Supplementary Material

# Materials and Methods

## Methodological Overview

We aim to quantify the carbon implications of restoring resilience to high fire risk forests in the American River watershed using the Forest Vegetation Simulator and statistical modeling to capture the cumulative probability of fire. To ground this analysis in ex-post observations, we apply remote sensing techniques to determine the annual rates of fire extent and severity from 2010 to 2020 within a reference region ecologically similar to the treatment area. Using these fire statistics, we simulate various fire scenarios, each weighted by the cumulative probability of fire, to quantify carbon dynamics under both treatment and no-treatment conditions. The same stands are used to model the treatment and no-treatment scenarios. Over 25 years, we calculate the annual carbon balance of the treatment scenario, focusing on aboveground live carbon, and compare carbon outcomes to the no-treatment scenario and pre-treatment carbon levels. When carbon benefits are quantified, we estimate potential revenues by monetizing carbon benefits from reduced wildfire emissions – evidenced by improved aboveground live carbon stocks – and various biomass utilization strategies (see Figure S1).

## Treatment area, reference region, and fire statistics

For our study, we determined the treatment area by identifying high-risk forest stands suitable for treatment within the American River watershed's Folsom Dam drainage. Selection was based on the dam's drainage area, a Wildfire Hazard Potential (WHP) score of ‘high’ or ‘very high’ (4 or 5) in 2020 (1), vegetation cover over 10% in 2020 (2), accessibility for mechanical treatment (3,4), and all Ecomap ecoregions encompassing more than 5% of the project area while excluding oak woodlands (5). Ecomap is a resource management map encompassing ecological regions, geology, and soils of the conterminous U.S. with level 4 divisions representing the finest scale units (6).

The treatment area consists of 287,021 acres within the 1,189,689-acre watershed between the American River's North and South Fork (see Table S1). It is largely composed of mixed conifer and softwoods (69%), with sections of white fir (14%), lodgepole pine (8%), and ponderosa pine (4%), plus some juniper woodland and western white pine. This area includes several Ecomap Level 4 divisions: northern Sierra subalpine, upper montane, mid-montane forests, central Sierra lower and mid-montane forests, and Sierra alpine forests.

To increase the robustness of fire extent and severity used in the model, we created a statistically representative reference region to match treatment area based on ecology and vulnerability criteria. The reference region included the Ecomap level 4 divisions which encompassed more than 5% of the treatment area, had Wildfire Hazard Potential score of 4 or 5 in 2012, and vegetation cover greater than 10% in 2012. Fire severity was analyzed annually between 2010 – 2020 following the methods of Parks et al. (7) to construct a pixel level Composite Burn Index (CBI) for fire perimeters (8) within the reference region. High-severity burns had a CBI over 2.25 (9).

The reference region, covering 2,860,418 acres across northern and southern Sierra Nevada landmarks, recorded 174 fires from 2010 to 2020. Annually, a mean of 5.12% of the landscape burned, with a range between 0.05% and 14.86% which was used to parametrize the Monte Carlo simulations. 32% of burned acres were high-severity, which was the percent high severity used to parametrize the no-treatment fire scenarios modeled in Forest Vegetation Simulator (FVS) using the PotFPAB function which predetermines the portion of each stand that FVS burned with high or moderate-severity.

## Forest modeling – Forest Vegetation Simulator (FVS)

We employ the Forest Vegetation Simulator (FVS) to assess the impacts of forest management and fire on carbon stocks and flows within the treatment area. FVS is an individual-tree forest growth model widely used in the U.S. to support decision making (Crookston and Dixon 2005) which includes region specific model variants developed on local data, allows for incorporation of specific management scenarios including thinning and fuel treatments, and includes the Fire and Fuels Extension which was developed to assess risk, behaviors, and impact of fire in forest ecosystems (10). Extensive forest thinning is modeled for the treatment scenario in the fifth simulation year on 287,021 acres within a 1,189,689-acre footprint, followed by prescribed fire in the ninth year to estimate model carbon dynamics over time. Forest thinning target a resilient Stand Density Index (SDI) of 175. A no-treatment scenario is also modeled which includes forest growth but no management intervention. We simulate both treatment and no-treatment scenarios across seven different fire scenarios: no fire, and fire in years 1, 5, 10, 15, 20, or 25, culminating in a total of 14 FVS runs ending in year 25 which assume thinning and prescribed fire with no re-treatment in the treatment scenario and no management in the no-treatment scenario. In the no-treatment scenario the proportion of high severity is fixed at 32% using the PotPFAB function in FVS based on observed fire history in the reference region. In the treatment scenario, we allow FVS to predict fire severity given that forest treatment is fundamentally altering forest structure, which is a key factor in determining fire severity.

Utilizing data from TreeMap (11), clipped to the polygon representing the treatment area, we identify forest plots for FVS modeling. TreeMap data represents Forest Inventory and Analysis (FIA) that are extrapolated into the landscape to estimate inventory at large scales. We run a 25 year simulation starting in 2016 (the most recent release of TreeMap) for the identified forest stands in both treatment and no-treatment scenarios. In the treatment scenario, we perform forest thinning in the fifth year aiming to achieve a Stand Density Index (SDI) of 175 without removing trees exceeding 30” diameter at breast height (DBH). This SDI corresponds to 30% of the maximum SDI of mixed conifer forest in the Western Sierra and is indicative of a resilient forest structure (12). We also implement prescribed fire in the ninth year, covering all treated stands, and use FlamAdj to limit the flame length of the prescribed fire to two feet which assumes that no prescribed fires escalate to crown fires. In the no-treatment scenario, we utilize FireSim to constrain the model by setting the proportion of the fire considered high severity to 32%, reflecting the observed fire severity in the reference region between 2010 and 2020. Each fire scenario run in FVS assumes 100% of each stand burns, allowing for secondary outputs to be calculated in R which weight the relative impact of fire on forest carbon based on the occurrence of fire (see *Predicting Carbon Dynamics and Fire Impact* section). Scaling from stand level to watershed scale involves counting unique stand identifiers in TreeMap on the treatment landscape and replicating FVS outputs based on the observed frequency.

## Predicting carbon dynamics and fire impact

Once FVS simulations are complete, outputs are exported to R for reorganization and weighting. We use observations from 2010 – 2020 for annual wildfire extent and severity to create a cumulative probability density function demonstrating the cumulative likelihood of fire over a 20-year stewardship contract period. This approach helps us statistically propagate the cumulative impact of fire over time by considering both the annual extent of the fire and its frequency in the simulation (13,14). Each year, we calculate a cumulative sum that represents the predicted cumulative extent of fire, based on the annual fire extent and a multiplier representing the fire year. This cumulative sum, capped at 1, indicates the proportion of the landscape predicted to have experienced fire up to that year.

For years when the simulation year is greater than or equal to the fire year, the cumulative extent is calculated as:

*Cumulative Wildfire Extent*

Where:

AE = observed annual extent of fire

n = number of years

Using this cumulative extent of fire, we integrate the FVS outputs from the fire and no fire scenarios based on the year of assumed fire for both the treatment and no-treatment scenario. This results in 12 integrated and weighted model outputs for both treatment and no-treatment scenarios (no fire, fire year 1, 5, 10, 15, and 20). For instance, if the mean 5-year cumulative extent of fire in the reference region is 25%, we calculate the aboveground live carbon (AGLC) for the treatment scenario in year t >= 5, when t >= FireYear, as:

*Net Carbon (tCO2e per acre)*

Where:

represents carbon under fire scenario j at time t

represents carbon under no fire scenario at time t

j represents fire occurrence timestep 1, 5, 10, 15, 20, 25

CWE represents the cumulative probability that wildfire has occurred

For years when the simulation year t is less than the fire year, we apply the NoFire scenario value, and no weighting occurs. In simple terms, we use values from the no-fire scenario up until the year of the modeled fire. Once the fire occurs, the outputs are weighted to reflect the cumulative extent of the landscape that would have burned.

To address uncertainty in fire extent, we conduct a Monte Carlo simulation with 100 iterations. For each iteration, we sample a random value for the annual fire extent from a normal distribution reflecting the observed annual fire extents in the reference region. The minimum annual fire extent used is 0.05%, the maximum 14.86%, and the mean 5.12% which represents the observed fire extent statistics in the reference region between 2010 – 2020. We use this random fire extent in the cumulative weighting model to calculate adjusted aboveground live carbon and wildfire emissions. When the predicted cumulative extent of the fire is 100%, only outputs from the fire FVS run are included. No stands are assumed to burn more than once. The Monte Carlo simulation generates a distribution of outcomes, providing a broad understanding of potential variability in carbon dynamics based on variations in annual fire extent.

## Sawtimber, low-value biomass, and carbon benefits of biomass utilization

To understand the carbon benefits of different biomass utilization options in the treatment scenario, we categorize biomass by size (DBH) and species. In the treatment scenario, we differentiate between merchantable saw-timber and low-value biomass based on the species and DBH of the trees removed. We consider species like true fir, douglas fir, ponderosa pine, and other softwoods accepted by the Sierra Pacific Industries sawmill in Lincoln, CA, as merchantable wood. Trees not exceeding 12” DBH and belonging to one of these merchantable species are classified as low-value, along with logging slash and bushes. We subtract the total carbon in merchantable saw logs from the total removed carbon, treating the remaining carbon as low-value.

We derive the carbon benefits of utilizing low-value biomass for fuels with carbon capture and sequestration (CCS), biochar, and traditional wood products in California from existing literature (15,16). For each product, we consider emissions from processing, and benefits associated with substitution and storage. For storing low-value material in wood vaults, a methodology for carbon removal that stores wood to prevent decomposition and thus sequesters carbon, we base benefits on the lower end of carbon benefits from wood vault purchasing applications to Frontier (17). We assume that all carbon benefits for each biomass utilization scenario accrue in the year the biomass is removed from the landscape, except for traditional wood products, which we assume have an economic half-life of 38 years. After this period, we assume 58% of the carbon becomes inert in a landfill, with the remainder released to the atmosphere (18). We largely base our selection of products for analysis on profitability, as outlined in Elias et al. (15). We consider several product types and average carbon benefits of each product type for carbon dynamics and carbon finance calculations: three fuel products with CCS, two fuel products without CCS, two biochar production technologies, two wood vault designs, traditional building materials, biopower, and pile burning.

## Carbon economics

We incorporate potential revenue from the voluntary carbon market from modeled increases in forest carbon stocks in the treatment scenario measured against the no-treatment counterfactual. We also include several pathways for monetizing the carbon benefits of biomass utilization via voluntary carbon markets for products like biochar and wood as well as policy incentives such as the Low Carbon Fuel Standard (LCFS), the Renewable Fuel Standard (RFS), and 45Q tax incentives for Carbon Capture and Sequestration (CCS). Prices used in the analysis are aligned with current market prices. Fuels produced with low-value biomass that incorporate CCS are assumed to generate $100 (low) or $150 (high) per tCO2e benefit, while fuels without CCS are estimated to generate $50 (low) or $100 (high) per tCO2e benefit, based on California's LCFS prices and 45Q tax incentives. We estimate wood vaults and biochar to generate $100 (low) or $150 (high) per tCO2e benefit, reflecting current prices in the voluntary market (“Nasdaq Carbon Removal Marketplace and Technologies,” n.d.). We assume that increases in aboveground live biomass in the treatment scenario, compared to the no-treatment scenario, will generate carbon credits at $35 (low) or $75 (high) per tCO2e based on current market prices. These carbon prices are used to generate the value of avoided wildfire emissions over the lifetime of the project.

# Supplementary figures and tables

Figure S1: Detailed depiction of the workflow

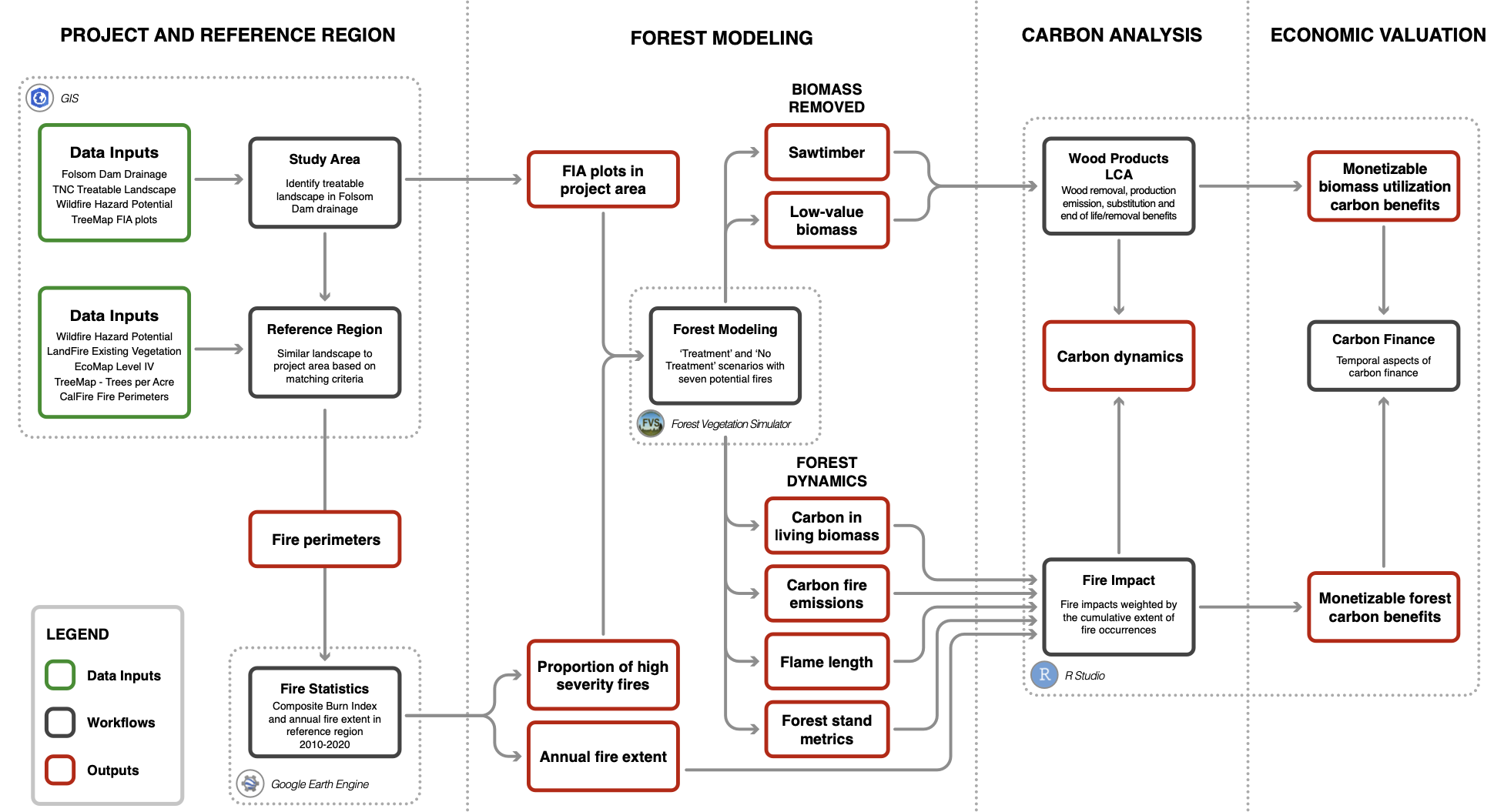


Table S1: The initial spatial characteristics of the treatment area per acre captured at the start of the simulation before any fire events of treatment interventions (11).

|  |  |  |  |
| --- | --- | --- | --- |
| Statistic | Stand Density Index (SDI) | Trees per Acre | Aboveground Live Carbon (tC) |
| Mean | 198 | 267 | 34 |
| Standard Deviation | 66 | 228 | 19 |
| Minimum | 131 | 66 | 6 |
| Maximum | 492 | 1710 | 121 |

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