsequent assessments of other ecosystem services followed similar steps.

Timber provisioning. We estimated timber volume of the study areas using the Scribner 16-ft log rule, a widely accepted log-scaling method employed in California for both softwood and hardwood species. Given the variation in tree morphology across species, we used species-specific equations derived from a U.S. Forest Service technical guide (USFS, 2014). Their equations take diameter at breast height (DBH) and stand height as the primary predictors, incorporating allometric relationships, taper functions, cubic form factors and log rules to estimate the wood volume and thus Scribner volume of timber. This ensures a standard estimation of wood volume and Scribner volume, aligned with established forestry practices (Table S2). Tree-species, DBH, stand-height, and tree-density data were obtained from the Landscape Ecology, Modeling, Mapping, and Analysis (LEMMA) dataset, using its most-recent data from 2017 for study area analysis (Table 1).

To assess the impact of wildfires on Scribner volume, we adopted an approach similar to our carbon-storage analysis. Leveraging time-series data on tree biomass from the Natural Climate Data Atlas, we conducted regression analyses to estimate the percentage loss of tree biomass resulting from past wildfire events. These estimates were then used to predict current tree biomass losses within the study areas under varying burn severities. Considering the potential for salvage logging, we approximated the percentage loss of tree biomass as equivalent to the percentage loss of wood volume, recognizing that not all wood volume is destroyed by wildfire. Finally, we converted the estimated losses into Scribner volume.

Erosion regulation. In this study we assessed the potential impact of wildfires on sediment delivery to downstream reservoirs. First, we estimated the potential soil loss following wildfires in the two study areas using the Revised Universal Soil Loss Equation (RUSLE) (K. Renard, 1997). The RUSLE model calculates average annual soil loss (A, tonnes/ha) as:

$$A = R \times K \times LS \times C \times P \tag{1}$$

where R is the annual rainfall-runoff erosivity factor (MJ·mm/ha·hr·yr), which quantifies the erosive power of rainfall. The R factor was calculated using the equation provided by Renard and Freimund (1994), using annual mean precipitation from PRISM. K is the soil erodibility factor (tonnes·ha·hr/ha·MJ·mm), which represents the susceptibility of soil to erosion by runoff and raindrop impact. The LS factor (dimensionless) represents the combined effects of slope length and slope steepness on erosion. K and LS values were obtained from the California State Water Resources Control Board (Table 1). The P factor (dimensionless) was set to 1 as no specific conservation practices were implemented in the study areas.

The C factor (dimensionless) reflects the extent to which vegetation or ground cover reduces soil detachment and runoff by dissipating the impact of rainfall and stabilizing the soil. The use of the Normalized Difference Vegetation Index (*NDVI*) to quantify the C factor is well established, with advancement in capturing spatial and temporal variations in vegetation cover compared to literature-derived values specific to particular conditions or locations (Woznicki et al., 2020). The function calculating the C factor follows:

$$C = \exp\left(-\alpha \times (NDVI/\beta - NDVI)\right) \tag{2}$$

where α and β are dimensionless fitting parameters, with $\alpha = 2$ and $\beta = 1$ adopted based on their reliable correlations reported in the literature (Ayalew et al., 2020; van der Knijff et al., 2000). Annual mean *NDVI* was calculated in Google Earth Engine using Landsat data, excluding pixels with clouds, shadows, or snow, and averaging smoothed time series values (Roche et al., 2018). We generated statewide *NDVI* time series data (2000–2020) and extracted pre- and post-fire values for each historical wildfire analyzed to evaluate the impacts of wildfire severity on *NDVI* through regression analysis. The regression model was further applied to predict potential post-fire *NDVI* in the study areas, where variations in *NDVI* and the corresponding C factor differentiated soil loss between pre- and post-wildfire conditions.

As the first analytical step in estimating sediment yield (tonnes/ha·yr), we first delineated the downstream reservoir and its contributing catchment for each study area using the 'wbt_watershed' function from WhiteboxTools via the R package 'whitebox' (Lindsay, 2023). Then we calculated the sediment delivery ratio (*SDR*), which represents the proportion of eroded sediment that is transported from its source to a downstream reservoir or waterbody. To calculate *SDR*, we employed the empirical equation developed by Williams and Berndt (1972), which expresses *SDR* as: $SDR = 0.627\times SLP^{0.403}$, where *SLP* is the slope gradient. The *SLP* was calculated by dividing the elevation difference between the sediment source and the receiving reservoir and the shortest path to the reservoir boundary through channels. We calculated *SDR* at the pixel level, with total sediment delivery determined by spatially multiplying soil loss by the corresponding *SDR*.

Air-quality regulation. We estimated wildfire-induced $PM_{2.5}$ emissions for the study areas using a modified implementation of the Wildfire Burn Severity and Emissions (WBSE) framework (Xu et al., 2022). This approach integrates wildfire burn severity, vegetation classification, and empirical emission factors to generate spatially explicit estimates of

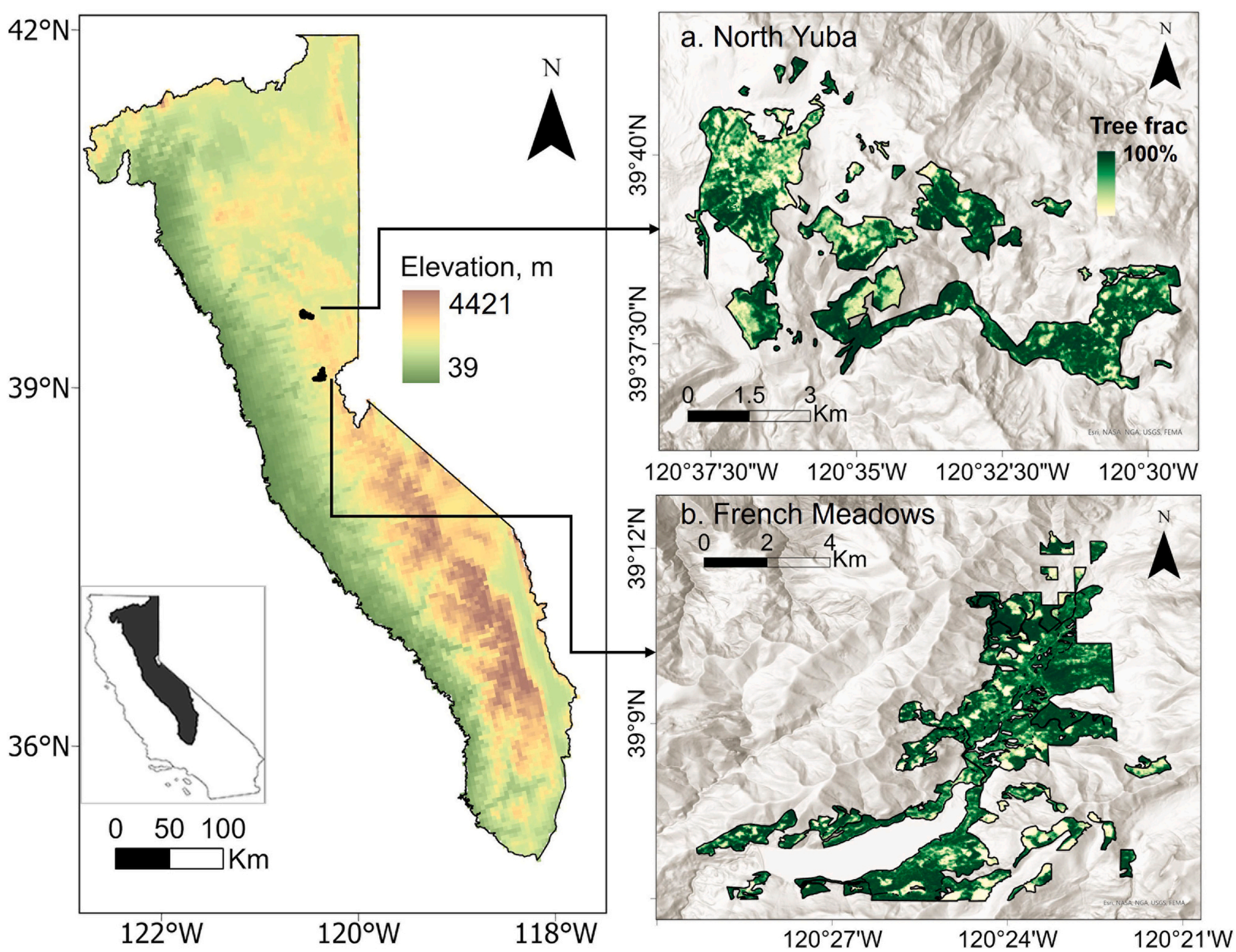


Fig. 1. Map of the study areas (a) North Yuba and (b) French Meadows in the Sierra Nevada of California. Subsequent maps maintain the same north arrow orientation and scale with this figure.

wildfire emissions, expressed using:

$$E = A_{vs} \times cr_{vs} \times F_v \times ef_v \tag{3}$$

where E is the mass of the total $PM_{2.5}$ emission (kg), A_{vs} and cr_{vs} refer to the area burned and fuel consumption rate of general vegetation class v under severity class s (low, moderate, and high severity). Vegetation classes within the study area were classified using the LANDFIRE Existing Vegetation Type product, grouped into five categories: grass, shrub, forest <1676 m (5500 ft., elevation), forest within 1676 m–2286 m (5500–7500 ft) and forest >2286 m (7500 ft). F_v is the fuel loading (kg biomass/m^2) for vegetation type v. cr_{vs} and F_v were estimated following Hurteau et al. (2014), with fuel loading and consumption values assigned to each severity class across five general vegetation categories, based on the First Order Fire Effects Model v5 (Reinhardt et al., 1997). ef_v is the emission factor for vegetation v. The emission estimates from this method were validated against existing inventories, including the California Air Resources Board and the Wildland Fire Emissions Information System (Xu et al., 2022). To address uncertainties in inputs (e.g., burn severity classification, fuel loading, and emission factors), we assigned a factor of 2 following Wiedinmyer et al. (2011), indicating that actual emissions could range between half and double our estimates.

2.3. Valuing the economic benefits of forest fuels treatment

The approach to quantifying the economic benefits of wildfire regulation through forest fuels treatment in this study builds upon the analytical framework established by Scott (2006) and Scott et al. (2013). This framework, widely cited in wildfire-risk assessments (e.g., Salis et al., 2016; Johnston et al., 2020; Bruni et al., 2024), quantifies wildfire risk through three key metrics: burn probability, burn severity, and the impacts of burn severity on ecosystem services. Forest fuels treatment can mitigate all three metrics, thereby reducing overall wildfire risk. The benefits of forest fuels treatment are defined as the difference in wildfire risk between treated and untreated scenarios, measured over the period during which this difference persists. Thus, we can derive the equation for the benefits of forest fuels treatment for a given landscape as follows:

$$Benefit = \sum_{i=1}^{4} \sum_{t=1}^{n} \sum_{k=1}^{3} \frac{(P_t \times S_{tk} - \widehat{P}_t \times \widehat{S}_{tk}) \times NVC_{ikt}}{(1+r)^t} \tag{4}$$

where i represents the i^{th} ecosystem service, with four services considered in total, t denotes the year after treatment, and n is the total number of years during which the treatment provides benefits, acknowledging that these benefits decline over time due to vegetation regrowth and fuel accumulation. Also, k refers to the burn severity. P_t represents the burn probability in year t, and S_{tk} represents the burn severity in year t. $\widehat{P}_t$ and $\widehat{S}_{tk}$ are the corresponding burn probability and severity post-treatment. NVC_{ikt} denotes the net value change of ecosystem service i at burn severity k in year t. The discount rate (r) is set at 3 %, with sensitivity analyses conducted to evaluate the impact of double versus half of this rate. The initial 3 % rate follows the U.S. Environmental Protection Agency Guideline (U.S. EPA, 2014), which recommends it for evaluating public policy benefits.

Impact of disturbance on wildfire. To examine the impact of forest fuels treatment on burn probability and predicted flame length of wildfire, we used historical forest disturbances, specifically changes in tree-canopy cover, shrub-canopy cover, and fuel, as proxies for treatment activities. This proxy approach reflects the reality that not all treatment records are spatially available at high resolution, but their biophysical impacts can be detected through disturbance patterns. With the available data, we performed regression analyses using burn probability and predicted flame length (m) one-year post-disturbance as dependent variables. The predictors included the area of disturbances (m^2), the extent of tree-canopy loss, shrub-canopy loss, and fuel loss (%), as well as pre-disturbance burn probability and predicted flame length. Wildfire polygons were used to clip forest-disturbance raster layers, and the mean value of each variable was calculated within each polygon. To ensure model robustness, we applied transformations (e.g., log and square-root) to burn probability and predicted flame length, and tested interaction terms among disturbance variables as well as between wildfire characteristics and disturbances. Model performance was evaluated using adjusted R^2 and the AIC, with final model selection based on both goodness-of-fit and parsimony. The models were validated using spatial cross-validation by dividing the data into 30 spatially distinct folds, with each fold split 7:3 into training and testing subsets, to evaluate performance while accounting for spatial autocorrelation.

To evaluate the impact of forest-disturbance extent on the time for burn probability and predicted flame length to return to pre-treatment values, we used 30 years of wildfire data (1986–2016) and extracted corresponding time series predicted flame-length data both pre- and post-disturbance, which allowed us to determine the time required for the mean predicted flame length within disturbance areas to return to pre-disturbance levels. Disturbance levels were categorized into 10 % increments, and mean recovery times were calculated for various combinations of tree-canopy and shrub-disturbance levels.

Uncertainty analysis. The economic analysis of forest fuels treatment incorporates multiple sources of uncertainty, including the effects of treatment on wildfire, the impacts of wildfires on ecosystem services, and the valuation of those services. To address these cumulative uncertainties, a Monte Carlo simulation framework was implemented, integrating random sampling and variability in key parameters through a multi-step process. Prediction intervals for post-treatment wildfire characteristics (burn probability and predicted flame length), and the effects of wildfires on ecosystem services were derived using residual errors and coefficients from the respective models. Uncertainty in the economic valuation of ecosystem services was addressed by sampling prices from appropriate distributions. For each study area, 1000 random samples were generated by drawing parameters for wildfire prediction models, ecosystem service response models, and ecosystem service values, and the benefit of each ecosystem service category was calculated. This process propagated uncertainty across the entire analysis chain, and final outputs were summarized using mean values and 95 % confidence intervals. Building on findings from Stephens et al. (2022), which identified 693 trees/ha as a threshold distinguishing high from moderate/low fire severity in the southern Sierra Nevada, we assumed this value as a benchmark for treatment planning. With pre-disturbance tree densities averaging 986 and 954 trees/ha in our study areas, we assumed a treatment scenario that reduces canopy cover and fuel load by 30 %, aligning with the reduction needed to reach the Stephens et al. threshold and the typical intensity of ongoing treatment projects.

Valuation of ecosystem services. The net value change of ecosystem services is determined by both the effects of wildfire on ecosystem services and the valuation of those services. For valuation, we applied local market price and unit value transfer method where the local studies are limited (Johnson et al., 2015). Carbon storage was valued using the social cost of carbon ($/ton), timber by local market prices ($/MBF), erosion regulation by sediment dredging costs ($/$m^3$), and air-quality values with BenMAP-CE to quantify health-related benefits.

The social cost of carbon estimates the economic loss of one additional ton of carbon dioxide emitted into the atmosphere (Tol, 2011; Nordhaus, 2017). We adopted the estimates from Rennert et al. (2022), who developed the Greenhouse Gas Impact Value Estimator to integrate climate science, socioeconomic modeling, and probabilistic analysis, with a mean of $185/ton ($44–$413 95 % percentile) for CO_2 emitted in 2020. Based on the associated Social Cost of Carbon Explorer Tool (Prest et al., 2022) derived from Rennert et al. (2022), we used projected social cost of carbon values of $226/ton ($54–$503, 95 % percentile) in 2030 and $263/ton ($64–$593, 95 % percentile). Values for intermediate years were estimated using linear interpolation. To consider the uncertainty of the social cost of carbon, we applied a log-normal distribution to the social cost of carbon, which is right-skewed and bounded below by zero. The distribution was fitted to the reported 5th, 50th, and 95th percentiles, and random samples were drawn during each Monte Carlo iteration. Local market timber prices were derived from the California Department of Tax and Fee Administration's half-yearly timber-harvest reports (CDTFA, 2024). These reports detail region-specific prices, with the study areas located in Zone 7. Species-specific timber prices were as follows: Ponderosa Pine at \$153/MBF (range: \$100–\$250), Hem/Fir at \$183/MBF (range: \$130–\$250), and Miscellaneous Conifer at \$73/MBF (range: \$50–\$130). Tree species in the two study areas were categorized into these price categories. Normal distributions were fitted to each timber category using reported mean and range of values (as 95 % percentiles), enabling uncertainty analysis via Monte Carlo simulation. We employed sediment removal cost models tailored for U.S. reservoirs, as outlined in the Anchor QEA report (QEA, 2020), to value erosion-regulation benefits. Mechanical dredging through water was identified as the most suitable method due to its effectiveness in handling coarse-grained sediment and woody debris commonly resulting from wildfire-induced erosion. The variable costs of sediment removal were accounted for, with unit costs ranging from \$55 to \$179/m^3 in 2020, with a normal distribution applied for uncertainty (mean and 95 % percentiles). For validation, a related study reported a cost of \$100/m^3, based on Denver Water's dredging of Strontia Springs Reservoir following the Buffalo Creek and Hayman fires (Jones et al., 2017). We used a ratio of 1.13 m^3/ton to convert sediment mass to volume, based on Snyder et al. (2004) for Yuba River sediment properties.

The valuation of air-quality regulation was conducted using BenMAP-CE (version 1.5.8.17), an open-source software developed by the U.S. EPA. BenMAP-CE is widely recognized for estimating the economic health costs associated with wildfires (Sacks et al., 2018; Wang et al., 2021). The calculation follows the equation below:

$$Value_{air} = \sum_{h=1}^{m} Y_{0h}\left(1 - e^{-\beta_h \Delta PM}\right) \times Pop \times Ch_h \quad (5)$$

where h represents to the h_{th} health outcome, and m is the total kinds of health outcomes we assessed. In this study we assessed two outcomes, namely hospital admission of all respiratory illnesses and hospital admission of all cardiovascular illnesses. $Y_{0h}\left(1 - e^{-\beta_h \Delta PM}\right) \times Pop$, known as the health-impact function, estimates the incidence of health outcome. 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 exposed population; Y_{0h} is the baseline health incidence rate of h_{th} health impact (Table S3). ΔPM is the expected change of air quality ($PM_{2.5}$) from wildfire. $PM_{2.5}$ emissions from wildfire were allocated based on established dispersion patterns: vertically decreasing exponentially to negligible levels at 2 km (Chen et al., 2022) and horizontally decreasing linearly within a 200-mile (322-km) radius (Moeltner et al., 2013; Aguilera et al., 2021). Ch_h reflects the economic valuation of each health outcome case. Monte Carlo simulation was performed inside BenMAP-CE to account for uncertainties in health impacts and economic valuation (Tables S4).

Sensitivity analysis. To identify key drivers of the total economic benefits of forest fuels treatment, we conducted a sensitivity analysis on five critical parameters: burn probability, predicted flame length, treatment intensity (baseline 30 %), ecosystem service value, and discount rate (baseline 3 %). Each parameter was independently adjusted by a factor of two (halved and doubled) while keeping all other variables constant at their baseline values. The total economic benefits were recalculated as the sum of the net value changes across all assessed ecosystem services for each parameter adjustment, and the percentage changes relative to the baseline scenario were recorded.

3. Results

3.1. Impacts of wildfires on ecosystem services

Carbon storage. For low, moderate, and high burn-severity levels, paired *t*-tests revealed significant reductions carbon storage (kg/m^2) one year after the wildfire compared to one year before, and a clear gradient with mean decrease of 1.75 kg/m^2 ($p < 0.001$; 95 % CI: 1.63–1.87), 6.43 kg/m^2 ($p < 0.001$; 95 % CI: 6.11–6.75), and 12.32 kg/m^2 ($p < 0.001$; 95 % CI: 11.80–12.83), respectively.

We constructed a linear-regression model to evaluate the relationship between pre-fire carbon storage, burn severity, and post-fire carbon storage:

$$C\_Post = \beta 0 + \beta 1 \times C\_Pre + \beta 2 \times (C\_Pre \times high) + \beta 3 \times (C\_Pre \times moderate) + \beta 4 \times low + \epsilon.$$

Where *C_Post* and *C_Pre* are carbon storage after and prior to the wildfire, respectively. High, moderate, and low are dummy variables referring to the observed burn severity. ϵ is the residual error. The final specification was selected based on a comparison of alternative model forms using adjusted R^2, AIC, and VIF as selection criteria (Table S5). The results of the model explained a substantial proportion of the variance in post-fire carbon storage (adj $R^2 = 0.9652$, $p < 0.001$), which highlights its effectiveness in quantifying wildfire impacts on carbon storage and projecting potential future losses under varying burn severity scenarios (Table S5). The significant negative coefficients for the interaction terms with pre-fire carbon storage ($\beta 2 = -0.42623$ for high severity and $\beta 3 = -0.31237$ for moderate severity, $p < 0.001$) suggest that as pre-fire carbon storage increases, wildfire-induced carbon loss is exacerbated under higher burn severities.

The results indicate that, in the event of a wildfire, the mean carbon storage in the North Yuba study area is projected to decline from 27.5 kg/m^2 to 20.6 kg/m^2, representing a mean reduction of 6.9 kg/m^2 (95 % CI: 2.3–11.6 kg/m^2), equivalent to a 25 % loss (8 %–42 %). In the French Meadows study area, the corresponding values are 29.0 kg/m^2 to 21.0 kg/m^2, a mean reduction of 8.0 kg/m^2 (95 % CI: 3.4–12.7 kg/m^2), or a 28 % loss (12 %–44 %) (Fig. 2). Considering the burn probability, the annual expected carbon loss is estimated to be 0.07 kg/m^2 (95 % CI: 0.03–0.11 kg/m^2) for North Yuba and 0.12 kg/m^2 (95 % CI: 0.05–0.19 kg/m^2) for French Meadows (details in Fig. S3 a and b).

Timber provisioning. We estimated the timber volume for two regions, as shown in Fig. 3 (a, c). In North Yuba, the average timber volume is 531 MBF/ha, and is 215 MBF/ha higher in the French Meadows, at 746 MBF/ha. Both areas are characterized by Sierra Nevada mixed-conifer forests, primarily composed of fir (Abies spp.), pine (Pinus spp.), and incense cedar (*Calocedrus decurrens*) (Fig. S4). Further, the average DBH, stand height, and density (trees with DBH > 2.5 cm) in French Meadows are 0.4 cm larger, 3.1 m taller, and 32 trees/ha lower, respectively, compared to North Yuba, indicating that trees in French Meadows tend to be larger on average. The histograms further reveal the distribution of volume across each landscape, showing a greater proportion of high-volume areas in French Meadows compared to North Yuba.

To assess the impact of wildfire on timber biomass, we modeled post-fire tree biomass as a function of pre-fire biomass, wildfire severity (high, moderate, low), and their interactions, with an adjusted R^2 of 0.967 (Table S5). Pre-fire biomass had an overall strong positive relationship with post-fire biomass ($\beta = 0.973, p < 0.001$), but this effect was significantly altered by fire severity. High-severity fires significantly weakened the positive relationship between pre-fire and post-fire biomass ($\beta = -0.434, p < 0.001$), indicating a substantial reduction in biomass. A similar but smaller effect was observed under moderate-severity fires ($\beta = -0.323, p < 0.001$).

The predicted mean Scribner timber-volume losses due to wildfire are 133 MBF/ha (95 % CI: 39–228) for North Yuba (Fig. 3b), and 211 MBF/ha (95 % CI: 94–334) for French Meadows (Fig. 3d), with substantial losses distributed more broadly across the region, particularly in areas of higher initial timber volume. The histograms below each panel show the distribution of volume losses, with the majority of pixels experiencing losses below 200 MBF/ha in both regions. However, in French Meadows, a notable fraction of pixels exhibits losses exceeding 400 MBF/ha, highlighting areas with significant timber impacts. When

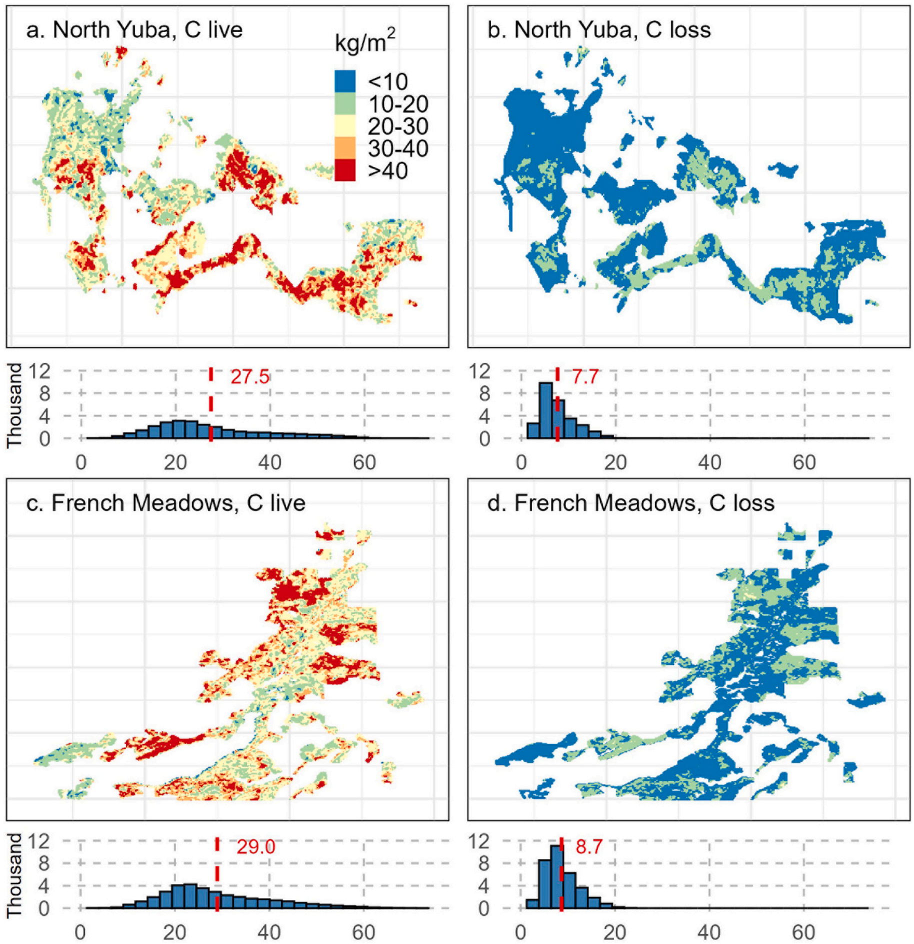


Fig. 2. Maps and histograms (30-m gridded) of carbon (C live) and carbon loss (C loss) due to wildfire in North Yuba (a, b) and French Meadows (c, d). Red lines in histograms indicate mean values.

incorporating annual burn probability, the mean annual volume loss is 1.2 MBF/ha (95 % CI: 0.4–2.0) in North Yuba and 3.2 MBF/ha (95 % CI: 1.4–4.9) in French Meadows (details in Fig. S3 c and d). These results underscore the greater susceptibility of French Meadows to wildfire-driven timber volume loss, likely due to its higher initial timber volume and potentially more-severe fire behavior.

Erosion regulation. A regression analysis of the historical impacts of fire severity on *NDVI* (Table S5) indicates that wildfire-induced vegetation loss leads to significant reductions in *NDVI* (Fig. S5 a and c). French Meadows has a higher projected mean reduction of 0.24 (95 % CI: 0.13–0.35, pre-fire NDVI: 0.62) compared to North Yuba's mean reduction of 0.20 (95 % CI: 0.10–0.31, pre-fire NDVI: 0.57). Correspondingly, the *C* factor (eq. 2) shows mean increases of 0.24 (95 % CI: 0.10–0.42) for French Meadows and 0.23 (95 % CI: 0.08–0.41) for North Yuba.

The estimated annual-soil-loss potential following wildfire exhibits significant spatial variation across the two study areas. The North Yuba region is projected to incur a mean annual soil loss of 4396 t per hectare per year (t/ha·yr) (95 % CI: 1587–7844), with values ranging from less than 1500 t/ha in low-risk zones to over 6000 t/ha in areas with steep slopes. Similarly, the French Meadows region is expected to experience a mean soil loss of 4761 t/ha·yr (95 % CI: 1964–8236) (Fig. 4 a and c), underscoring the high erosion susceptibility in wildfire-affected landscapes, particularly in areas characterized by steep topography and high rainfall erosivity (Fig. S6).

Both study areas are located within watersheds supplying downstream reservoirs. Specifically, North Yuba corresponds to the New Bullards Bar Reservoir, while French Meadows is associated with the French Meadows and Hell Hole Reservoirs (Fig. S7). The *SDR*, which quantifies the connectivity between eroded areas and downstream reservoirs, differs significantly between the two regions. French Meadows has a mean *SDR* of 0.231, indicating higher connectivity compared to North Yuba's mean of 0.154. This difference is driven by French Meadows' steeper slope gradients and closer proximity to the reservoir (Fig. S7). Accounting for SDR, sediment delivery to reservoirs is estimated at a mean of 909 t/ha·yr (95 % CI: 243–1207) for North Yuba and 1293 t/ha·yr (95 % CI: 443–1863) for French Meadows (Fig. 4 b and d). Areas with SDR values exceeding 0.3 and significant soil loss contribute substantially to the total sediment delivery (Fig. S5 c and d). When accounting for the annual burn probability, the expected annual sediment delivery is estimated at 6.8 t/ha·yr (95 % CI: 2.5–12.2) for the North Yuba and 16.0 t/ha·yr (95 % CI: 6.6–27.8) for the French Meadows (details in Fig. S3 e and f).

Air-quality regulation. The spatial analysis of wildfire-induced $PM_{2.5}$ emissions reveals distinct patterns and magnitudes between the North Yuba and French Meadows study areas. The results reveal that, if wildfires occur across the study areas, North Yuba's mean $PM_{2.5}$ emissions are estimated at 213 kg/ha, with an uncertainty range of 107–426 kg/ha, resulting in a total emission of 488 t (244–976 t). French Meadows, by comparison, has a higher mean emission of 284 kg/ha, with a range of 142–426 kg/ha and a total emission of 807 t (403–1614 t), indicating a potentially greater contribution to regional air pollution (Fig. 5). Incorporating burn probability, the annual expected $PM_{2.5}$ emissions are 2.11 kg/ha (1.06–4.22) for North Yuba and 4.21 kg/ha (2.1–8.42) for French Meadows, reflecting the latter's higher fire risk on the $PM_{2.5}$ emissions potential per hectare (details in Fig. S3 g and h).

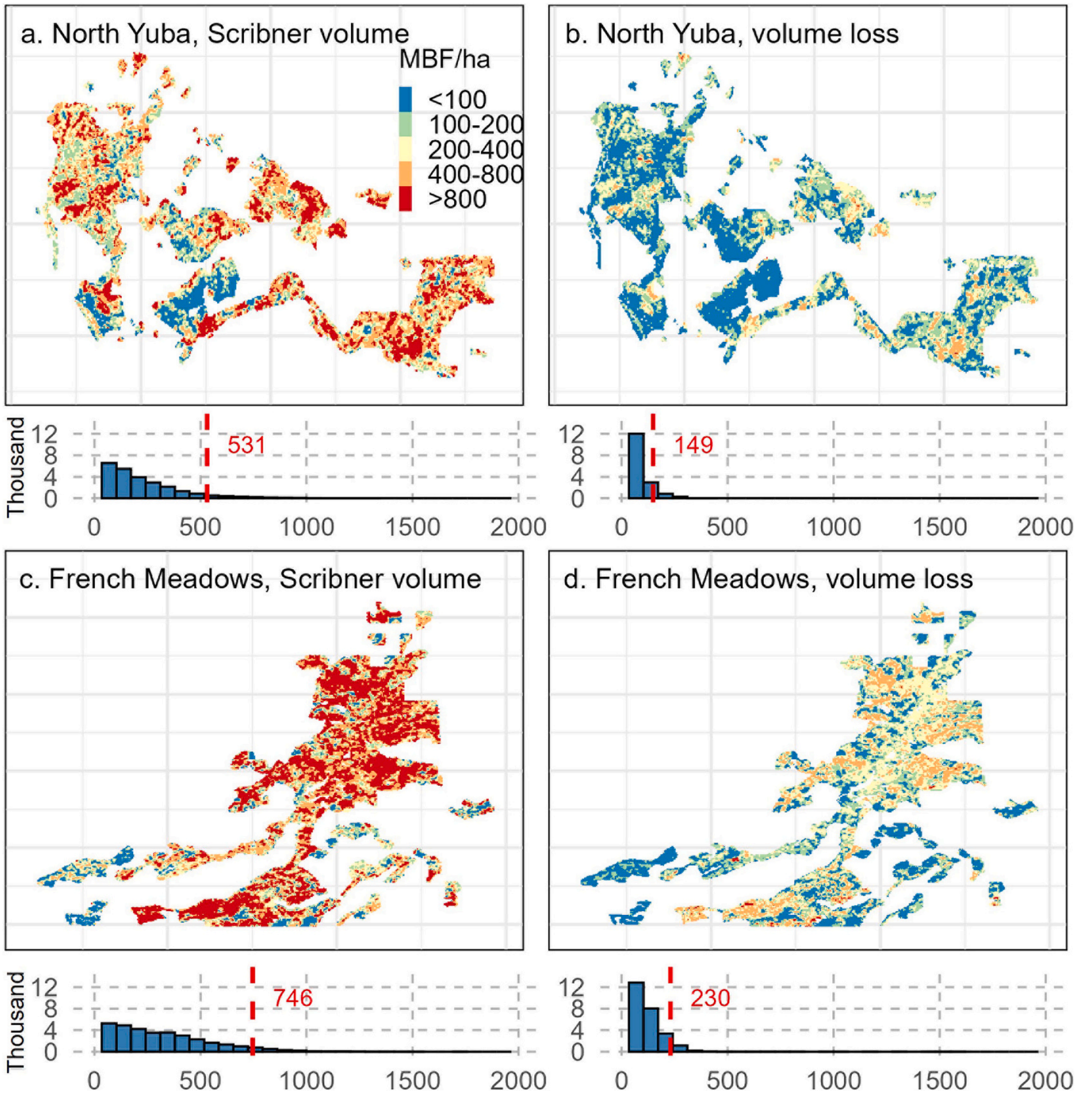


Fig. 3. Maps and histograms (30-m gridded) of timber volume and timber volume loss due to wildfire in North Yuba (a, b) and French Meadows (c, d). Red lines in histograms indicate mean values.

3.2. Valuing the benefits of forest fuels treatment

The predictor variables for post-disturbance burn probability explained 82.8 % of its variance (adjusted $R^2 = 0.8277$, $p < 0.001$; Table S6), with pre-disturbance burn probability, tree canopy change, and wildfire disturbance area as significant predictors. Tree canopy change demonstrated a significant mitigating effect, with a 1 % reduction in tree canopy cover corresponding to a 2.3 % decrease in burn probability ($p < 0.001$). Additionally, the extent of the wildfire disturbance area showed a significant negative effect on burn probability (coefficient $= -4.60 \times 10^{-10}$, $p < 0.001$). Pre-disturbance burn probability showed a direct scaling relationship with post-disturbance burn-probability values (coefficient $= 1.02$, $p < 0.001$). For predicted flame length, the predictor variables accounted for 83.5 % of the variance (adjusted $R^2 = 0.83$, $p < 0.001$). Unlike burn probability, changes in tree canopy, shrub canopy, and fuel disturbances all significantly influenced predicted flame length. Specifically, a 1 % increase in tree canopy disturbance resulted in approximately a 1.25 % reduction in predicted flame length ($p < 0.001$), while reductions in shrub canopy disturbance and fuel disturbance decreased predicted flame length by approximately 0.72 % ($p < 0.001$) and 0.70 % ($p < 0.001$), respectively. Pre-disturbance predicted flame length is another significant predictor, with a coefficient $= 0.90$ ($p < 0.001$). The spatial cross-validation results showed consistent model performance for both models, with stable R^2 values across total data, training samples, and testing samples (Fig. S8). For the study areas, model predictions indicate that increasing treatment intensity from 10 % to 70 %, measured by the overall percentage reduction in tree canopy, shrub canopy, and fuel load, leads on average to a 20.4 % to 79.8 % reduction in overall burn probability and a 23.4 % to 84.5 % reduction in predicted flame length (Fig. 6a and b). Recovery time for predicted flame length increased with greater reductions in tree and shrub canopies. Minimal reductions (<10 %) showed recovery within 10 years, while higher reductions (>50 %) extended recovery up to 18 years (Fig. 6c).

Wildfires lead to substantial ecosystem service losses (Fig. 7a). Carbon storage losses were estimated at $52,876/ha (95 % CI: $8562–$140,759) in North Yuba (23.1 km^2) and $62,652/ha (95 % CI: $13,495–$165,367) in French Meadows (28.6 km^2). Losses in timber provisioning were $22,270/ha (95 % CI: $5976–$41,556) in North Yuba and $36,733/ha (95 % CI: $13,969–$63,878) in French Meadows. Erosion regulation resulted in the highest economic losses, amounting to $82,075/ha (95 % CI: $42,515–$125,952) in North Yuba and $130,848/ha (95 % CI: $72,809–$195,525) in French Meadows. Air quality regulation losses were also significant, reaching $14,433/ha (95 % CI: $4762–$33,150) in North Yuba and $28,647/ha (95 % CI: $9563–$74,204) in French Meadows. Aggregating across all ecosystem services,

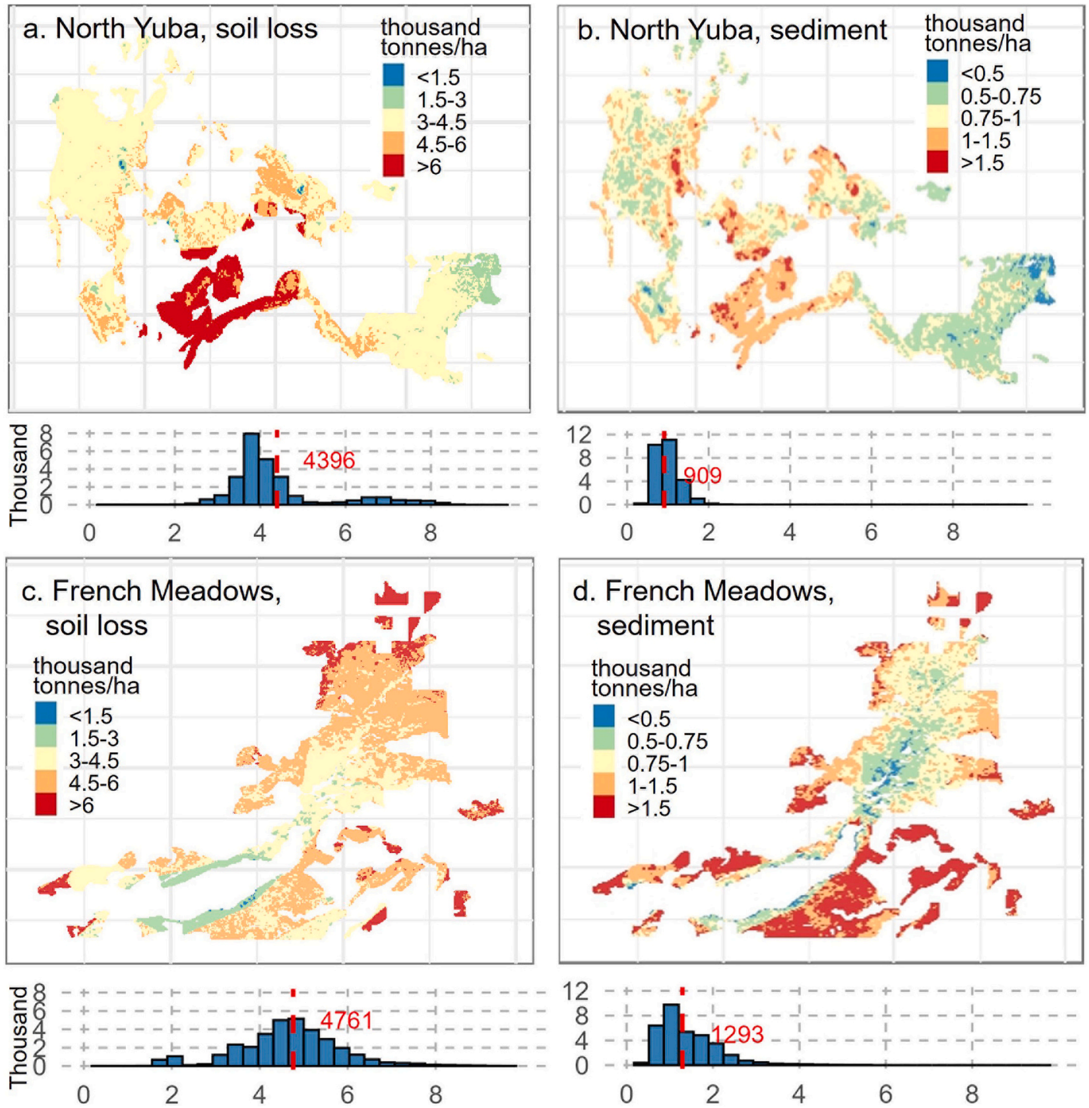


Fig. 4. Maps and histograms (30-m gridded) of soil loss and sediment delivery due to wildfire in North Yuba (a, b) and French Meadows (c, d). Soil loss (a, c) and sediment delivery (b, d) are shown in tonnes/ha, with red lines in histograms indicating mean values.

total economic losses were $396.86 million (95 % CI: $142.92 million–$789.36 million) for the North Yuba region and $740.40 million (95 % CI: $314.13 million–$1.43 billion) for the French Meadows region.

Forest fuels treatment with a 30 % reduction in tree canopy, shrub canopy, and fuel load, can significantly mitigate wildfire-induced losses and provide measurable economic benefits (Fig. 7b). In the North Yuba region, this treatment intensity reduced burn probability by 49.6 % (95 % CI: 15.1–84.1), and predicted flame length by 55.0 % (95 % CI: 18.6–75.1) in the first year after treatment. The French Meadows region showed similar outcomes, with average reductions of 49.7 % in burn probability and 55.9 % in predicted flame length. The recovery time for these treatments was estimated at 13 years, during which wildfire risk is expected to gradually increase following an initial reduction in the first year. This recovery time also represents the period over which the benefits from the avoided cost of wildfire are expected to be realized. For carbon storage, the benefits of treatment over the recovery years were estimated at $2173/ha (95 % CI: $511–$4051) in North Yuba and $3702/ha (95 % CI: $1107–$6762) in French Meadows. Timber provisioning benefits were $838/ha (95 % CI: $248–$1527) in North Yuba and $2178/ha (95 % CI: $795–$3802) in French Meadows. Erosion regulation provided the largest avoided costs, with benefits of $2679/ha (95 % CI: -$231 to $5515) in North Yuba and $6379/ha (95 % CI: $108 to $12,452) in French Meadows. However, it also showed the greatest uncertainty, primarily driven by variability in post-fire NDVI values and the associated uncertainty in the *C* factor. For air quality regulation, benefits reached $374/ha (95 % CI: $137–$968) in North Yuba and $777/ha (95 % CI: $288–$1811) in French Meadows. Aggregating across ecosystem services, the total benefits were $6069/ha (95 % CI: $667–$12,074/ha) for North Yuba, and $13,035/ha (95 % CI: $2297–$24,829/ha) for French Meadows. These differences reflect variations in wildfire risk and baseline ecosystem service values between the two study areas.

The sensitivity analysis revealed consistent patterns across both study areas (Fig. 8). Ecosystem service value was the most influential parameter, with doubling leading to a 100 % increase in total benefits and halving causing a 50 % decrease. Burn probability ranked second, with a doubling yielding 80–90 % higher benefits and halving reducing benefits by roughly 40 %. Treatment intensity also showed a strong effect, where doubling increased benefits by 70 %, and halving resulted in a 50 % loss. In contrast, predicted flame length had a relatively minor influence: doubling increased benefits by only 15–20 %, while halving reduced them by 10 %. The discount rate exhibited the smallest effect, with halving producing just a 4 % gain and doubling resulting in a 2 % loss.

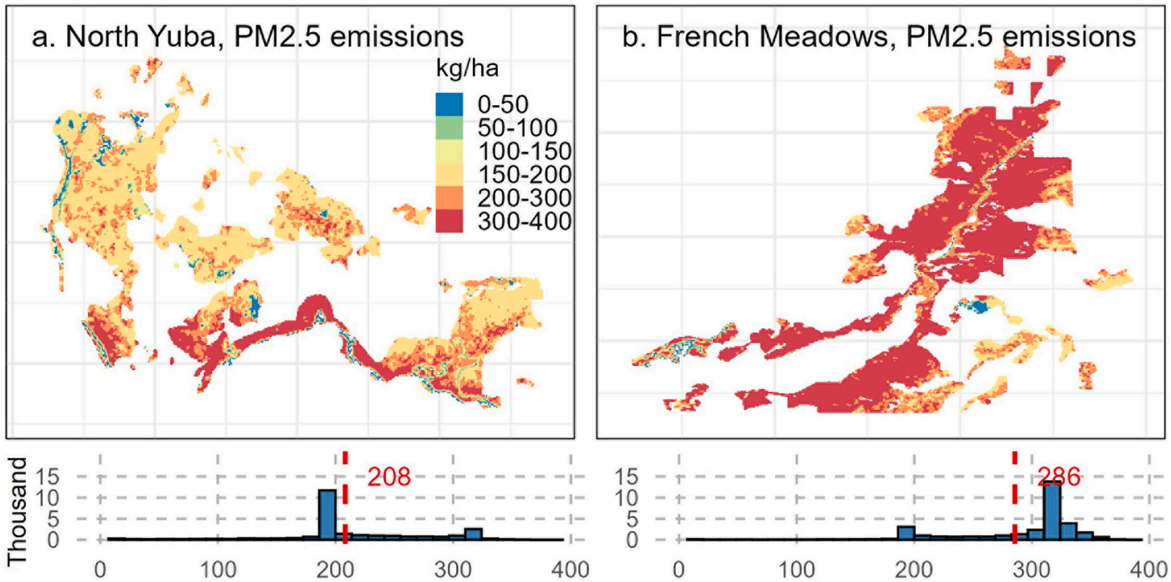


Fig. 5. Wildfire-induced $PM_{2.5}$ emissions (kg/ha, 30-m gridded) in North Yuba (a) and French Meadows (b). Red lines in histograms indicate mean values.

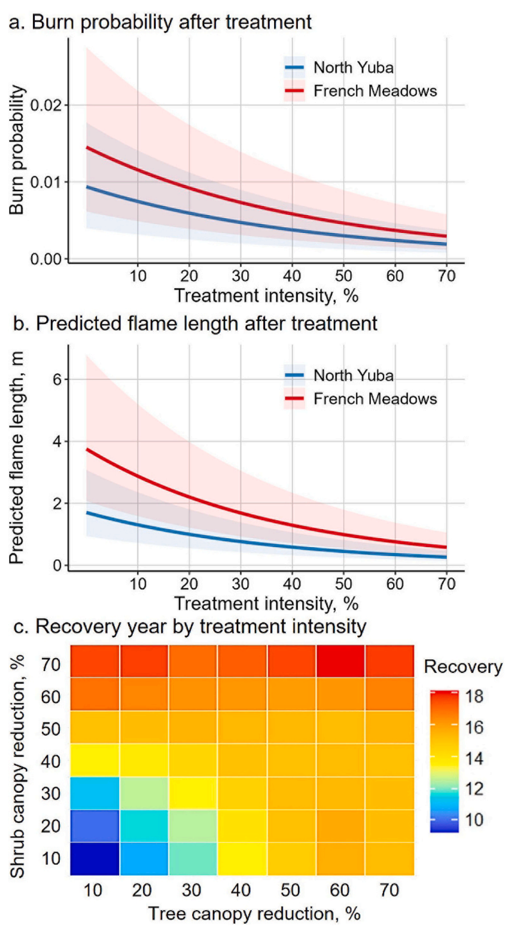


Fig. 6. (a) Burn probability by treatment intensity of the two project areas, with shaded area showing the 95 % CI; The intensity refers to the percentage of reduction applied to tree canopy, shrub canopy and fuel load (b) Predicted flame length by treatment intensity of the two project areas, with shaded area showing the 95 % CI; (c) Recovery years of wildfire characteristics by treatment intensity of tree and shrub canopy.

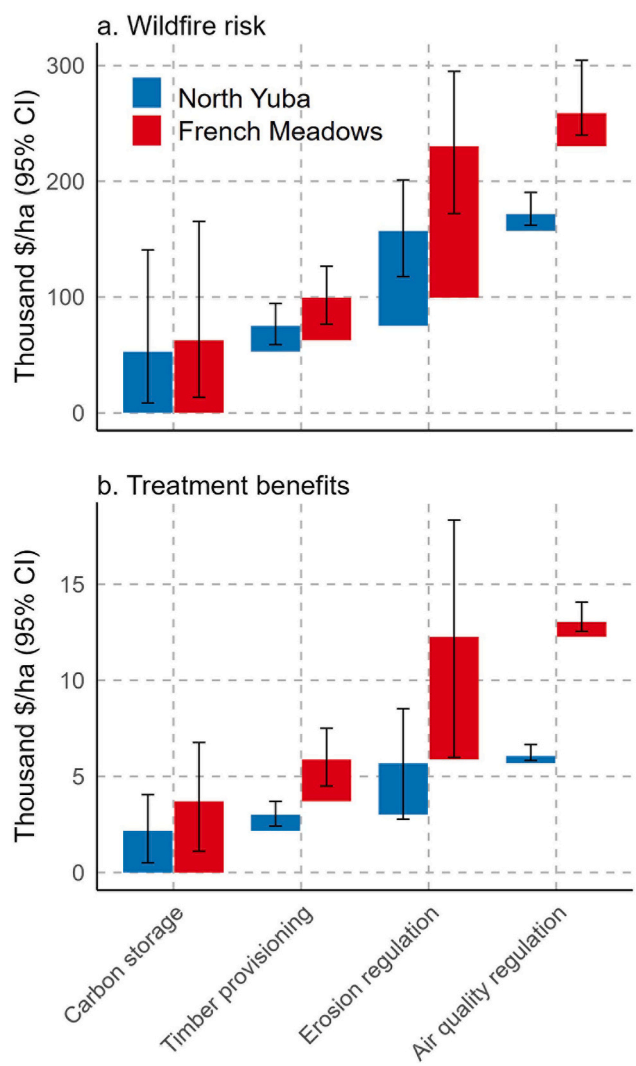


Fig. 7. (a) Wildfire risk and (b) treatment benefits for each ecosystem service in North Yuba and French Meadows, with 95 % confidence intervals.

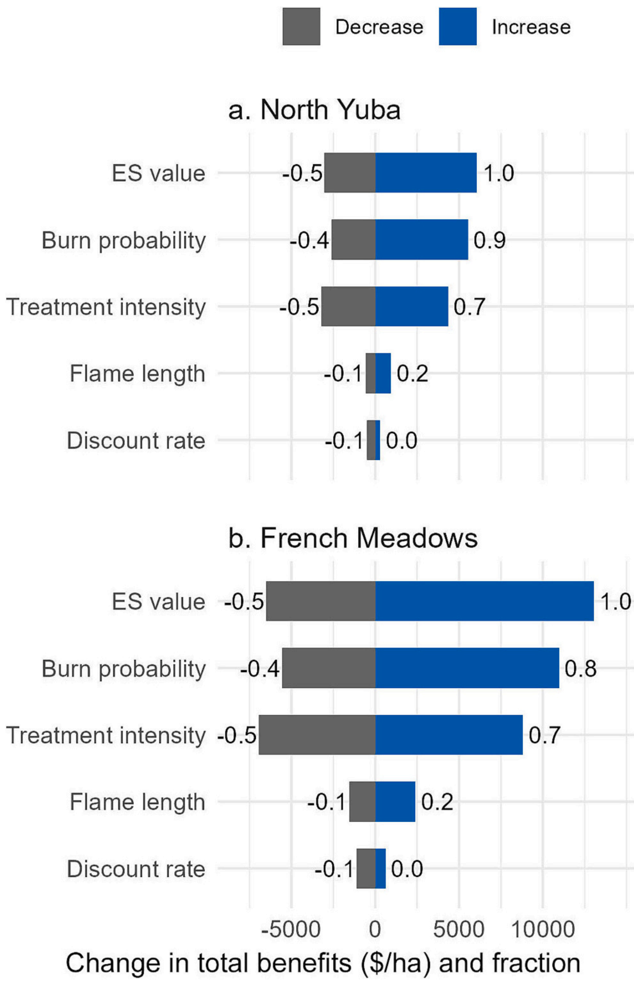


Fig. 8. Sensitivity analysis of applying multiplier factor to increase or decrease key variables for (a) North Yuba and (b) French Meadows. Bars show the resulting changes in mean total benefits reported in Fig. 7 and numbers indicate the magnitude of positive or negative change.

4. Discussion

4.1. Drivers and variability in benefits

Based on the results of the sensitivity analysis, the notable influence of ecosystem service value highlights the economic sensitivity of forest fuels treatment activities, where market fluctuations can influence economic feasibility alongside ecological factors. Given this, rigorous local market assessments and context-specific valuation of ecosystem services are essential for accurate cost-benefit analyses. Similarly, the critical role of burn probability suggests that maximizing economic efficiency requires prioritizing treatments in areas where wildfires are most likely to occur, rather than focusing solely on regions with the most severe fire behavior potential. Increasing treatment intensity also enhances economic benefits, but sensitivity analysis reveals that the relative loss from halving treatment intensity is 25 % greater than the gain from doubling it, indicating diminishing marginal returns to increased treatment intensity. This asymmetry also suggests that it may be more cost-effective to ensure a minimum intensity threshold across high-risk areas than to concentrate very high intensity in a limited set of sites. The relatively minor effects of predicted flame length and discount rate suggest that uncertainties in these factors are less critical to total benefit estimates, although they may still influence local-scale outcomes or long-term projections.

Comparing the two study areas, regional variability in benefits was observed. Under the same treatment intensity, French Meadows showed significantly higher per-hectare treatment benefits ($13,034/ha vs $6069/ha in North Yuba). The benefits of forest fuels treatment are site-specific, influenced not only by wildfire characteristics identified in the sensitivity analysis but also by the ecological characteristics of the treatment area and the attributes of affected nearby regions. For example, French Meadows has 15 t/ha more carbon storage and 215 MBF/ha more timber stock than North Yuba. In the wildfire impact models, these higher baseline values, coupled with their interaction with fire severity, result in greater losses in areas with higher carbon or timber stocks under similar fire severity. Moreover, the soil loss risk in French Meadows is 1.08 times that of North Yuba, but downstream sediment deposition is 1.42 times that of North Yuba. This difference is largely due to the geographic position of the associated reservoir relative to the study area. This indicates that when placing treatments, we should not only consider factors influencing soil loss but also take into account the landscape's *SDR* relative to downstream reservoirs, especially for areas with similar ecogeographic conditions, where *SDR* may be more decisive. Regarding air quality, $PM_{2.5}$ emissions per hectare in French Meadows are 1.33 times those in North Yuba, while the resulting economic health losses are 1.98 times greater. This discrepancy suggests a more vulnerable population near French Meadows.

Forest fuels treatment also comes with associated costs. Beyond mechanical and labor costs, additional factors must be considered for achieving specific benefits. For instance, prescribed fire, a commonly used method, reaches a carbon benefits break-even point in our study area when its carbon loss is equivalent to 27 % of the carbon loss from a low-severity wildfire. Prescribed fire may also pose health risks to densely populated areas due to smoke emissions. The short-term health-related economic costs of these emissions were not quantified here and could partially offset the air-quality benefits gained from lowering the probability and severity of wildfires. Additionally, forest fuels treatment can potentially increase soil loss, due to soil disturbance and reduced ground cover. In areas where soil retention is critical, and when treatment intensity is high, erosion mitigation interventions can be employed to mitigate the risk of soil loss (USDA, 2006). Forest fuels treatment that prioritizes areas with high burn probability and significant ecosystem service values, while strategically adjusting treatment intensity to balance economic benefits and environmental risks, can deliver greater benefits.

4.2. Implications of quantifying benefits

Wildfires result in tremendous economic losses, yet the pace and scale of forest fuels treatment to mitigate wildfire risks remain far below what is needed. This study quantifies the economic benefits of treatment across multiple ecosystem services and provides a scalable methodology to enable such quantification. Despite uncertainties, these benefits are potentially substantial and provide a range of advantages to diverse stakeholders. In our case studies, direct beneficiaries include residents of California and downwind areas (air quality), carbon-credit developers, wood-product companies, infrastructure owners such as counties, municipalities, and water agencies (erosion regulation), and the U.S. Forest Service as the land manager. These benefits also support state agencies such as the California Department of Forestry and Fire Protection, the Air Resources Board, and others in fulfilling their statutory responsibilities in wildfire prevention, public health protection, habitat and biodiversity conservation, water security, and assistance to underserved communities. Sufficient monetized benefits can create opportunities to overcome financial and resource constraints in forest fuels treatment. For example, the framework proposed by Quesnel Seipp et al. (2023) facilitates public-private partnerships and cost-sharing mechanisms, enabling private capital to finance forest fuels treatment. Beneficiaries of forest fuels treatment provide phased payments to investors, offering competitive returns based on projected outcomes. This approach can expand funding for forest fuels treatment, accelerating and scaling up treatment to enhance forest sustainability and resilience. The quantification of the multi-benefits can provide crucial support for such financing models.

4.3. Limitations

While the study identifies key economic benefits of forest fuels treatment in mitigating wildfire-induced losses to ecosystem services, three main limitations remain. First, the analysis spans multiple interconnected processes, from treatment effects on wildfire behavior to ecosystem service responses and valuations, each introducing uncertainty due to data limitations, model assumptions, and real-world variability. Future research should refine models in these stages incorporating higher-resolution data and improved calibration to reduce these uncertainties. Second, the analysis does not account for climate change, a critical driver of wildfire occurrence, severity, and extent. Rising temperatures, prolonged droughts, and vegetation shifts are expected to exacerbate these characteristics, amplifying impacts on ecosystem services and potentially altering the cost-effectiveness of treatment. Integrating climate projections into wildfire models can provide a more comprehensive and long-term estimation of wildfire impacts and the benefits of forest fuels treatment. Third, while this study quantifies several key ecosystem services, it does not capture the full suite of potential benefits, especially the non-market benefits. These include recreation, biodiversity conservation and other cultural services. Quantifying these services typically requires alternative data sources and methods, such as visitor surveys, mobile phone mobility data, or regional tourism statistics for recreation, and species richness indices for biodiversity. The analytical framework developed here could be extended in future work to incorporate these additional services where credible datasets are available.

5. Conclusions

This study presents an integrative methodology to quantify the economic benefits of forest fuels treatment in mitigating wildfire-induced losses across multiple ecosystem services, including carbon storage, timber provisioning, erosion regulation, and air-quality regulation. By linking historical data on forest disturbances, ecological variables, and market-based valuation models, we demonstrate that treatments can substantially reduce wildfire risk to both ecological systems and public health, and deliver measurable, significant economic benefits, particularly in high-risk forested regions in California's Sierra Nevada. When treatments are strategically implemented, individual ecosystem service benefits can range from several hundred to several thousand dollars per hectare, with total benefits exceeding $10,000/ha at a landscape level. The magnitude of these benefits is site specific and sensitive to burn probability, treatment intensity, and the baseline value of affected ecosystem services. This quantitative analysis provides a scalable approach to inform regional forest-management strategies and support innovative financing mechanisms such as public–private cost-sharing models, which can accelerate the pace and scale of forest fuels treatment efforts that enhance ecosystem sustainability and community resilience in wildfire-vulnerable landscapes.

CRediT authorship contribution statement

Han Guo: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation. **Michael Goulden:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Funding acquisition, Data curation. **Min Gon Chung:** Writing – review & editing, Validation, Software, Methodology. **Qingqing Xu:** Writing – review & editing, Validation, Software, Methodology. **Charity Nyelele:** Writing – review & editing, Validation, Software, Methodology. **Weichao Guo:** Writing – review & editing, Validation, Software, Methodology. **Benis Egoh:** Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition. **Martha Conklin:** Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition. **Catherine Keske:** Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition. **Mohammad Safeeq:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Funding acquisition. **Roger Bales:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

This research was supported by a graduate fellowship to the first author by the California Department of Forestry and Fire Protection (award#8GG21812), by the California Climate Investments program, through the Strategic Growth Council (CCR20021) and by USDA National Institute of Food and Agriculture (grant 2018-67004-24705).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2025.180487.

References

Agee, J.K., Skinner, C.N., 2005. Basic principles of forest fuel reduction treatments. For. Ecol. Manage. 211 (1–2), 83–96. https://doi.org/10.1016/j.foreco.2005.01.034.

Aguilera, R., Corringham, T., Gershunov, A., Benmarhnia, T., 2021. Wildfire smoke impacts respiratory health more than fine particles from other sources: observational evidence from Southern California. Nat. Commun. 12 (1). https://doi.org/10.1038/s41467-021-21708-0.

Ayalew, D.A., Deumlich, D., Šarapatka, B., Doktor, D., 2020. Quantifying the sensitivity of NDVI-based C factor estimation and potential soil Erosion prediction using Spaceborne earth observation data. Remote Sens 12 (7). https://doi.org/10.3390/rs12071136.

Bousfield, C.G., Lindenmayer, D.B., Edwards, D.P., 2023. Substantial and increasing global losses of timber-producing forest due to wildfires. Nat. Geosci. 16 (12), 1145–1150. https://doi.org/10.1038/s41561-023-01323-y.

Bruni, C., Aparício, B., Lourenço, B., Marta-Almeida, M., Benali, A., Barreiro, S., Rocha, A., Sá, A.C.L., 2024. Wildfire exposure and risk in pulp paper companies' plantations under extreme weather conditions: a case study in North-Western Portugal. Int. J. Disaster Risk Reduct. 100 (April 2022), 104064. https://doi.org/10.1016/j.ijdrr.2023.104064.

Burke, M., Driscoll, A., Heft-Neal, S., Xue, J., Burney, J., Wara, M., 2021. The changing risk and burden of wildfire in the United States. Proc. Natl. Acad. Sci. U. S. A. 118 (2), 1–6. https://doi.org/10.1073/PNAS.2011048118.

CalFire, 2018. 2018 Strategic Fire Plan for California. https://osfm.fire.ca.gov/media/5590/2018-strategic-fire-plan-approved-08_22_18.pdf.

CDTFA, 2024. Timber harvest values schedule: effective January 1, 2024, through June 30, 2024. www.cdtfa.ca.gov.

Chen, B., Song, Z., Pan, F., Huang, Y., 2022. Obtaining vertical distribution of PM2.5 from CALIOP data and machine learning algorithms. Sci. Total Environ. 805, 150338. https://doi.org/10.1016/j.scitotenv.2021.150338.

Daum, K.L., Hansen, W.D., Gellman, J., Plantinga, A.J., Jones, C., Trugman, A.T., 2024. Do vegetation fuel reduction treatments alter forest fire severity and carbon stability in California forests? Earths Future 12 (3), 1–18. https://doi.org/10.1029/2023EF003763.

Duffield, J.W., Neher, C.J., Patterson, D.A., Deskins, A.M., 2013. Effects of wildfire on national park visitation and the regional economy: a natural experiment in the northern Rockies. Int. J. Wildland Fire 22 (8), 1155–1166. https://doi.org/10.1071/WF12170.

East, A.E., Logan, J.B., Dartnell, P., Lieber-Kotz, O., Cavagnaro, D.B., McCoy, S.W., Lindsay, D.N., 2021. Watershed sediment yield following the 2018 Carr fire,

Whiskeytown National Recreation Area, northern California. Earth Space Sci. 8 (9), 1–24. https://doi.org/10.1029/2021EA001828.
Elliot, W.J., Miller, M.E., Enstice, N., 2016. Targeting forest management through fire and erosion modelling. Int. J. Wildland Fire 25 (8), 876–887. https://doi.org/10.1071/WF15007.
Finco, M., Quayle, B., Zhang, Y., Lecker, J., Megown, K., a., & Brewer, C. K., 2012. Monitoring Trends and Burn Severity (MTBS): Monitoring Wildfire Activity for the Past Quarter Century Using LANDSAT Data. Forest Inventory and Analysis Symposium, Moving from Status to Trends, pp. 222–228.
Finney, M. A. (2006). An overview of FlamMap fire modeling capabilities. *Fuels management—how to measure success: conference proceedings*, 213–220.
Finney, M.A., McHugh, C.W., Grenfell, I.C., Riley, K.L., Short, K.C., 2011. A simulation of probabilistic wildfire risk components for the continental United States. Stoch. Env. Res. Risk A. 25 (7), 973–1000. https://doi.org/10.1007/s00477-011-0462-z.
Forest Climate Action Team. (2018). California Forest carbon plan: managing our Forest landscapes in a changing climate. May, 1–178.
Gellman, J., Walls, M., Wibbenmeyer, M., 2022. Wildfire, smoke, and outdoor recreation in the western United States. Forest Policy Econ. 134 (October 2021), 102619. https://doi.org/10.1016/j.forpol.2021.102619.
Goulden, M., Wang, J., Randerson, J., Battles, J., O'Geen, T., 2022. The natural climate solutions data atlas. https://cecs.ess.uci.edu/dev/data-atlas/.
Guo, H., Goulden, M., Chung, M.G., Nyelele, C., Egoh, B., Keske, C., Conklin, M., Bales, R., 2023. Valuing the benefits of forest restoration on enhancing hydropower and water supply in California's Sierra Nevada. Sci. Total Environ. 876 (August 2022), 162836. https://doi.org/10.1016/j.scitotenv.2023.162836.
Hurteau, M.D., Westerling, A.L., Wiedinmyer, C., Bryant, B.P., 2014. Projected effects of climate and development on California WildfireEmissions through 2100. Environ. Sci. Technol. 48, 2298–2304.
Johnson, R.J., Rolfe, J., Windle, J., Benner, J., 2015. The Economics of Non-Market Goods and Resources: Benefit Transfer of Environmental and Resource Values. In: Benefit Transfer of Environmental and Resource Values. http://www.springer.com/series/5919.
Johnston, L.M., Wang, X., Erni, S., Taylor, S.W., McFayden, C.B., Oliver, J.A., Stockdale, C., Christianson, A., Boulanger, Y., Gauthier, S., Arseneault, D., Wotton, B.M., Parisien, M.A., Flannigan, M.D., 2020. Wildland fire risk research in Canada. Environ. Rev. 28 (2), 164–186. https://doi.org/10.1139/er-2019-0046.
Jones, K.W., Cannon, J.B., Saavedra, F.A., Kampf, S.K., Addington, R.N., Cheng, A.S., MacDonald, L.H., Wilson, C., Wolk, B., 2017. Return on investment from fuel treatments to reduce severe wildfire and erosion in a watershed investment program in Colorado. J. Environ. Manage. 198, 66–77. https://doi.org/10.1016/j.jenvman.2017.05.023.
Jumps, N., Gray, A.B., Guilinger, J.J., Cowger, W.C., 2022. Wildfire impacts on the persistent suspended sediment dynamics of the Ventura River, California. J. Hydrol. Reg. Stud. 41 (February), 101096. https://doi.org/10.1016/j.ejrh.2022.101096.
van der Knijff, J.M., Jones, R.J.A., Montanarella, L., 2000. Soil erosion risk assessment in Europe. Office for Official Publications of the European Communities, Luxembourg. EUR 19022, 32. http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Soil+Erosion+Risk+Assessment+in+Italy#0.
Lindsay, J.B., 2023. *WhiteboxTools: Open-Source Geospatial Analysis Tools* (2.3.0). University of Guelph. https://www.whiteboxgeo.com/manual/wbt_book/%0A%0A.
Liu, Y., Goodrick, S., Heilman, W., 2014. Wildland fire emissions, carbon, and climate: wildfire-climate interactions. For. Ecol. Manage. 317, 80–96. https://doi.org/10.1016/j.foreco.2013.02.020.
Loehman, R.A., 2020. Drivers of wildfire carbon emissions. Nat. Clim. Chang. 10 (12), 1070–1071. https://doi.org/10.1038/s41558-020-00922-6.
Moeltner, K., Kim, M.K., Zhu, E., Yang, W., 2013. Wildfire smoke and health impacts: a closer look at fire attributes and their marginal effects. J. Environ. Econ. Manag. 66 (3), 476–496. https://doi.org/10.1016/j.jeem.2013.09.004.
Müller, A., Olschewski, R., Unterberger, C., Knoke, T., 2020. The valuation of forest ecosystem services as a tool for management planning – a choice experiment. J. Environ. Manage. 271, 111008. https://doi.org/10.1016/j.jenvman.2020.111008.
Nordhaus, W.D., 2017. Revisiting the social cost of carbon. Proc. Natl. Acad. Sci. U. S. A. 114 (7), 1518–1523. https://doi.org/10.1073/pnas.1609244114.
Nyelele, C., Keske, C., Gon, M., Guo, H., Egoh, B.N., 2023. Using social media data to estimate recreational travel costs : a case study from California. Ecol. Indic. 154 (August 2022), 110638. https://doi.org/10.1016/j.ecolind.2023.110638.
O'Donnell, F.C., Flatley, W.T., Springer, A.E., Fulé, P.Z., 2018. Forest restoration as a strategy to mitigate climate impacts on wildfire, vegetation, and water in semiarid forests. Ecol. Appl. 28 (6), 1459–1472. https://doi.org/10.1002/eap.1746.
Otrachshenko, V., Nunes, L.C., 2022. Fire takes no vacation: impact of fires on tourism. Environ. Dev. Econ. 27 (1), 86–101. https://doi.org/10.1017/S1355770X21000012.
Prest, B.C., Rennert, K., Newell, R.G., Wingenroth, J., 2022. Social cost of carbon explorer. Resources for the Future. https://www.rff.org/publications/data-tools/scc-explorer/.
Prichard, S.J., Hessburg, P.F., Hagmann, R.K., Povak, N.A., Dobrowski, S.Z., Hurteau, M.D., Kane, V.R., Keane, R.E., Kobziar, L.N., Kolden, C.A., North, M., Parks, S.A., Safford, H.D., Stevens, J.T., Yocom, L.L., Churchill, D.J., Gray, R.W., Huffman, D.W., Lake, F.K., Khatri-Chhetri, P., 2021. Adapting western North American forests to climate change and wildfires: 10 common questions. Ecol. Appl. 31 (8). https://doi.org/10.1002/eap.2433.
QEA, A., 2020. *Development of Basic Cost Model for Removal of Sediment from Reservoirs Development of Basic Cost Model for Removal of Sediment from Reservoirs* (Issue February).
Quesnel Seipp, K., Maurer, T., Elias, M., Saksa, P., Keske, C., Oleson, K., Egoh, B., Cleveland, R., Nyelele, C., Goncalves, N., Hemes, K., Wyrsch, P., Lewis, D., Chung, M.G., Guo, H., Conklin, M., Bales, R., 2023. A multi-benefit framework for funding forest management in fire-driven ecosystems across the Western U.S. J. Environ. Manage. 344 (June), 118270. https://doi.org/10.1016/j.jenvman.2023.118270.
Reid, W. V., Mooney, H. A., Cropper, A., Capistrano, D., Carpenter, S. R., Chopra, K., Dasgupta, P., Dietz, T., Duraiappah, A. K., Hassan, R., Kasperson, R., Leemans, R., May, R. M., McMichael, A. J., Pingali, P., Samper, C., Scholes, R., Watson, R. T., & Zakri, A, M. B. (2005). Ecosystems and Human Well-Being : Synthesis. Island Press.
Reinhardt, E.D., Keane, R.E., Brown, J.K., 1997. First order fire effects model: FOFEM 4.0, user's guide (No. 344-345). *USDA Forest Service*. Intermountain Research Station. INT-GTR-344. https://www.fs.fed.us/rm/pubs_int/int_gtr344.pdf.
Renard, K., 1997. Predicting Soil erosion by Water: a Guide to Conservation Planning with the Revised Universal Soil Loss Equation (RUSLE). US Department of Agriculture, Agricultural Research Service.
Renard, K.G., Freimund, J.R., 1994. Using monthly precipitation data to estimate the R-factor in the revised USLE. J. Hydrol. 157 (1–4), 287–306. https://doi.org/10.1016/0022-1694(94)90110-4.
Rennert, K., Errickson, F., Prest, B.C., Rennels, L., Newell, R.G., Pizer, W., Kingdon, C., Wingenroth, J., Cooke, R., Parthum, B., Smith, D., Cromar, K., Diaz, D., Moore, F.C., Müller, U.K., Plevin, R.J., Raftery, A.E., Ševčíková, H., Sheets, H., Anthoff, D., 2022. Comprehensive evidence implies a higher social cost of CO2. Nature 610 (October). https://doi.org/10.1038/s41586-022-05224-9.
Rhoades, C.C., Nunes, J.P., Silins, U., Doerr, S.H., 2019. The influence of wildfire on water quality and watershed processes: new insights and remaining challenges. Int. J. Wildland Fire 28 (10), 721–725. https://doi.org/10.1071/WFv28n10_FO.
Roche, J.W., Goulden, M.L., Bales, R.C., 2018. Estimating evapotranspiration change due to forest treatment and fire at the basin scale in the Sierra Nevada, California. Ecohydrology 11 (7), 1–10. https://doi.org/10.1002/eco.1978.
Rust, A.J., Hogue, T.S., Saxe, S., McCray, J., 2018. Post-fire water-quality response in the western United States. Int. J. Wildland Fire 27 (3), 203–216. https://doi.org/10.1071/WF17115.
Sacks, J.D., Lloyd, J.M., Zhu, Y., Anderton, J., Jang, C.J., Hubbell, B., Fann, N., 2018. The environmental benefits mapping and analysis program – community edition (BenMAP–CE): a tool to estimate the health and economic benefits of reducing air pollution. Environ. Model. Softw. 104 (2), 118–129. https://doi.org/10.1016/j.envsoft.2018.02.009.
Salis, M., Laconi, M., Ager, A.A., Alcasena, F.J., Arca, B., Lozano, O., Fernandes de Oliveira, A., Spano, D., 2016. Evaluating alternative fuel treatment strategies to reduce wildfire losses in a Mediterranean area. For. Ecol. Manage. 368, 207–221. https://doi.org/10.1016/j.foreco.2016.03.009.
Salis, M., Del Giudice, L., Robichaud, P.R., Ager, A.A., Canu, A., Duce, P., Pellizzaro, G., Ventura, A., Alcasena-Urdiroz, F., Spano, D., Arca, B., 2019. Coupling wildfire spread and erosion models to quantify post-fire erosion before and after fuel treatments. International Journal of Wildland Fire 28 (9), 687–703. https://doi.org/10.1071/WF19034.
Sanderfoot, O.V., Bassing, S.B., Brusa, J.L., Emmet, R.L., Gillman, S.J., Swift, K., Gardner, B., 2021. A review of the effects of wildfire smoke on the health and behavior of wildlife. Environ. Res. Lett. 16 (12). https://doi.org/10.1088/1748-9326/ac30f6.
Schollaert, C.L., Jung, J., Wilkins, J., Alvarado, E., Baumgartner, J., Brun, J., Busch Isaksen, T., Lydersen, J.M., Marlier, M.E., Marshall, J.D., Masuda, Y.J., Maxwell, C., Tessum, C.W., Wilson, K.N., Wolff, N.H., Spector, J.T., 2024. Quantifying the smoke-related public health trade-offs of forest management. Nature Sustainability 7 (2), 130–139. https://doi.org/10.1038/s41893-023-01253-y.
Scott, J.H., 2006. An analytical framework for quantifying wildland fire risk and fuel treatment benefit. *Fuels management—how to measure success: conference proceedings. 28-30 march 2006; Portland, OR. Proceedings RMRS-P-41. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.*, 169–184.. http://www.fs.fed.us/rm/pubs/rmrs_p041/rmrs_p041_169_184.pdf.
Scott, J.H., Thompson, M.P., Calkin, D.E., 2013. A wildfire risk assessment framework for land and resource management. *USDA Forest Service - general technical report RMRS-GTR, 315 RMRS-GTR*.
Snyder, N.P., Rubin, D.M., Alpers, C.N., Childs, J.R., Curtis, J.A., Flint, L.E., Wright, S.A., 2004. Estimating accumulation rates and physical properties of sediment behind a dam: Englebright Lake, Yuba River, northern California. Water Resour. Res. 40 (11), 1–19. https://doi.org/10.1029/2004WR003279.
Srivastava, A., Wu, J.Q., Elliot, W.J., Brooks, E.S., Flanagan, D.C., 2018. A simulation study to estimate effects of wildfire and Forest management on hydrology and sediment in a forested watershed, Northwestern U.S. Trans. ASABE 61 (5), 1579–1601.
State of California, USDA, 2020. Agreement for Shared Stewardship of California's Forests and Rangelands. https://www.rcrcnet.org/california-and-usfs-announce-joint-forest-health-initiative.
Stephens, S.L., Westerling, A.L.R., Hurteau, M.D., Peery, M.Z., Schultz, C.A., Thompson, S., 2020. Fire and climate change: conserving seasonally dry forests is still possible. Front. Ecol. Environ. 18 (6), 354–360. https://doi.org/10.1002/fee.2218.
Stephens, S.L., Thompson, S., Boisramé, G., Collins, B.M., Ponisio, L.C., Rakhmatulina, E., Steel, Z.L., Stevens, J.T., van Wagtendonk, J.W., Wilkin, K., 2021. Fire, water, and biodiversity in the Sierra Nevada: a possible triple win. Environ. Res. Commun. 3 (8). https://doi.org/10.1088/2515-7620/ac17e2.
Stephens, S.L., Bernal, A.A., Collins, B.M., Finney, M.A., Lautenberger, C., Saah, D., 2022. Mass fire behavior created by extensive tree mortality and high tree density not predicted by operational fire behavior models in the southern Sierra Nevada. For. Ecol. Manage. 518 (April), 120258. https://doi.org/10.1016/j.foreco.2022.120258.
Stephens, S.L., Foster, D.E., Battles, J.J., Bernal, A.A., Collins, B.M., Hedges, R., Moghaddas, J.J., Roughton, A.T., York, R.A., 2024. Forest restoration and fuels

reduction work: different pathways for achieving success in the Sierra Nevada. Ecol. Appl. 34 (2), 1–17. https://doi.org/10.1002/eap.2932.

Taye, F.A., Folkersen, M.V., Fleming, C.M., Buckwell, A., Mackey, B., Diwakar, K.C., Le, D., Hasan, S., Ange, C. Saint, 2021. The economic values of global forest ecosystem services: a meta-analysis. Ecol. Econ. 189 (November 2020), 107145. https://doi.org/10.1016/j.ecolecon.2021.107145.

Tol, R.S.J., 2011. The social cost of carbon. Ann. Rev. Resour. Econ. 3, 419–443. https://doi.org/10.1146/annurev-resource-083110-120028.

U.S. EPA, 2014. Guidelines for preparing economic analyses, National Center for environmental economics Office of Policy - U.S. Environmental Protection Agency. *National Center for environmental economics Office of Policy - U.S.* Environmental Protection Agency 2010 (May), 1–302.

USDA, 2006. Erosion Control Treatment Selection Guide.

USFS, 2014. FIA Volume Equation Documentation, Updated 9 September 2014.

Voelker, S.L., Merschel, A.G., Meinzer, F.C., Ulrich, D.E.M., Spies, T.A., Still, C.J., 2019. Fire deficits have increased drought sensitivity in dry conifer forests: fire frequency and tree-ring carbon isotope evidence from Central Oregon. Glob. Chang. Biol. 25 (4), 1247–1262. https://doi.org/10.1111/gcb.14543.

Vogler, K.C., Brough, A., Moran, C.J., Scott, J.H., Gilbertson-day, J.W., 2021. Contemporary wildfire hazard across California.

Wang, D., Guan, D., Zhu, S., Kinnon, M. Mac, Geng, G., Zhang, Q., Zheng, H., Lei, T., Shao, S., Gong, P., Davis, S.J., 2021. Economic footprint of California wildfires in 2018. Nature Sustainability 4 (3), 252–260. https://doi.org/10.1038/s41893-020-00646-7.

Wasserman, T.N., Mueller, S.E., 2023. Climate influences on future fire severity: a synthesis of climate - fire interactions and impacts on fire regimes, high - severity fire, and forests in the western United States. Fire Ecol. https://doi.org/10.1186/s42408-023-00200-8.

Weston, C.J., Di Stefano, J., Hislop, S., Volkova, L., 2022. Effect of recent fuel reduction treatments on wildfire severity in southeast Australian *Eucalyptus sieberi* forests. For. Ecol. Manage. 505 (November 2021), 119924. https://doi.org/10.1016/j.foreco.2021.119924.

Wiedinmyer, C., Akagi, S.K., Yokelson, R.J., Emmons, L.K., Al-Saadi, J.A., Orlando, J.J., Soja, A.J., 2011. The fire INventory from NCAR (FINN): a high resolution global model to estimate the emissions from open burning. Geosci. Model Dev. 4 (3), 625–641. https://doi.org/10.5194/gmd-4-625-2011.

Williams, J.R., Berndt, H.D., 1972. Sediment yield computed with UNIVERSAL equation. Journal of the Hydraulics Division 98 (HY12). https://doi.org/10.1061/jyceaj.0003498.

Woznicki, S.A., Cada, P., Wickham, J., Schmidt, M., Baynes, J., Mehaffey, M., Neale, A., 2020. Sediment retention by natural landscapes in the conterminous United States. Sci. Total Environ. 745, 140972. https://doi.org/10.1016/j.scitotenv.2020.140972.

Xu, Q., Westerling, A.L.R., Notohamiprodjo, A., Wiedinmyer, C., Picotte, J.J., Parks, S.A., Hurteau, M.D., Marlier, M.E., Kolden, C.A., Sam, J.A., Baldwin, W.J., Ade, C., 2022. Wildfire burn severity and emissions inventory: an example implementation over California. Environ. Res. Lett. 17 (8). https://doi.org/10.1088/1748-9326/ac80d0.

Yao, R., Palmer, D., Hock, B., Harrison, D., Payn, T., Monge, J., 2019. Forest investment framework as a support tool for the sustainable management of planted forests. Sustainability (Switzerland) 11 (12), 1–22. https://doi.org/10.3390/SU11123477.