California Biopower Impact Project: Fire Emissions and Fuels Report

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Table of Contents

List of Figures

List of Tables

Executive Summary

Effective forest management practices are needed in much of California to reduce the negative impacts from wildfires. While the basic principles to modify forest structure and treat surface fuels are relatively well understood, the pace and scale of these treatments is currently insufficient to adequately address the mounting fire deficit. Additionally, treatments increasingly need to consider the carbon consequences of these actions to mitigate or reduce greenhouse gas emissions (GHG) that contribute to climate change and criteria pollutants that affect human and environmental health. One approach that could aid in reducing hazardous fuels generated from forest harvest and thinning activities (i.e. residues) with a lower GHG emissions impact is to utilize woody surface fuels for biomass energy production. However, the magnitude of surface fuel and carbon emissions reduction associated with biomass removal treatments for energy production in comparison to reference cases (e.g., pile burning, broadcast burning) has not been thoroughly examined. Here we generated a statewide dataset at a 30m resolution of surface fuel loading estimates following a wide range of silvicultural treatments and residue treatments for all forested regions in California that are not federally-designated wilderness areas. We further modeled fuel consumption and smoke emissions for a suite of residue treatment scenarios – including its removal for biomass energy production, prescribed burning, and retention on site. All treatment scenarios were modeled over a 100 year timespan with considerations for residue decomposition and exposure to wildfire over time. Biomass treatments that remove all technically recoverable residues resulted in substantive modeled reductions in fuel loading and wildfire smoke emissions. The broadcast burning treatment reduced fuel loading by 14-23% more than mechanical removal of all technically recoverable biomass, but with the trade-off of smoke emissions associated with the combustion of residues. Pile burn and pile removal treatments were less effective in reducing fuel loads and generated more emissions during wildfire compared to broadcast burning or removal of all technically recoverable biomass treatments. The results from this study and the datasets generated can provide California land managers with high-resolution information on surface fuel loading and smoke emissions to estimate the potential benefits and drawbacks of different silvicultural and residue treatment scenarios.

CHAPTER 1 Introduction

1.1 Background

California has experienced an increase in the frequency and size of large wildfires over the past few decades (Westerling, 2016), with some regions experiencing increased fire severity (Miller et al., 2009). These conditions are largely attributed to the anthropogenic increase in greenhouse gas emissions, promoting increased temperatures that dry out fuels more readily and extend the fire season throughout much of the American west (Abatzoglou and Williams, 2016; Westerling, 2016). Combined with over a century of fire exclusion, these conditions have prompted the need for effective treatments that can reduce smoke emissions and other negative impacts of wildfire.

Treatments that focus on reducing stand densities and removing residues have clearly demonstrated their ability to reduce fire behavior and effects (e.g., Agee and Skinner, 2005; Fulé et al., 2012). Additionally, wildfire modeling scenarios have shown that fuel treatments can effectively increase the carbon stability of forests (Hurteau and North, 2009; North et al., 2009; Krofcheck et al., 2017). While treatments can typically result in short-term reductions in carbon stock (Campbell et al., 2012; Krofcheck et al., 2018), longer-term projections demonstrated that increases in carbon stability from fuel treatments are persistent when climate and wildfire scenarios are considered (Hurteau, 2017; Krofcheck et al., 2018) or if treatments are implemented at a large enough scale (Liang et al., 2017).

Many forests contain unmerchantable small diameter trees that can often preclude or limit treatment due to financial considerations. Areas that are financially conducive to thinning and harvesting treatments often generate substantial residues that can exacerbate wildfire behavior and effects (Kalies and Yocum Kent, 2016). These conditions have prompted interest in utilizing this woody biomass for energy production for a wide range of objectives, including the potential to reduce fuel hazards, offset fossil fuel use, and reduce emissions of greenhouse gases and health-impacting pollutants from wildfire (Reinhardt et al., 2008; Evans and Finkral, 2009).

Existing research has not explicitly considered the effectiveness of biomass residue utilization to reduce emissions compared to other, more commonly used forest residue treatments (e.g., pile burning, broadcast burning) or the retention of material on-site. Previous work that has considered biomass utilization treatments has mostly included it as part of a suite of treatments that are applied to a particular area of interest (e.g., Ganz et al., 2007; Chiono et al., 2017). While this approach is informative for a given region and provides insight into the effectiveness of these forest residue treatments across a broader scale, more detailed information on the direct comparisons among alternative residue treatment scenarios is needed.

1.2 Objectives

The objective of this portion of the California Biopower Impacts Project (http://schatzcenter.org/cbip/) is to evaluate the fire emissions associated with different fates that could be applied to residues from a variety of silvicultural treatments across California's forested landscapes. To this end, we modeled emissions of eight smoke by-products from pile burn, broadcast burn, and wildfire occurrence out to 100 years from the time of treatment. The primary objective of this research is to provide emissions estimates for both cases in which residues are collected as well as those in which they are exposed to a counterfactual or "reference" fate for input into a full life cycle greenhouse gas (GHG) analysis. The secondary objectives of this work are to:

1) quantify fuel conditions that result from forest residues following a suite of silvicultural, disposition, and forest residue treatment scenarios;

2) estimate the charcoal and emissions production from the in-field combustion of forest residues associated with silvicultural, disposition, and forest residue treatment scenarios; and

3) examine wildfire emission trajectories for each scenario over time.

1.3 Alignment with broader California Biopower Impacts Project objectives

This report is part of the California Biopower Impacts (CBI) Project supported by the California Energy Commission under Grant Funding Opportunity 16-306. This project seeks to determine the environmental performance of bioenergy from forest and agricultural residues. As part of this work, emission estimates per ton of technically recoverable residues associated with use (biomass removal treatments for energy production) and reference cases (pile burning, broadcast burning, and no residue treatment), with exposure to subsequent wildfire, are being incorporated into the California Biomass Residue Emissions Characterization (C-BREC) model. Results of that modeling effort are not presented here but will be included as part of the final report for the project. Further information on the overall project, including detailed model description and report on Life Cycle Assessment results are available at the project website (http://schatzcenter.org/cbip/).

1.4 Defining fire "risk"

The term "risk" in the wildfire literature is the subject of some discussion. The technically accepted definition relates explicitly to the probability of a fire occurring on a given site (e.g., Hardy, 2005). However, some researchers assert that the term represents the compilation of burn probability, fire behavior, and fire effects (Miller and Ager, 2013). This latter definition considers the impact of fires, not just their likelihood of occurring. This is better aligned with the broader public conception of "risk" but is perhaps more rigorously referred to as fire "hazard."

This study is concerned with the removal of residues from forestry treatments that are occurring in California. The scope of this work begins with the presence of residue in piles or scattered on the ground, excluding the primary treatment that generated this residue, as the residue is considered a "true waste" meaning that primary treatment decisions are not being altered by demand for the residue. Given this scope, the residue removals we consider will not affect fire risk in the formal sense of its probability of occurrence (Hardy, 2005). The primary silvicultural treatments that generate the residues may have an impact on fire risk, but that is beyond the scope of this analysis.

On the other hand, the residue mobilization choices considered in this project can have a significant impact on the fuelbed characteristics, and therefore on the combustion conditions when a fire occurs. It has an impact on fuel loading, type, size class distribution, moisture, and fuel disposition (fraction that is aggregated in piles). These characteristics in turn affect the characteristics of a fire, and therefore its impacts, such as the potential emissions of both GHGs and health-harming criteria air pollutants emitted by a fire. Because the probability of a fire occurring is not meaningfully altered by the decisions surrounding residue mobilization that are the subject of this research, it is these impacts—or risks—of fire that we quantify in this study.

1.5 Scope

The analysis presented here considers all forested regions in California, excluding designated wilderness and urban areas (Figure 1). All analyses were conducted at a 30m resolution. The residue base generated for this analysis is based on estimated conditions with the start date of 2018. Presented data does not consider the presence of a pulp market and thus residues between 10.2 and 15.2 cm in diameter are retained following treatments. Residues were tracked over a 100-year timespan (2018-2118), where they were subjected to annual decay. Wildfire simulations were conducted along five timesteps (0, 25, 50, 75, and 100 years following treatment). Subsequent treatments in these stands during this time span are not considered. The primary focus of this work was to examine fuel loading and emissions specific to surface forest residues (e.g., litter, woody fuels) generated from silvicultural activities under varying dispositions and residue treatments. Additionally, we only report a subset of silvicultural treatments (clearcut, TFB40, and TFA40) to allow for greater feasibility and clarity of communicating our results (see section 2.1 for specific treatments). Data generated from our model can be utilized to assess fuel treatment prioritization and reduction in potential fire behavior and effects for specific regions (e.g., counties, watersheds, etc.) of interest through subsequent analysis.

1.6 Transparency and Model Sharing

To facilitate the broader application and use of our data and analysis, we will provide open-source access to our generated code through the Schatz Energy Research Center's Github repository (https://github.com/schatzcenter/CBREC-Fire). Statewide data of generated surface forest residues will also be available upon request.

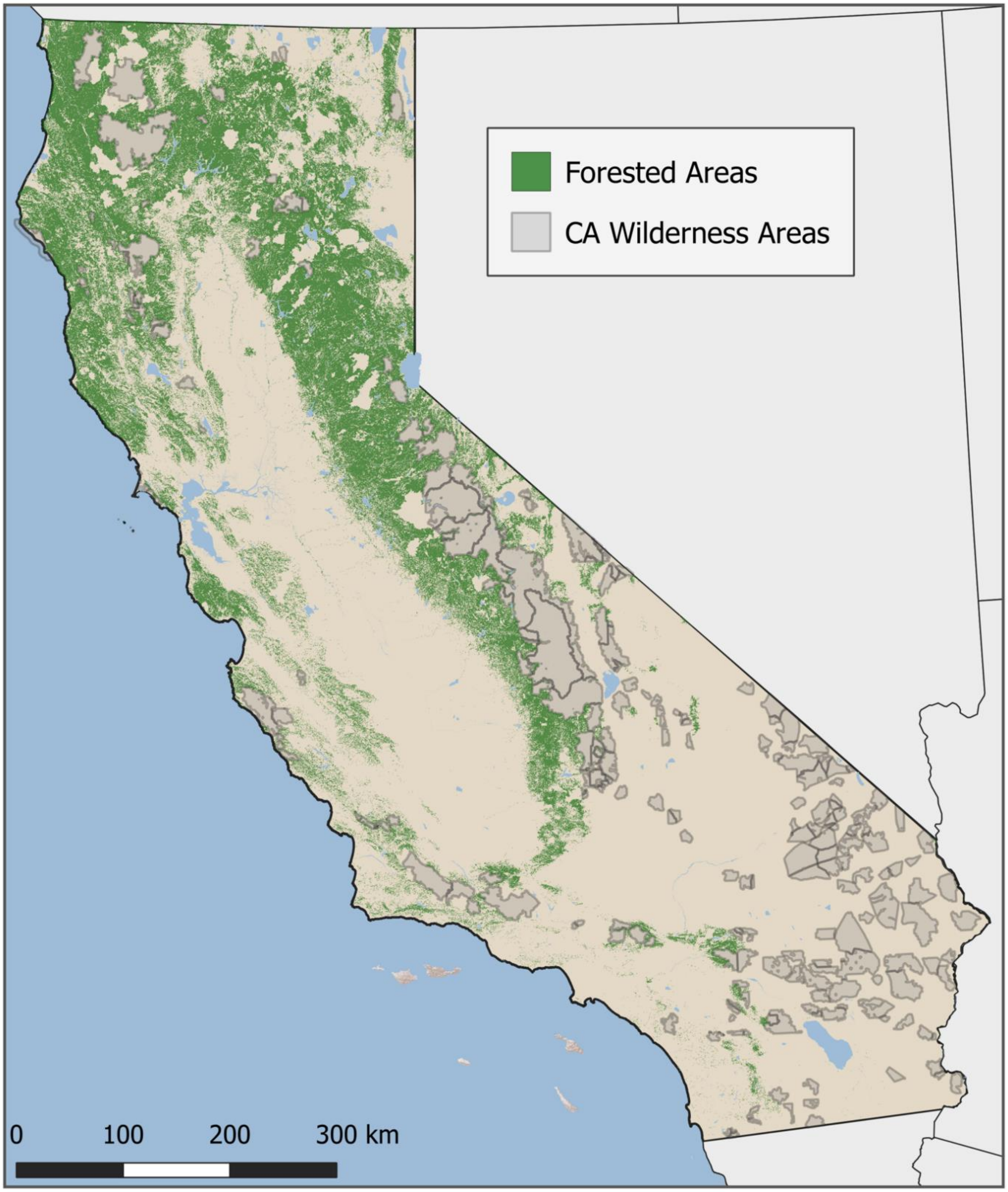

Figure 1: Forested regions of California considered for this study, excluding designated wilderness areas.

CHAPTER 2
Modeling Approach and Methods

This section describes the methods used to estimate the emissions associated with prescribed burning (pile burning and broadcast burning) and wildfire for surface residues generated from forest management treatments.

2.1 Overview of Silvicultural and Forest Residue Treatments

Silvicultural treatments

At a 30m resolution of non-wilderness, forested areas that spanned all ownership types, the Natural Resources Spatial Informatics Group (NRSIG) at University of Washington modeled 13 silvicultural scenarios encompassing a wide range of thinning and harvesting activities commonly applied for various resource objectives (e.g., production, forest health, and fuel hazard reduction) were modeled and applied to each grid cell (see Chapter 4 of the C-BREC Framework – Carman et al., 2020 – for more detailed information). The treatments employed varied by tree size (e.g., thin from below, thin from above, and proportional thinning) and fraction of basal area removed from the stand (Table 1). The basal area targeted for the suite of silvicultural treatments considered aligned with the California Forest Practice Rules (CALFIRE, 2018) that set requirements for residual standing basal area. In this report we only provide results for a subset of these silvicultural treatment scenarios, including clearcut, TFB40, and TFA40 to limit the number of possible scenarios reported but still highlight a broad spectrum of results.

Table 1: Description of forest silvicultural treatments.

Treatment	Treatment Code	Description
Remove 100%	Clearcut	Clear-cut 100% of standing trees
Thin from Below by 20%	TFB20	Remove 20% of basal area starting with smallest DBH trees
Thin from Below by 40%	TFB40	Remove 40% of basal area starting with smallest DBH trees
Thin from Below by 60%	TFB60	Remove 60% of basal area starting with smallest DBH trees
Thin from Below by 80%	TFB80	Remove 80% of basal area starting with smallest DBH trees
Thin from Above by 20%	TFA20	Remove 20% of basal area starting with largest DBH trees
Thin from Above by 40%	TFA40	Remove 40% of basal area starting with largest DBH trees
Thin from Above by 60%	TFA60	Remove 60% of basal area starting with largest DBH trees
Thin from Above by 80%	TFA80	Remove 80% of basal area starting with largest DBH trees
Proportional Thin by 20%	PT20	Remove 20% of basal area proportionally across all tree sizes
Proportional Thin by 40%	PT40	Remove 40% of basal area proportionally across all tree sizes
Proportional Thin by 60%	PT60	Remove 60% of basal area proportionally across all tree sizes
Proportional Thin by 80%	PT80	Remove 80% of basal area proportionally across all tree sizes

Disposition

To account for variation in the amount of piled and scattered residues across the potential range of harvest equipment and yarding systems of each silvicultural treatment scenario, we modeled emissions for five different residue disposition categories: 1) 100% scattered, 2) 30% piled and 70% scattered, 3) 50% piled and 50% scattered, and 4) 70% piled and 30% scattered.

Forest residue treatments

In addition to examining a suite of silvicultural treatments and different dispositions (piled or scattered) we also modeled outcomes of reference and use cases related to how forest residues were treated (Table 2). Reference cases included: 1) biomass retained (no removal or burn treatment applied), 2) pile burning (landing and in-field piles are burned), 3) broadcast burn (all residues are scattered and subjected to a prescribed fire). Two use cases were considered, 1) where residues were only collected from all piles (landing and in-field piles) and 2) all technically recoverable residues, where 70% of the gross residue loading were collected.

Table 2: Definition of Reference and Use Cases for Forest Residues

Reference Cases

Biomass Left On-Site
- Residues are left on-site to decay and are subjected to annualized wildfire probability.

Pile Burn
- All piles are burned in year 1 – the same year as the primary treatment. Any scattered residues are left unburned. Residues that remain are treated as scattered and subjected to decay and annualized wildfire probability.

Broadcast Burn
- All scattered residues are burned in year 1 – the same year as the primary treatment. Any piles that exist are unburned. Residues that remain are subjected to decay and annualized wildfire probability.

Pile and Broadcast Burn
- All piles and all scattered residues are burned in year 1 – the same year as the primary treatment. Residues that remain are treated as scattered and subjected to decay and annualized wildfire probability.

Use Cases

Collect All Piles
- All piled residues are collected. Residues that remain are subjected to decay and annualized wildfire probability.

Collect All Technically Recoverable Residues
- All piled residues are collected, and all technically recoverable scattered residues are collected. Residues that remain are subjected to decay and annualized wildfire probability.

Collect All Piles and Broadcast Burn
- All piled residues are collected. Following collection, a broadcast burn is applied to all remaining residue in year 1 – the same year as the primary treatment. Residues that remain are subjected to decay and annualized wildfire probability.

Collect All Technically Recoverable Residues, and Broadcast Burn
- All piled residues are collected, and all technically recoverable scattered residues are collected. Following collection, a broadcast burn is applied to all remaining residue in year 1 – the same year as the primary treatment. Residues that remain are subjected to decay and annualized wildfire probability.

2.2 Overview of Decay Methodology

To account for reductions in residue loading over time, we modeled annual decay by size class and fuel type (litter, fine woody fuels, coarse woody fuels, and duff). The model took the form of a simple exponential decay function. The decay constants and climate multipliers were based on a community-weighted mean decay value of species and climatic values (temperature and moisture content) for each 30m pixel (see Chapter 5 of the C-BREC framework – Carman et al., 2020 – for more detailed information). All litter and surface woody fuels were assigned to annually recruit 2% of the mass lost to decay each year to duff. Recruitment of litter to duff occurred when 50% of the original litter mass was lost.

2.3 Wildfire and Prescribed Burn Emissions Modeling

We modeled emissions from broadcast burning, pile burning, and wildfire using the "activity" fuels equations from Consume (version 4.2, Prichard et al., 2006), software created by the USDA Forest Service. A flowchart of our sequential methods to generate emissions estimates over time is provided (Figure 2). Emissions species from combustion considered in our modeling included carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), nitrogen oxides (NO_x), sulfur oxides (SO_x), non-methane hydrocarbons (NMHC), and particulate matter ($PM_{2.5}$ and PM_{10}), which are key greenhouse gases or criteria air pollutants. Values for all emissions species are reported as megagrams per hectare.

The activity fuels equations were developed for fuels "resulting from or altered by forestry practices such as timber harvesting or thinning" (p.141, Prichard et al., 2006), and are thus directly applicable to the silvicultural scenarios considered here. The activity fuels equations calculate consumption and emissions estimates for scattered (i.e., non-piled) fuels. The activity equations provide estimates of fuel consumption for each fuel size class, weighted by combustion phase: flaming, smoldering, and residual. The consumption estimates are then multiplied by species-specific emissions factors (e.g., CO, CO_2). The general workflow for estimating emissions is illustrated in the equation below, where $emissions_{cp}$ is the emissions by combustion phase, BC_{cp} is the biomass consumed by combustion phase for fuel size class i of decay class j, and EF_{cp} is the emissions factor for each pollutant, which are also weighted by combustion phase.

$$emissions_{cp} = \sum_{i=1}^{m}\sum_{j=1}^{n} BC_{cp,ij} \times EF_{cp}$$

Smaller (1 and 10-hour) fuels are assumed to be fully consumed, while 100-hour fuel consumption is estimated based on fire weather, slope, and fuel load. The consumption of the larger fuel size classes is calculated using fuel moisture and 100-hour fuel consumption to estimate a seasonally specific reduction in average fuel particle diameter, which is then used to calculate the total mass consumed. Duff consumption was determined as a function of forest floor reduction that included several explanatory terms, such as days since rain, large fuel reduction, duff depth. Conceptual depictions of the consumption algorithms adapted from Prichard et al. (2006) are provide in Appendix A: Figure A1-3.

The modeled estimates of fuel consumption were then multiplied by an emission factor to estimate the amount of emissions generated by prescribed fire and wildfire smoke. The Consume emissions database (Prichard et al., 2006) includes field (Table 3) and pile-specific (Table 4) emissions factors for carbon dioxide, carbon monoxide, methane, particulate matter (PM 2.5 and PM 10), and non-methane hydrocarbons (NMHC). We extended this database with updated emissions factors from the BlueSky wildfire emissions modeling framework (Larkin et al., 2009), which can be found at the AirFire Github site (https://github.com/pnwairfire/eflookup).

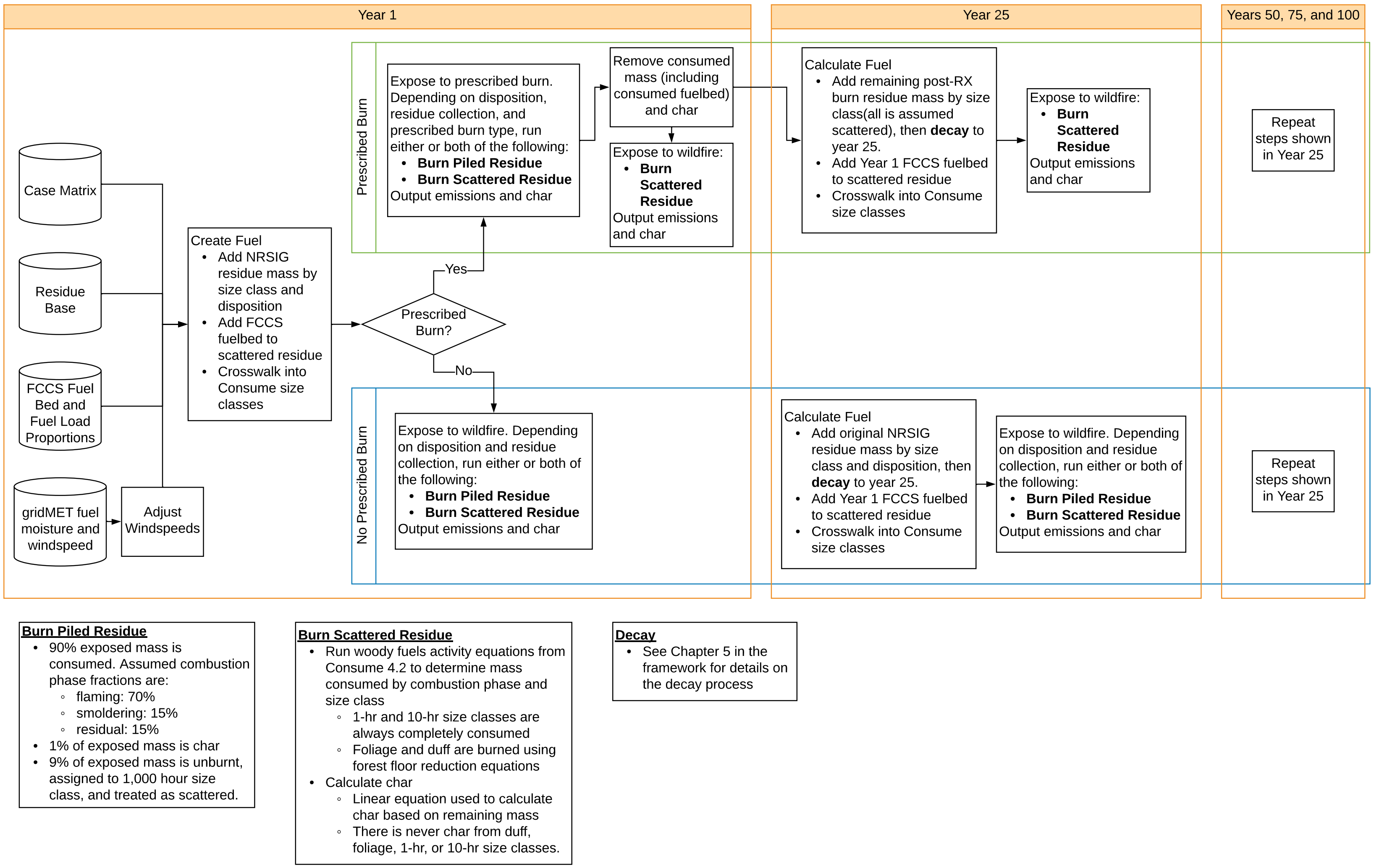

Figure 2: Overview of model structure used to predict consumption and emissions associated with prescribed fire and wildfire over a 100 year period.

Table 3: Emissions factors (kg/metric ton) used to model smoke emissions from prescribed fire and wildfire treatments. All values were retrieved from the BlueSky wildfire emissions modeling framework (Larkin et al. 2009).

Emission Type	Emissions Factor
PM 10 flaming	8.4
PM 2.5 flaming	7.34
CO flaming	52.35
CO_2 flaming	1682.65
CH_4 flaming	2.1
NO_x flaming	0.00121
SO_x flaming	0.00049
NMHC flaming	3.25
PM 10 smoldering & Residual	13.95
PM 2.5 smoldering & Residual	12.8
CO smoldering & Residual	146.15
CO_2 smoldering & Residual	1147.2
CH_4 smoldering & Residual	7.8
NMHC smoldering & Residual	7.55

Table 4: Piled fuel emissions factors (kg/metric ton) for CO, CO_2, CH_4, and non-methane hydrocarbons (NMHC). Values taken from Prichard et al. (2006). Emissions factors for other constituents resulting from pile burns are reported in Table 3.

Combustion Phase	CO	CO_2	CH_4	NMHC
Flaming	26.33	857.31	1.64	1.78
Smoldering	65.19	772.47	5.52	3.39
Residual	65.19	772.47	5.52	3.39

Consume 4.2 was written in python and is distributed within the Fire Fuel Tools software suite. To streamline our workflow, we translated the necessary activity fuels equations into the R language for statistical computing (R Development Core Team, 2019). While translating the equations, we made some limited modifications to better fit the algorithm to our project needs, including the charcoal production model described below. The original Consume activity equations include functions to assign categorical fire intensity based on the total ignition time, which is the time it takes to ignite the entire project area. Consume assumes that fuel consumption for 1,000 hour and larger time-lag classes (coarse woody debris that is ≥3 inches) is lower in more intense fires because the rapidly moving fire has lower residence time (Prichard et al., 2006), resulting in fewer emissions due to the reduction in consumption of 1,000 hour fuels. In order to eliminate the need to specify either fire size or ignition time, we modified the

algorithm for 1000-hr and larger time-lag classes with a consumption reduction factor of 33% for all wildfire scenarios, and no consumption reduction factor for prescribed fire scenarios. A consumption reduction factor of 33% corresponds to the "extreme" intensity reduction factor in the original algorithm (Prichard et al., 2006). We elected to use this consumption reduction factor because we used extreme (97th percentile) fire weather conditions for all wildfire model runs and assumed that fireline intensity would also represent extreme intensity conditions. We checked the R version of the Consume algorithm using a variety of diagnostic tests to confirm output consistency, including comparing outputs between the original python and translated R version. The R version can be found on GitHub under scripts/Consume.

We estimated combustion emissions from piled fuels by multiplying the total mass consumed by the specific pile emissions factor (see Tables 4 & 5 in Prichard et al., 2006). For those emissions species that do not have a pile-specific emissions factor, we used the emissions factor for scattered fuels. We assumed 90% consumption for piled fuels, the default value used by Consume (Prichard et al., 2006). We partitioned the consumed piled material by combustion phase, assigning 70% flaming, 15% smoldering, and 15% residual, following examples outlined in Wright et al. (2017). Consume uses specific emissions factors for particulate matter depending on pile "cleanliness" (i.e., soil contaminants; Table 3). We calculated pile emissions for both "clean" and “very dirty” scenarios.

Table 5: Particulate matter emissions factors (kg/metric ton) based on pile cleanliness category. Values taken from Prichard et al. (2006).

Pile Cleanliness	Soil Contaminants % of Pile Mass	$PM_{2.5}$	PM_{10}
Clean	0%	6.75	2.75
Dirty	>0-10%	8.5	10
Very Dirty	>10%	11.8	14

We also estimated charcoal production of scattered fuels during combustion using published data that examined a range of fire intensities generated from both prescribed fire and wildfire (Pingree et al. 2012; Appendix A, Figure A4). We modeled the change in charcoal production, measured as the percentage of biomass consumed, as a function of biomass consumed in tons per acre, applying the following equation

$$charcoal = BC \times ((11.3053417 + -0.6386391 \times BC) \div 100)$$

where *BC* is total woody biomass consumed, and *charcoal* is the total amount of charcoal produced during combustion. Charcoal production for piled fuels that are burned is assumed to be 1% of the total preburn fuel loading of a pile (Wright et al., 2019).

Model Inputs

The activity fuels equations require inputs for fuel loading, fire weather, and topography. Data sources for each input are summarized in Table 6.

Table 6: Inputs and data sources for use in the Consume model

Variable	Data Source	Citation
Fuel moisture	GRIDMET	Abatzoglou and Brown, 2012; Cohen and Deeming, 1985
Mid-flame windspeed	GRIDMET	Abatzoglou and Brown, 2012; Andrews, 2012
Fuel loading	GNN/FVS/FCCS	Dixon, 2002; Ohmann and Gregory, 2002; Riccardi et al., 2007
Slope	NED	Gesch, 2007

Fuel Loading

We used data from the Fuel Characteristic Classification System (FCCS, Riccardi et al., 2007) to estimate the baseline (prior to silvicultural treatment or harvest) surface fuel loading. FCCS characterizes fuels by individual fuelbeds. The FCCS fuelbed arranges fuels over six different horizontally-arranged "strata", including woody surface fuels and a litter–lichen–moss layer (Sandberg et al., 2001; Riccardi et al., 2007). The FCCS data are provided in a Consume-ready 30m raster format for the state of California through the LANDFIRE website (**landfire.gov**). Woody surface fuel values are given in the 1, 10, 100, 1,000, 10,000, and >10,000 hour time-lag size classes commonly used in fire modeling. Timelag size classes refer to the response time to gain or lose moisture to reach 67% of the equilibrium moisture content. Along with the breakdown by size class, FCCS characterizes 1,000-hour and larger fuels as either sound or rotten. Litter depth and loading values are also given for each fuelbed.

The additional fuel load simulating treatment residues was produced in 30m resolution raster format by collaborators at the University of Washington. They used data obtained from the 2012

LEMMA GNN dataset (https://lemma.forestry.oregonstate.edu/data/structure-maps; Ohmann and Gregory, 2002) as inputs to Forest Vegetation Simulator (Dixon, 2002) to estimate 2018 conditions. See Chapter 4 of the CBI Framework (Carman et al., 2020) for a more detailed methodology.

Our biomass resource base projections combined treatment residues into five size classes using thresholds based on assumptions about merchantable timber and silvicultural methods: foliage, branches, stems between 10.2-15.2 cm, 15.2-22.9 cm, and >22.9 cm in diameter. In order to join the residue and FCCS data sets, the residue needed to be reclassified into the size classes listed in the previous section. **Error! Reference source not found.** depicts the method we used to translate and reclassify the residue into fuel classes. All foliage was classified as litter, and litter depth was estimated using fuelbed-specific depth-to-loading ratios. The FCCS fuelbed and residual biomass data were joined spatially. Wilderness areas and FCCS fuelbeds that did not contain woody fuels were omitted from analysis. The proportion of residue piled was dependent on the disposition scenario modeled (see Section 2.1 above for more details). When the modeled residue size classes spanned multiple time-lag size classes, such as with branches and fuels 9" and larger, we partitioned the residue according to the proportions of each time-lag size class in the existing FCCS fuelbed assigned to each 30m pixel.

Table 7: Forest biomass resource size classifications.

Resource Size Class	FCCS	Consume	C-BREC Decay Model
Stem, >22.9 cm DBH to 15.2 cm top & Bark, >22.9 cm DBH to 15.2 cm top	Ø > 50.8 cm	>10,000 hr	Coarse Woody Debris (CWD)
	22.9 < Ø ≤ 50.8 cm	10,000 hr	
Stem, ≤22.9 cm DBH to 15.2 cm top & Bark, ≤22.9 cm DBH to 15.2 cm top	7.6 < Ø ≤ 22.9 cm	1,000 hr	
Pulp Wood, 10.1 cm ≤ Ø < 15.2 cm & Bark, 10.1 cm ≤ Ø < 15.2 cm			
Branches + tops (Ø < 10.1 cm) & Bark, Ø < 10.1 cm	2.5 < Ø ≤ 7.6 cm	100 hr	Fine Woody Debris (FWD)
	0.6 < Ø ≤ 2.5 cm	10 hr	
	Ø ≤ 0.6	1 hr	
Foliage	Litter	--	Litter
--	--	--	Duff
Stump	--	--	--
Stump Bark	--	--	--
Root	--	--	--

Terrain

We used 30m Digital Elevation Models (DEM) from the National Elevation Dataset (NED, **usgs.gov**) to calculate the slope for each pixel. Additionally, we used a normalized terrain prominence index (TPI, De Reu et al., 2013) to correct windspeed, described below. To calculate TPI, we used the following equation, taken from De Reu et al. (2013),

$$TPI_i = \frac{z_i - \bar{z}}{z_{sd}}$$

Where z_i is elevation for i^{th} pixel, $\underline{z}$ and z_{sd} are the mean and standard deviation of the elevation for the specified neighborhood around the i^{th} pixel. The ability of TPI to detect landscape features is related to neighborhood size (De Reu et al., 2013). We wanted to capture coarse landscape features, so we used a neighborhood of approximately 2,000 m (67 pixels). Finally, we used values modified from Weiss, 2001) to determine landform classification, listed below.

Ridgeline: TPI > 0.5
Upper slope: TPI > 0 & < 0.5
Lower slope: TPI > -0.5 & < 0
Valley: TPI < -0.5

Following landform classification, we used the landform classifications with treatment-specific tree cover to estimate wind adjustment factor (See Appendix A, Figure A5).

Fire Weather

The consumption equations for activity fuels require inputs for 1-, 10- and 1,000-hour fuel moisture, mid-flame wind speed, and days since rain. To estimate these inputs, we are using the University of Idaho gridded surface meteorological (GRIDMET; http://www.climatologylab.org/) dataset (Abatzoglou and Brown, 2012; Abatzoglou, 2013). GRIDMET data are 4km resolution raster datasets available on a daily time scale from 1979 to the present, and are available through Google Earth Engine (earthengine.google.com/datasets), Google's cloud-based platform for obtaining and processing large remote-sensing data sets. For wildfire simulations, we calculated the 97th percentile conditions for all climate variables constrained to the months of June through September for all years from 2000 to 2017, when over 90% of the area burned in California forests occurs (Westerling, 2016). We assumed that the number of days since rain under wildfire conditions was 50 for input into the consume model. For prescribed fire simulations, we calculated the 37.5th percentile conditions for all climate variables constrained to September and October (the typical fall prescribed fire season) for the same time period as the wildfire scenarios. We assumed five days since rain prior to a prescribed fire.

Fuel moisture

The GRIDMET dataset includes 100- and 1,000-hour fuel moisture, but 1- or 10-hour fuel moisture are not available. Both emissions and fire behavior models require 1- and 10-hour fuel moistures. We estimated fuel moistures for 1- and 10-hour fuels using equations taken from the National Fire Danger Ratings System (NFDRS, Cohen and Deeming, 1985).

The calculations for both 1- and 10-hour fuel moistures require equilibrium moisture content (EMC) at the fuel-atmosphere interface (Cohen and Deeming, 1985). EMC, is a function of relative humidity (RH) and temperature ($TEMP$), and is calculated differently depending on RH (Cohen and Deeming, 1985). When RH values are less than 10%, The following equation was used to calculate *EMC*:

$$EMC = 0.03229 + 0.281073 * RH - 0.000578 * TEMP * RH$$

If RH values are greater than 10% but less than 50%, the following equation was used to calculate *EMC*:

$$EMC = 2.22749 + 0.160107 * RH - 0.014784 * TEMP$$

The final step to obtain 1- and 10-hour fuel moistures is simply to multiply EMC by 1.03 (1-hour fuels) or 1.28 (10-hour fuels). Temperature and relative humidity inputs for Eq. 2 & 3 were obtained from GRIDMET data. As with other climate data, values were calculated for the 97th percentile. For the prescribed burning of scattered fuels treatment (i.e. broadcast burn) we use the same methodology for estimating fuel moisture as explained above.

Mid-flame wind speed

We used GRIDMET 10m wind speed data to characterize mid-flame wind speed, which we corrected for instrument height with wind adjustment factors (WAF; Andrews, 2012). We calculated spatially-explicit WAF for each silvicultural treatment, adjusting for TPI and post-treatment trees per acre. A full decision tree diagram can be found in Appendix A, Figure A5.

2.4 Probabilistic assessment of fire emissions

As discussed above, the net fire emissions associated with residue mobilization is the difference between the emissions in a reference case where these residues are left in place and the use case where they are removed. Sections 2.1-2.3 above describe how emissions from wildfire and prescribed burn were calculated for every forest treatment and residue mobilization scenario going forward 100 years. However, there is much uncertainty regarding the timing and location of actual wildfires. Given this, the emissions associated with these fires must be assigned to the residue on a probabilistic basis. We don't know when residues will burn if left in place, but we have calculated the emissions if they do burn in a given year, and we know the probability of fire at any given location now and in the future. By combining these two, we can generate a probabilistic estimate of expected fire emissions going forward. For example, if there is a 100-year mean fire return interval on a given site, 1% of the net emissions from wildfire at that site would be allocated to the reference case of a given scenario.

As wildfire on any given site is a probabilistic phenomenon, we needed to evaluate the effect of fires across the 100-year time horizon of our study. To this end, we modeled wildfires five times at a given site—at 0, 25, 50, 75, and 100 years from present. The net effect of residue presence on wildfire emissions changes over time as decay removes some of the fuels and changes others from sound to rotten, which increases their smoldering time. Not only is the fuelbed changing over time, but so is the probability of wildfire as climate change leads to an increased occurrence of wildfire in California. To account for this, we also alter the probabilistic annual allocation of emissions from later wildfires based on projected wildfire return intervals over the period from 2020 to 2120.

Present and future wildfire probability in California are modeled using data published in Cal-Adapt (Westerling, 2019). Data available from Cal-Adapt predicts the number of hectares burned each year in every 6 km by 6 km grid cell in California (Figure 3). The annual area burned in each cell is predicted stochastically in Cal-Adapt and shows the trend of future wildfire across the state based on different climate projections and emissions scenarios. We used future wildfire probability data from the climate model HadGEM2-ES (Warm/Drier), emissions scenario with representative concentration pathway (RCP) 4.5, and business as usual population growth.

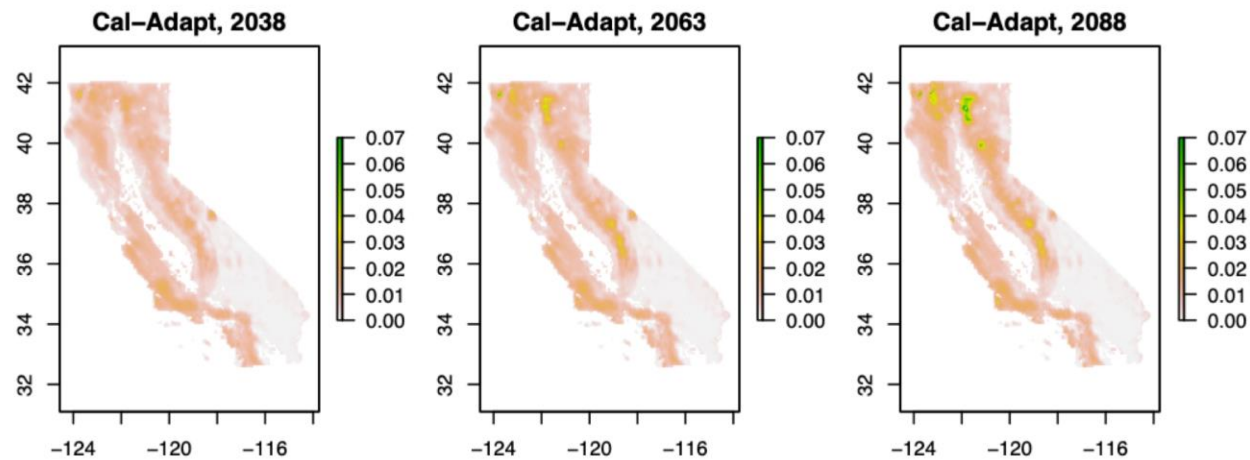

Figure 3: Fire probability projections going forward. The years presented here are the mid-points of the 2025-2050, 2050-2075, and 2075-2100 periods respectively.

CHAPTER 3
Results

3.1 Wildland Fuel Responses

Effects of silvicultural treatments

The amount of fuels generated for a given silvicultural treatment varied widely across forested regions in California owing to differences in forest stand characteristics (Figure 4). For the TFB40 treatment, the average fine woody fuel (1-100 hour) loading was 12 Mg ha^{-1} and ranged between <1 and 134 Mg ha^{-1}. Greater fine woody fuel loading commonly occurred in the central and north coast forests, middle elevation forests of the northern Sierra Nevada, and western Klamath Mountains. Similar spatial variation in fine woody fuels were observed following other silvicultural treatment types.

Estimates of fuel loading varied among surface fuel components and silvicultural treatments (Figure 5). On average, litter represented between 8 and 12% of the total surface fuel loading of residues, with the TFA40 treatment having the highest proportion of litter loading. Average loading of fine woody fuels ranged between 45% and 65% of the total residues. Coarse woody fuels (≥1000 hour) were 43% and 48% of the total treatment-generated woody surface fuels. Expectedly, treatments that removed more basal area of trees resulted in greater total amounts of surface fuels, with the clearcut treatment having the highest average fine woody fuel loading, 30.1 Mg ha^{-1} (range <1 to 309 Mg ha^{-1}). However, the TFB40 treatment resulted in about 5% less fine woody fuel loading compared to the thin from above treatment with the same proportion of basal area removed. TFB40 resulted in an average of 1.8 Mg ha^{-1} less fuels than thin from above treatment with the equivalent proportion of basal area removed.

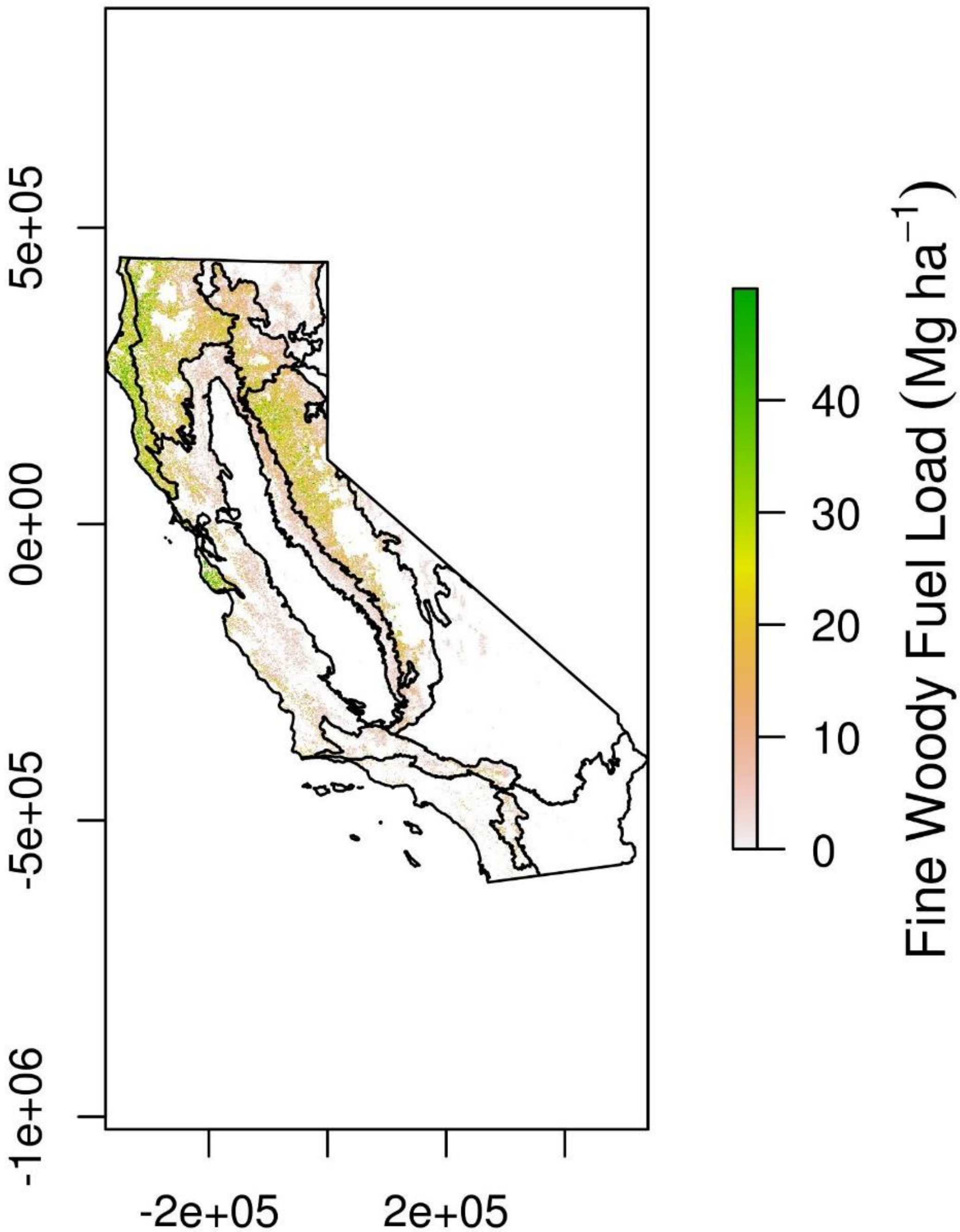

Figure 4: Variation in fine woody fuel loading (Mg ha^{-1}) in the non-wilderness, forested regions of California resulting from a thin from below silvicultural treatment with 40% basal area removed (TFB40) and all resultant fuels scattered. The rare instances where estimates were greater than 50 Mg ha^{-1} are not depicted to visually highlight variation in fine woody fuels across the state that is otherwise compressed when larger values are included. Black boundary lines designate the US EPA level III ecoregions.

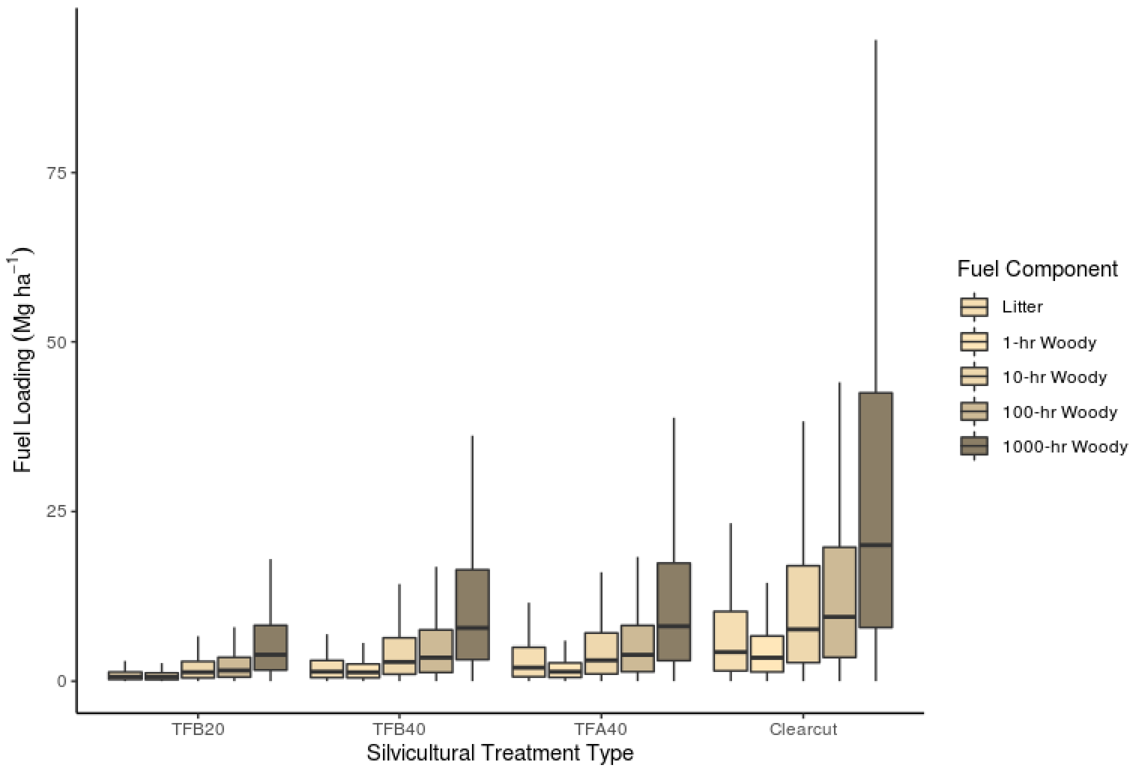

Figure 5: Variation in estimated surface fuel loading (Mg ha^{-1}) by fuel component type across all forested, non-wilderness regions of California resulting from a subset of the modeled silvicultural treatments that include thin from below with 20% basal area removed (TFB20), thin from below with 40% basal area removed (TFB40), thin from above with 40% removal (TFB40), and clearcut. Estimates only include the additional residues that were generated from the silvicultural treatments without subsequent residue treatments. See Table 1 for a more detailed description of the silvicultural treatments. Note that duff was not considered to accumulate immediately following silvicultural treatments.

Effects of residue treatments

All residue treatments reduced estimated surface fuel loading but varied substantially in the amount reduced among treatments (Figure 6). Broadcast burning resulted in the greatest estimated reductions in surface fuels compared to all other residue treatments. For example, surface fuels decreased by 81% and 90% following broadcast burning in both the TFB40 and TFA40 treatments, respectively. Removing all technically, recoverable fuels for biomass energy production resulted in removal of 67% of the surface fuels generated from silvicultural treatments. In areas where 30% of the fuels were piled and subsequently burned or removed for biomass energy production, 19 to 25% of the fuels were projected to be removed or burned.

Effects of decay over time on residues

Broadcast burning treatments had persistently lower estimated fuel loading over the 100 years compared to all other treatments (Figure 7). However, decay was responsible for substantial decreases in fuel load 25 years after silvicultural treatment implementation. Removal of all technically recoverable fuel resulted in the second lowest surface fuel levels compared to other treatments. The mean surface fuel loading without subsequent residue treatment resulted in a 70% decrease in surface fuel loading, 25 years after treatment. Over the full 100 year modeling period, fuel loading of residues decreased by 90% or more across all treatment scenarios.

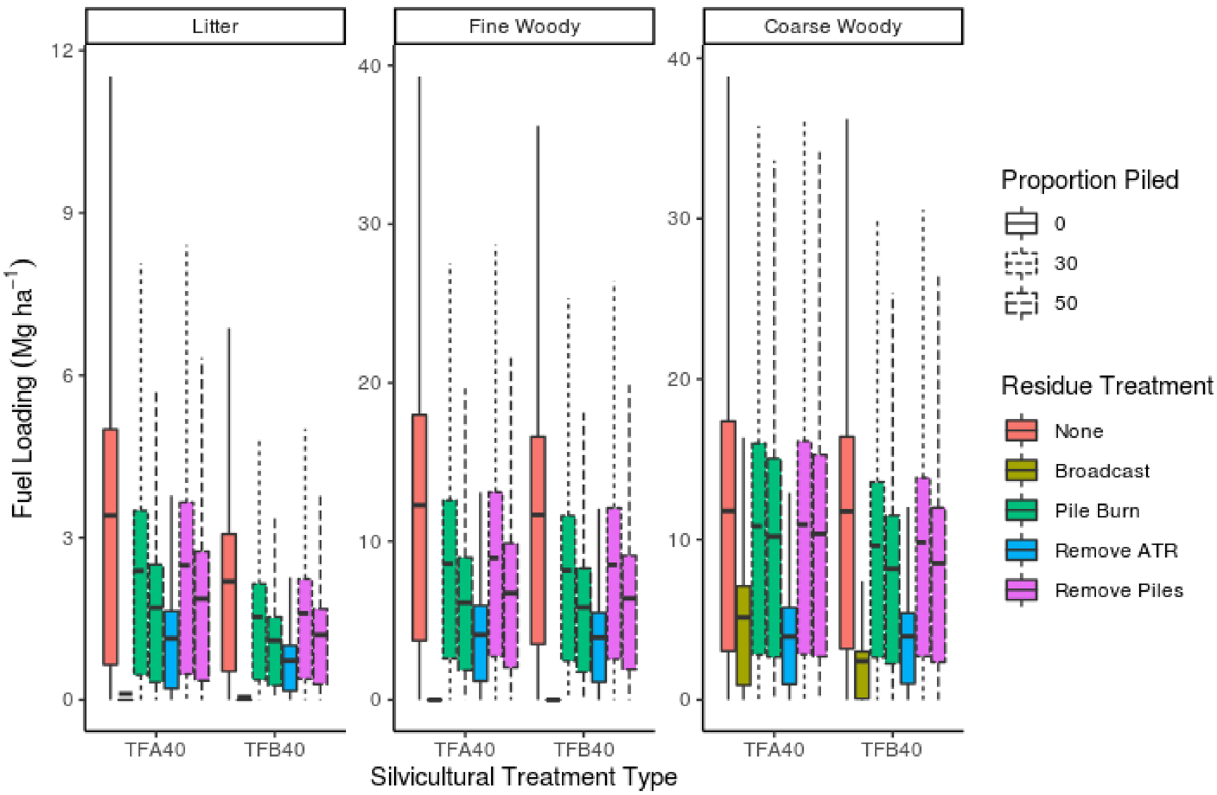

Figure 6: Estimated surface fuel loading (Mg ha^{-1}) by fuel component type (litter, fine woody, and coarse woody fuels across all forested, non-wilderness regions of California following either a thin from below with 40% basal area removed (TFB40) or thin from above with 40% removal (TFB40) silvicultural treatments and subsequent residue treatments. Residue treatments included a no treatment (None), broadcast burning (Broadcast), pile burning (Pile Burn), removal of all technically recoverable fuels (Remove ATR) or piled fuels (Remove Piles) for biomass energy production. Pile burn and removal treatments were modeled for both 30% or 50% of residues piled.

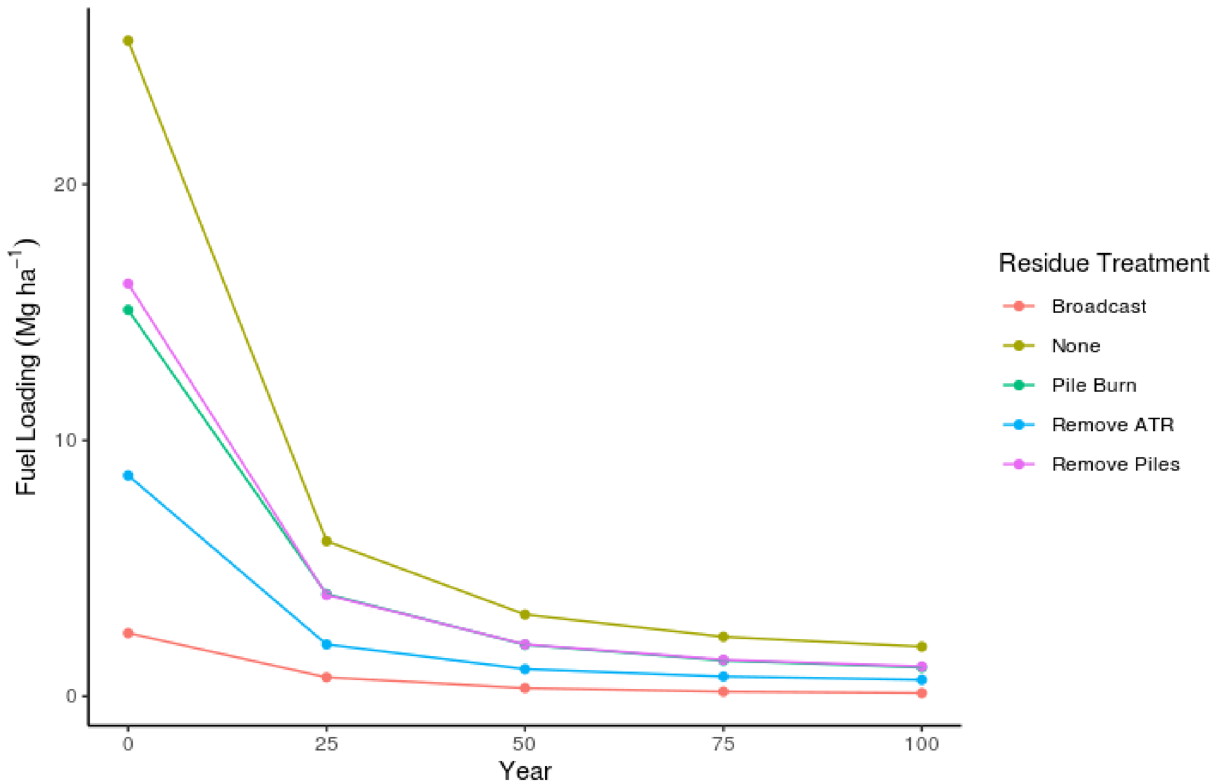

Figure 7: Mean total surface fuel loading (Mg ha^{-1}) following a thin from below treatment with 40% basal area removal and subsequent residue treatments across all forested, non-wilderness regions of California. Residue treatments included a no treatment (None), broadcast burning (Broadcast), pile burning (Pile Burn), removal of all technically recoverable fuels (Remove ATR) or piled fuels (Remove Piles) for biomass energy production. Only 50% piled treatments are shown to allow for better visual comparisons among residue treatment trajectories.

3.2 Char and Smoke Emissions Among Treatments

Char

Char production was generally low and did not vary markedly among silvicultural treatments (Figure 8), with average char production ranging from approximately 0.03 to 0.9 Mg ha^{-1}, or 0.3 to 2.4% of woody fuel residues. However, broadcast burning treatments typically had approximately 4 to 8 times more char than pile burning treatments because of a greater amount of fuels exposed to fire and a lower assumed consumption rate. Only small differences in char production were observed among silvicultural treatments; however, treatments that generated more surface fuels due to removing greater proportions of basal area (e.g., clearcut) did produce more char. As expected, we found that broadcast burning and pile burning treatments generate more char than other residue treatments that lacked burning treatments (e.g., removal for biomass energy production).

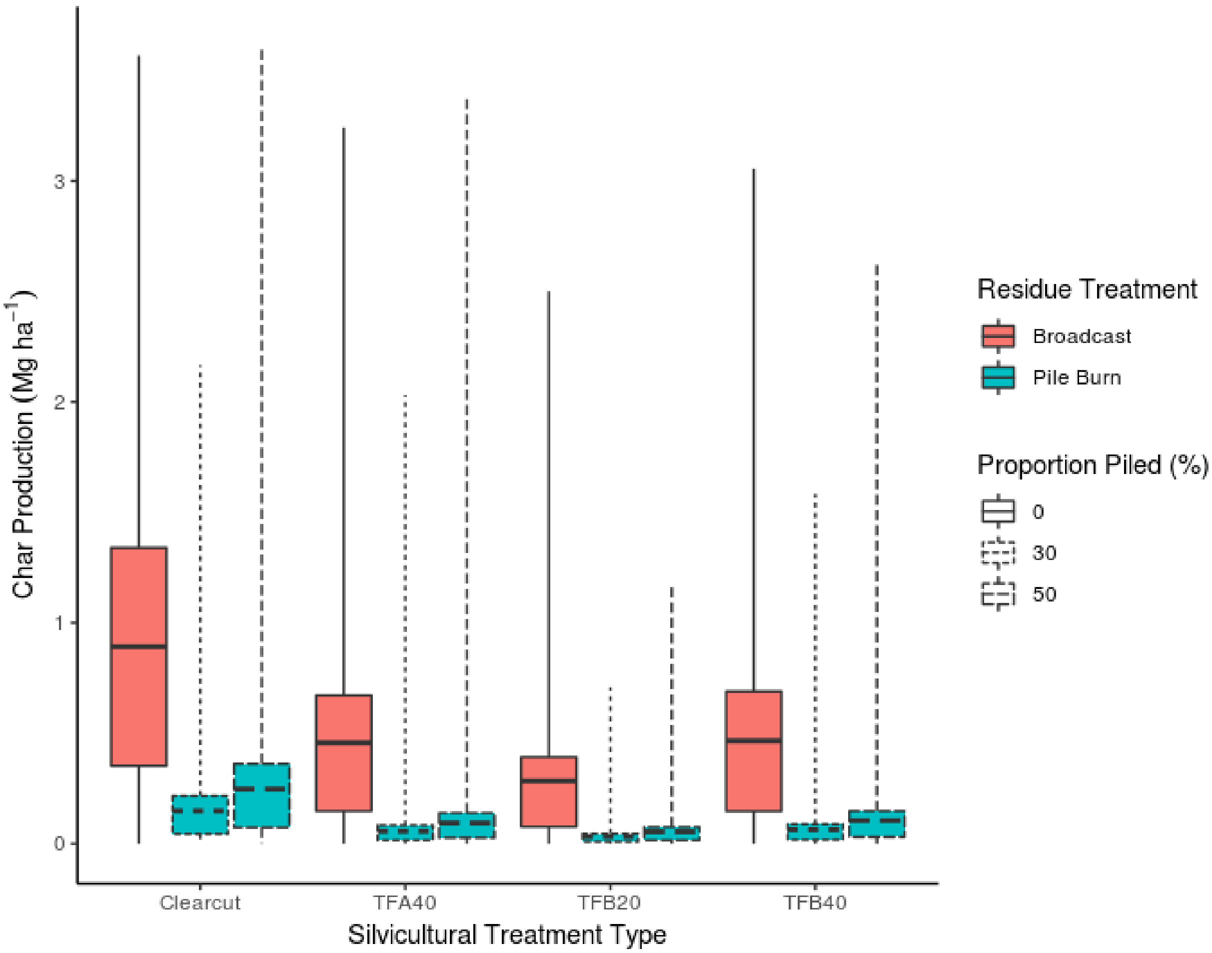

Figure 8: Variation in char production (Mg ha^{-1}) generated from broadcast burning (Broadcast) and pile burning (Pile) of surface residues following a thin from below treatment with 40% basal area removal and subsequent residue treatments across all forested, non-wilderness regions of California. Proportion piled represents the percentage of surface fuels that were generated from the silvicultural treatment and piled.

Smoke emissions

Emissions following wildfire in areas subject to silvicultural treatments without subsequent residue treatments varied spatially across California (Figure 9). For the thin from below treatment with 40% basal area removed, the average CO_2 emissions was 34.8 Mg ha^{-1} and ranged between <1 and 748 Mg ha^{-1}. Greater CO_2 emissions were modeled to occur in north and central coast regions and in the middle elevation forests of northern Sierra Nevada and Klamath Mountains, likely associated with the higher productivity, and thus, greater residues generated in these areas. Similar spatial patterns were observed for the other constituents of smoke. When we examined the CO_2 emissions following wildfire for the same treatment relativized by the amount of exposed fuel loading, the range of values was between 0.9 and 1.7 with higher CO_2 emissions per Mg ha^{-1} of exposed fuel concentrated in the northern Sierra Nevada and western Klamath Mountains (Figure 10).

Carbon dioxide comprised the most smoke emissions resulting from broadcast burning and pile burning treatments. Broadcast burning resulted in 1.5 to 3× more CO_2 emissions on average than pile burning only treatments. Smoke emissions varied linearly with fuel loading but differed among residue treatments, with greater emissions associated with silvicultural treatments resulting in greater residues. Other constituents of smoke generated by prescribed fire treatments followed similar patterns to carbon dioxide emissions (Figure 11). While the amount of these other constituents was lower, broadcast burning treatments sometimes generated much higher amounts than pile burning treatments. For example, broadcast burning had 3 to 6× higher CH_4, $PM_{2.5}$, PM_{10} emissions than pile burning, depending on the silvicultural treatment and proportion of fuels that were pile burned (Figure 10).

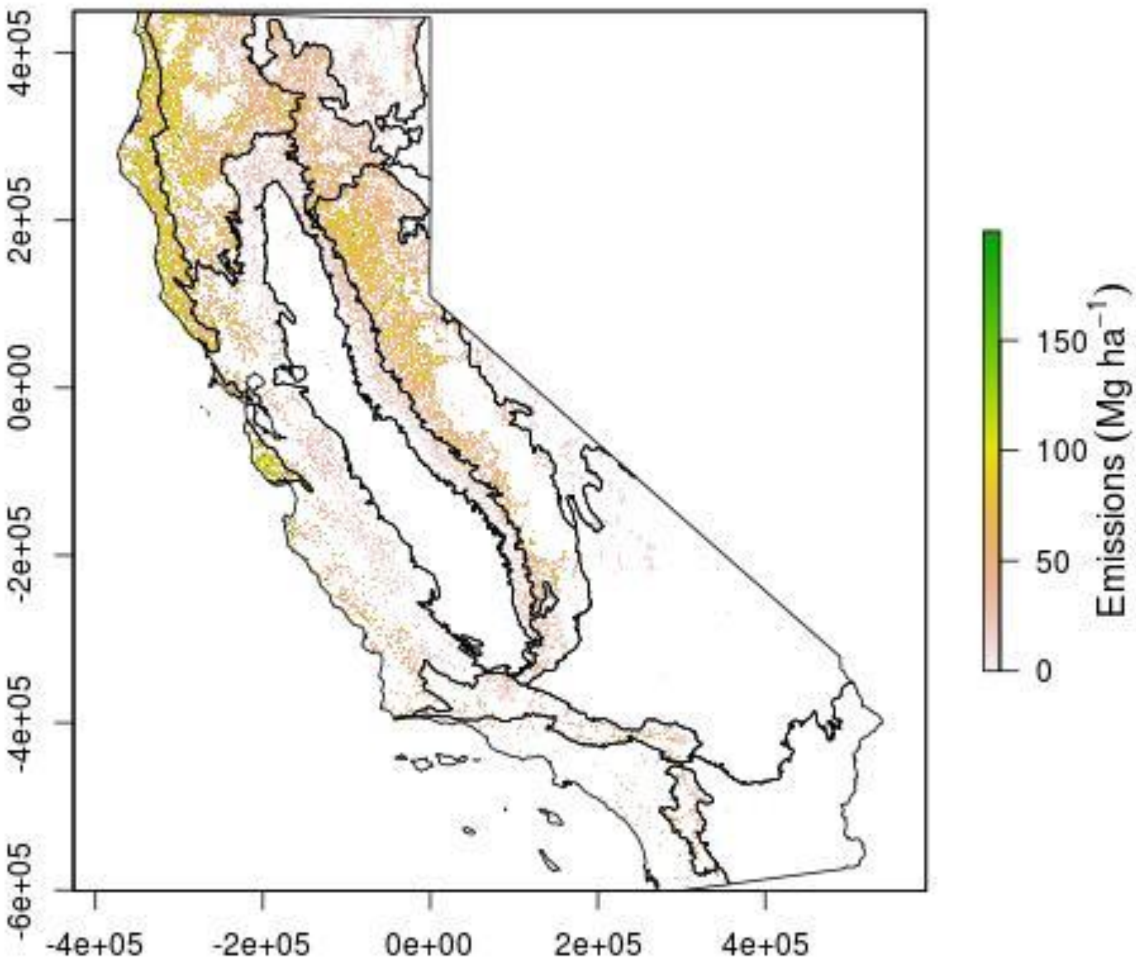

Figure 9: Spatial variability in wildfire CO_2 emissions (Mg ha^{-1}) following a thin from below silvicultural treatment with 40% basal area reduction in which all residues were 100% scattered and not subject to a prescribed burn. Values over 200 Mg ha^{-1} were omitted to better highlight variation among most areas. Black boundary lines designate the US EPA level III ecoregions.

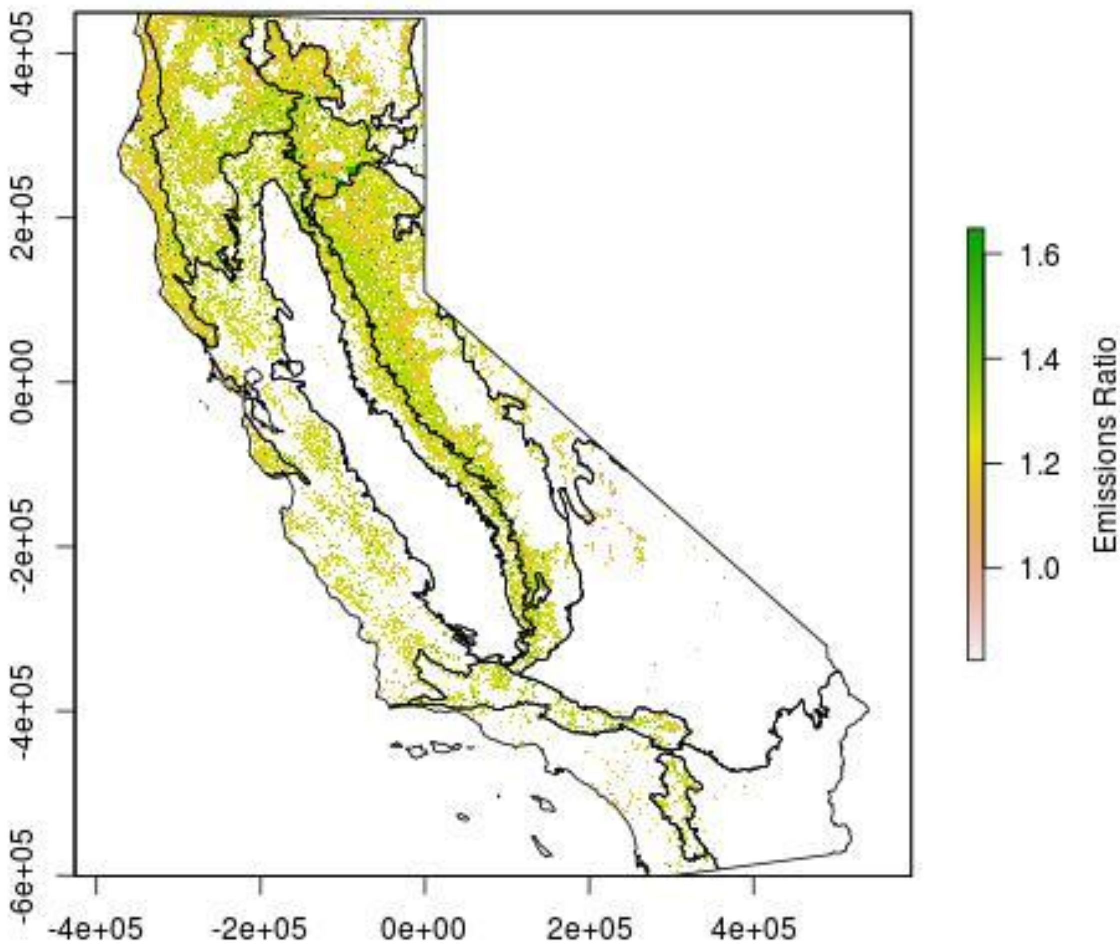

Figure 10: Spatial variability in wildfire CO_2 emissions (Mg ha^{-1}) per exposed fuel loading (Mg ha^{-1}) following a thin from below silvicultural treatment with 40% basal area reduction in which all residues were 100% scattered and not subject to a prescribed burn. Black boundary lines designate the US EPA level III ecoregions.

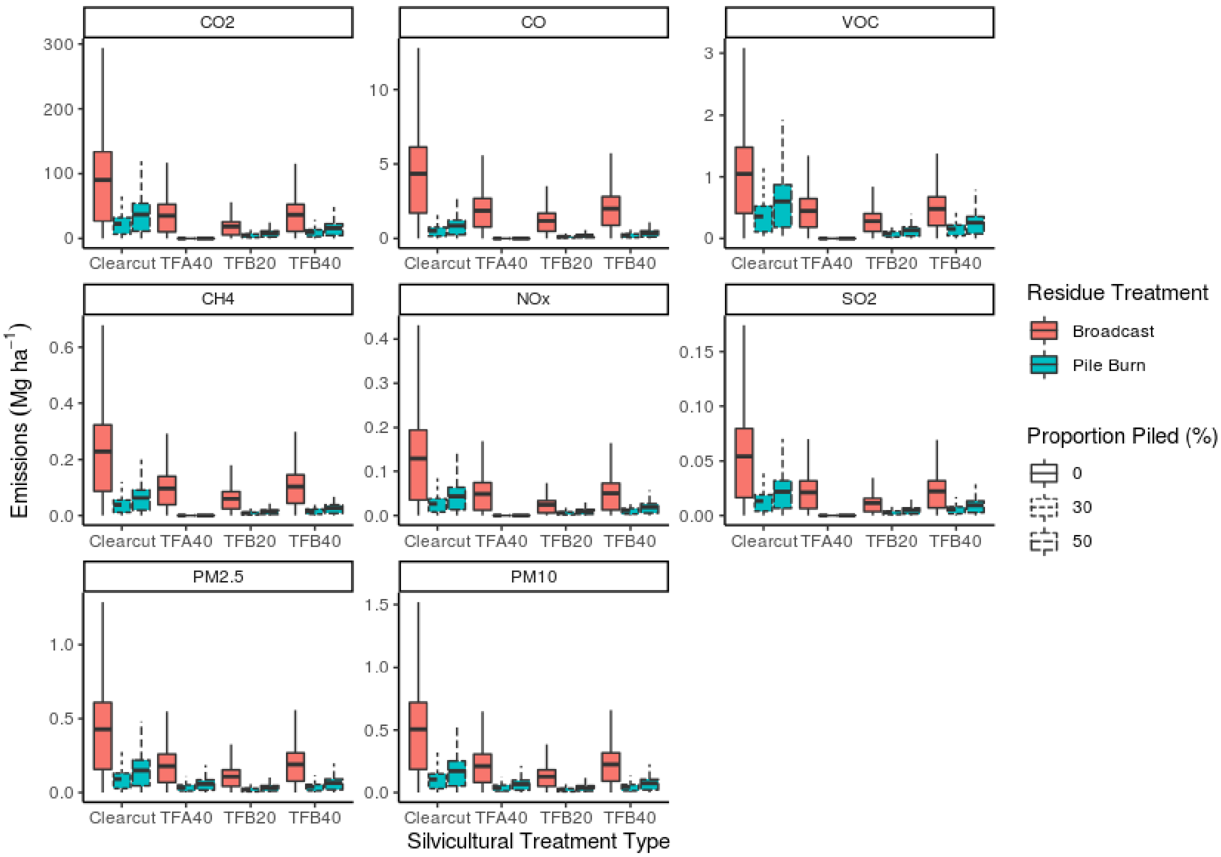

Figure 11: Emissions (Mg ha^{-1}) from smoke generated by prescribed burning treatments (Broadcast and Pile Burn) for a subset of silvicultural treatments across all forested, non-wilderness areas in California. Proportion piled represents the percentage of surface fuels that were generated from the silvicultural treatment and piled.

Char and smoke emission changes over time

Char production following wildfire was minimal for all residue treatment types (Figure 12). Broadcast burning and removal of all technically recoverable residues for biomass energy production treatments yielded less than 0.3 Mg ha^{-1} of char following wildfire compared to pile burn or pile removal only treatments. Pile treatments generated slightly higher amounts of char following wildfire. All residue treatments had much lower estimates of char production from wildfires occurring 25 years or more after treatment due to decay of residues over time.

Smoke emissions for all residue treatment types were lower than untreated residues for the thin from below with 40% basal area reduction (Figure 13). The differences among treatments declined over time, as fuels decayed. Broadcast burning and removal of all technically recoverable residues yielded 98% and 68% lower modeled CO_2 emissions during wildfire immediately following treatment compared to no residue treatments. This difference in the mass of CO_2 emissions compared to no residue treatments was consistent when wildfire was modeled 25 years after residue treatment, although the absolute production of emissions was lower. Pile burn or removal treatments resulted in a 24% to 43% reduction in CO_2 emissions compared to no residue treatment. Similar trajectories of emissions from wildfire were observed for other smoke constituents and following other modeled silvicultural treatments (e.g., thin from above).

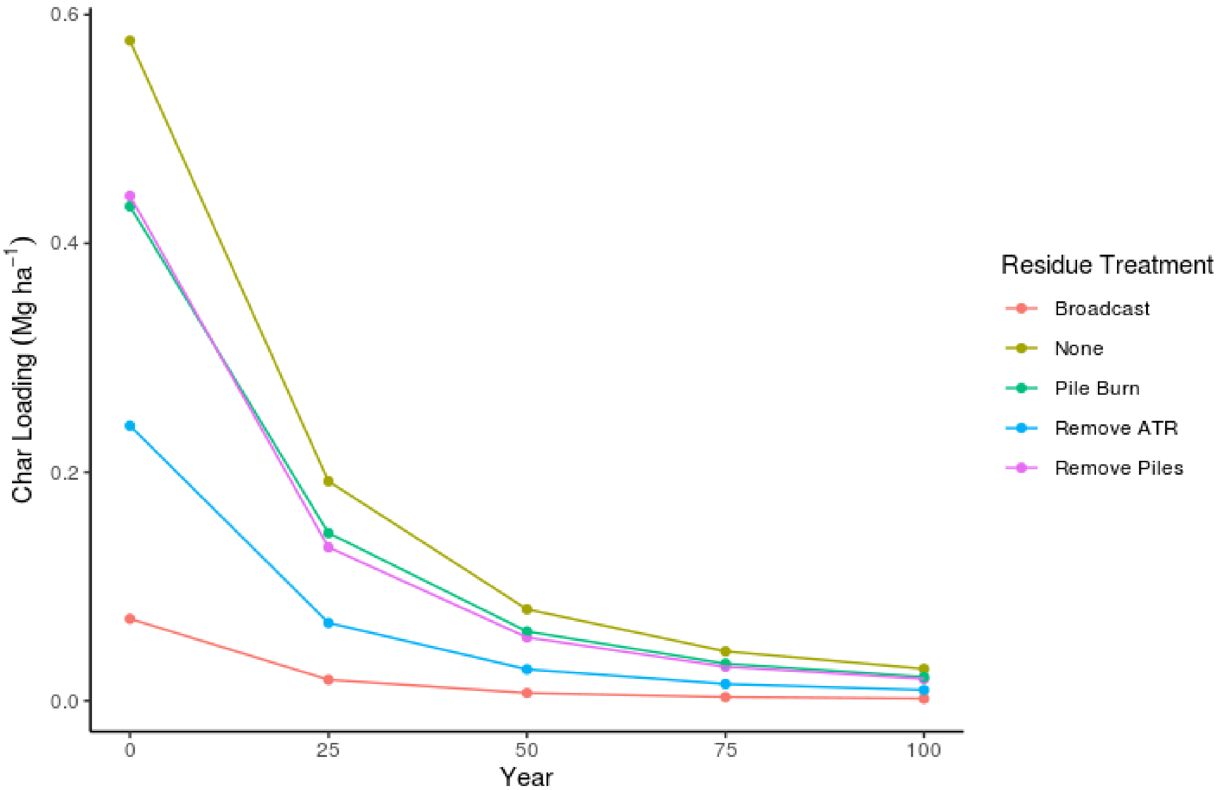

Figure 12: Comparisons of char production following wildfire from 0 to 100 years after a suite of residue treatment types. Residue treatments included a no treatment (None), broadcast burning (Broadcast), pile burning (Pile Burn), removal of all technically recoverable fuels (Remove ATR) or piled fuels (Remove Piles) removed for biomass energy production. Only 50% piled treatments are shown to allow for better visual comparisons among residue treatment trajectories.

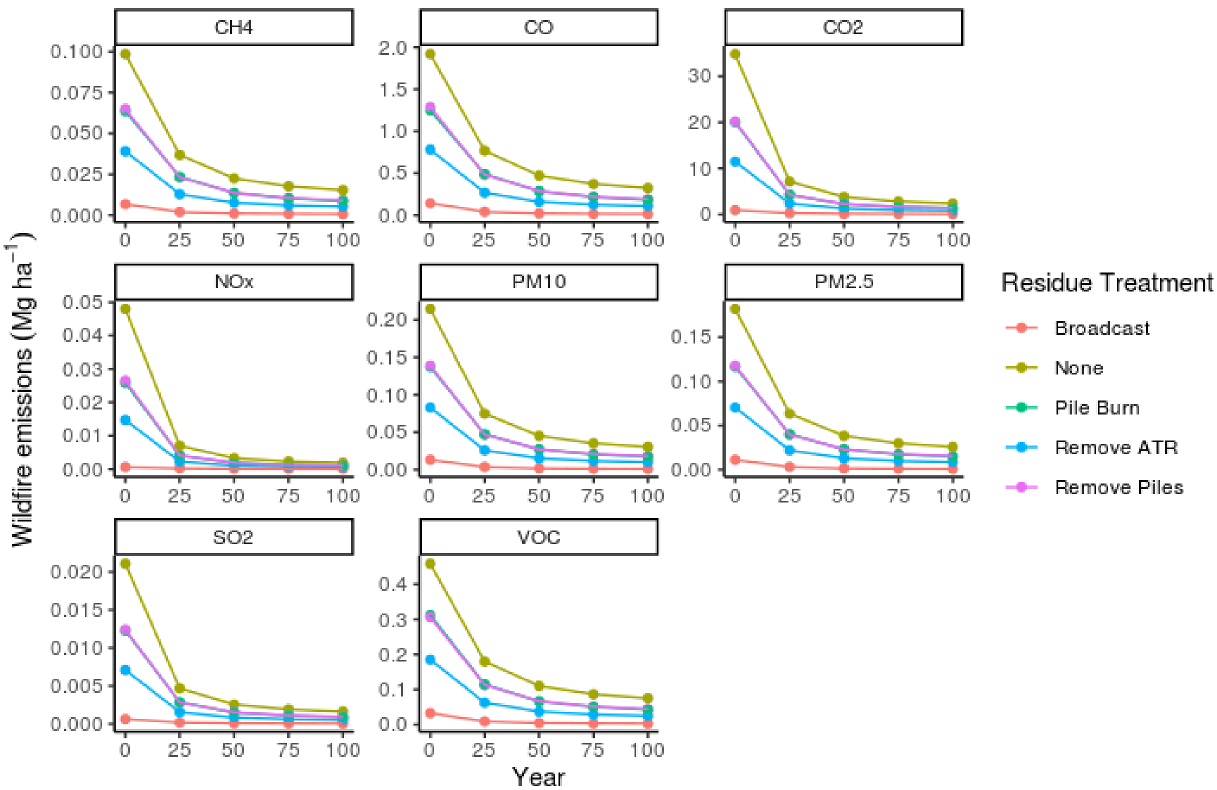

Figure 13: Modeled mean smoke emissions from wildfire over time following a suite of residue treatments following a thin from below with 40% of the basal area removed. Emission estimates do not include those associated with the residue treatment (e.g., broadcast burning or pile burning). Only 50% piled treatments are shown to allow for better visual comparisons among residue treatment trajectories.

CHAPTER 4
Discussion

4.1 Wildland Fuel Responses

The amount of generated surface fuels from forest and fuels management activities is dependent on forest types, stand conditions, intensity of the silvicultural treatment, and the type of residue treatment employed. Our modeled estimates of surface fuel loading varied considerably but were consistent with published observations in California and other regions of the western US (e.g., (Schwilk et al., 2009; Safford et al., 2012; Vaillant et al., 2015), although site-specific validations of our work is needed. Without subsequent treatment of the residues, these accumulated fuels from forest management activities can contribute to substantial fire behavior, increased fire severity, and additional carbon emissions if subjected to a wildfire (Agee and Skinner, 2005; Raymond and Peterson, 2005; Hurteau, 2017).

Based on our findings at the statewide level, broadcast burning treatments were consistently the most effective treatment at reducing surface fuels compared to all other residue treatment types. These findings are largely aligned with both modeling and empirical studies that have examined fuels following silvicultural thinning and broadcast burning treatments combined (e.g., Schwilk et al., 2009; Reinhardt et al., 2010). Our analysis assumes that prescribed burning occurred during the 37.5th percentile weather conditions, which commonly represents typical conditions used for modeling. However, actual broadcast burning conditions can vary widely with substantial variability in the resultant consumption of woody fuels, with some cooler or wetter season burns resulting in less consumption (Ryan et al., 2013). We employed the Consume model to estimate fuel consumption, which models that litter, 1 hour, and 10 hour as 100% consumed (Prichard et al., 2006), an assumption that is corroborated by empirical observations and validation studies, but that may result in overestimation of fuel consumption under certain conditions (Ottmar, 2014). While broadcast burning is an effective way to remove surface fuels, it is important to point out that our modeling scenarios only tracked the fate of fuels generated from silvicultural treatments and did not include additional inputs over time. Existing research that examines fuel loading changes over time is not available for many forest types, but research has indicated that some fuel (e.g., litter and fine woody fuels) can recover within 7 to 10 years following broadcast burning treatments (van Mantgem et al., 2016). Thus, subsequent broadcast burns is likely necessary to maintain reduced fuel loads to decrease fire behavior and effects during wildfire.

The biomass removal for energy production treatment that aims to recover 70% of the surface fuels resulted in the second lowest surface fuel loading of residues from silvicultural treatment. Removal of this proportion of fuels would likely be quite effective in reducing potential fire behavior, granted that the silvicultural treatment employed is also effective in reducing crown fire initiation and spread (i.e. raises canopy base height and reduces canopy bulk density). Prior research that modeled the effects of different silvicultural and residue treatments in forests of Montana found that biomass removal treatments were effective at reducing potential fire behavior in the short term, but that longer-term effects were highly varied (Reinhardt et al., 2010). Empirical studies that have quantified fuel reduction following biomass removal for energy production treatments is not available and, thus, we do not know how well our modeled results compare to field-based results. Future work that examines the change in fuel loading following these treatments would be beneficial. While this treatment is potentially effective at reducing fuel accumulations, broadcast burning treatments may be required or desired in some locations to promote further reductions in fuel loading, maintain fuel reductions over time, and to promote other ecological benefits provided by fire.

Pile burn and pile removal treatments resulted in the lowest amount of fuel reduction compared to other treatments. It is unclear whether these reductions would result in reduced fire behavior and effects during a subsequent wildfire. Although, pile burn treatments were effective at reducing bole char height and fire effects resulting from the 2007 Angora Fire in the Lake Tahoe Basin, California (Safford et al., 2009).

4.2 Char and Smoke Emissions Among Treatments

Estimations of char production was generally low following either broadcast burning or pile burning, but broadcast burning did result in substantially more char production than pile burning. Carbon stored in the form of charcoal can be very resistant to decay and can offset some of the losses of carbon from combustion (DeLuca and Aplet, 2008). Assuming that 60% of the generated charcoal is carbon (Wiechmann et al., 2015), the predicted range of charcoal carbon produced by either pile burning or broadcast burning of residues ranged between 0.02 and 0.54 Mg C ha^{-1}, depending on the silvicultural treatment employed. Generally, areas that had more pre-fire surface fuel loading were predicted to generate more char production, a finding that is corroborated by other studies (Pingree et al., 2012; Wiechmann et al., 2015). Our modeled estimates of char production were consistent with empirical estimates ranging between 0.02 and 0.78 Mg C ha^{-1}, based on a study in a mixed-conifer forest in the Sierra Nevada following thinning and broadcast burning treatments (Wiechmann et al., 2015). However, both of these estimates were considerably lower than range of 2.0-4.5 Mg C ha^{-1} observed in another study within mixed-conifer forests of California (MacKenzie et al., 2008), likely reflecting methodological differences that were able to account for micro-particles of char in the latter work.

While broadcast burning treatments were predicted to be highly effective at reducing surface fuels and therefore emissions during subsequent wildfire, these treatments also resulted in higher direct emissions relative to other residue treatments. However, the statewide mean CO_2 emissions generated from a prescribed fire was slightly higher than CO_2 emissions generated from a wildfire without prescribed fire, 36.7 Mg ha^{-1} and 34.8 Mg ha^{-1}, respectively. Our modeled emissions estimates were slightly less than a recent study that modeled wildfire emissions for a range of silvicultural and residue treatment scenarios in the northern Rockies (Hyde and Strand, 2019), likely due to our focus on dead surface fuels generated from silvicultural activities. Total emissions estimates will likely be higher during wildfire in conditions that contribute to a high proportion of canopy fuel consumption. The emission estimates for wildfire scenarios will also be sensitive to the emission factors used in the model. There is substantial variation in the emission factors for some constituents across modeling frameworks (e.g., Prichard et al. 2006, Larkin et al. 2009) that can lead to meaningful differences among estimates (Drury et al. 2014). Research that provides more guidance on the most appropriate emission factors to use for a given region and treatment scenario is needed.

4.3 Applications for Management

To our knowledge, this study has generated the finest resolution of spatially explicit fuel loading and emissions data following the widest range of silvicultural and residue treatment scenarios for non-wilderness, forested regions in California. Fuel management decisions are complex, multi-faceted, and location-dependent. Managers require input data that captures the spatial variability across a landscape and often need to consider different strategies across these areas for range of reasons. Data from our study can aid site-specific modeling over a wide range of scenarios that are specific to given site and the desired objectives. Additionally, this information can aid in the strategic location and prioritization of fuel treatments for managed landscapes that limit the amount of area that needs to be effectively treated (e.g., Finney et al., 2007; Ager et al., 2010; Tubbesing et al., 2019).

CHAPTER 5
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APPENDIX A
Fire Methodology Details

Figure A1: Flow Diagram for 1-, 10-, and 100-hour Fuel Algorithms

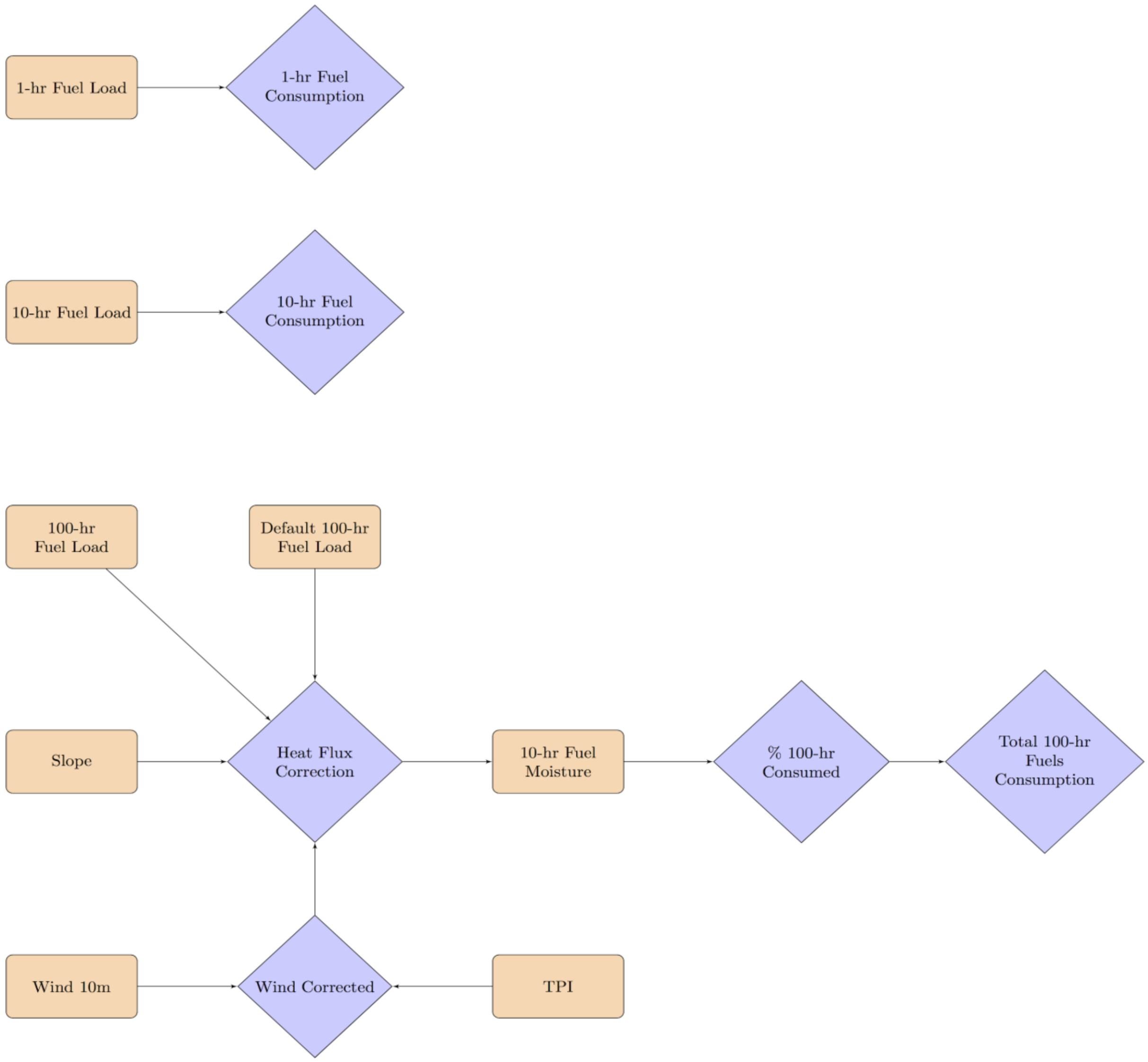

Figure A2: Flow Diagram Fuel Algorithm for 1,000-hour and Larger Fuels

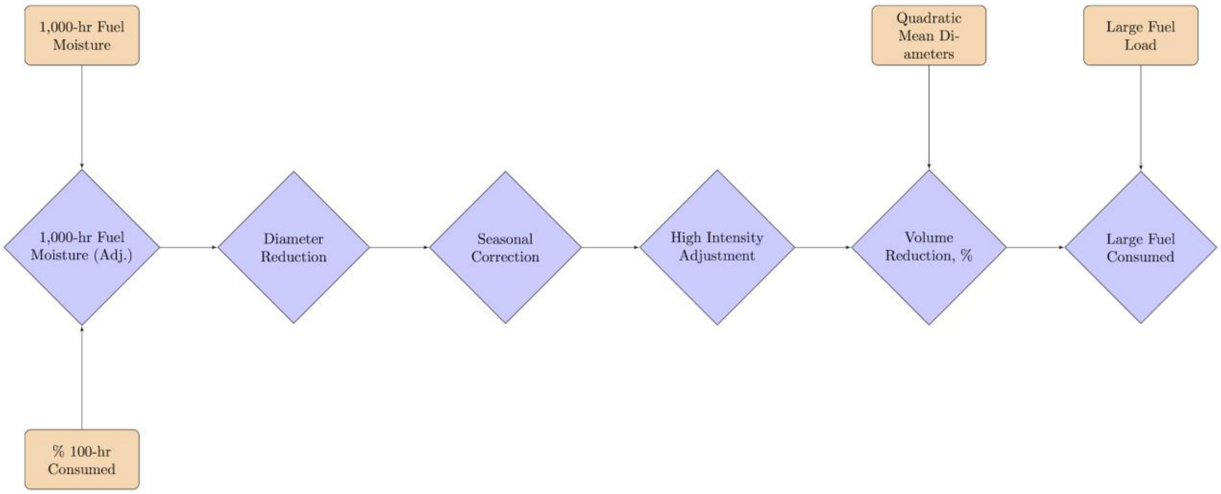

Figure A3: Flow Diagram for Litter Fuel Algorithm

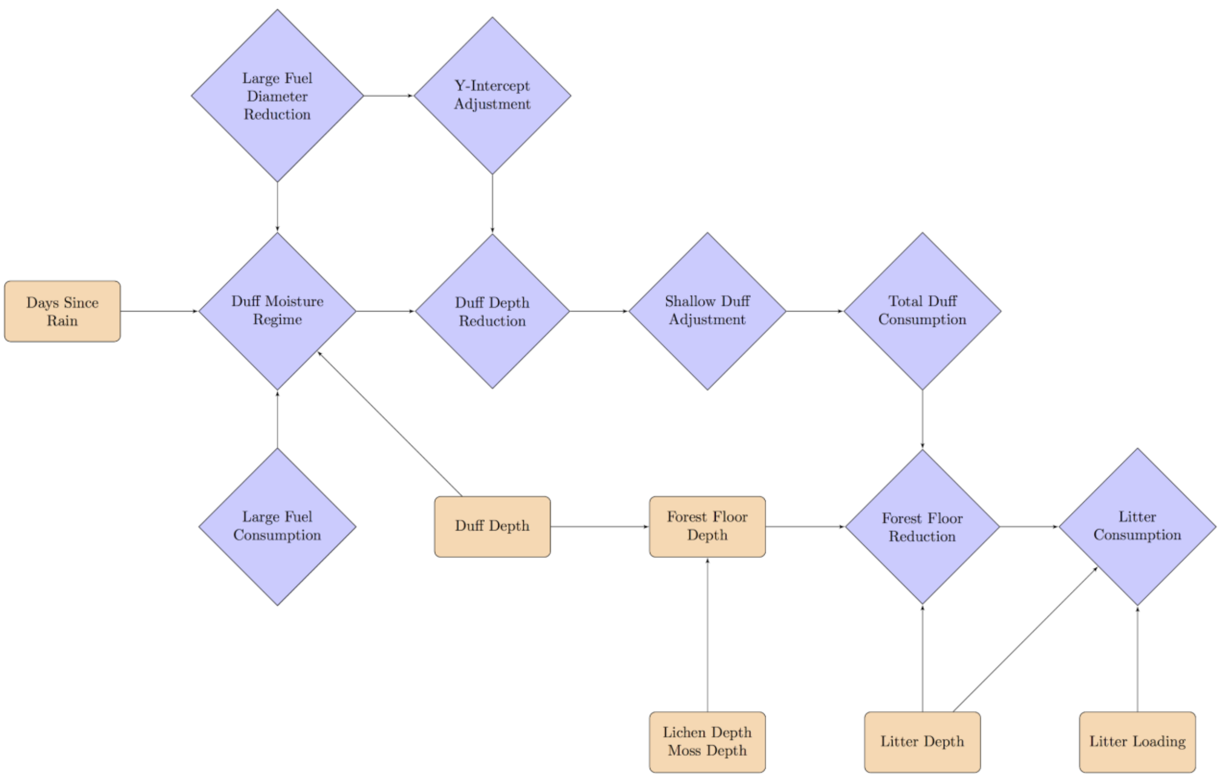

Figure A4. Observed charcoal production (% of fuel consumed, points) versus fuel consumed (tons/acre). The dotted line is the fitted model. Data taken from figure 3 in Pingree et al. (2012).

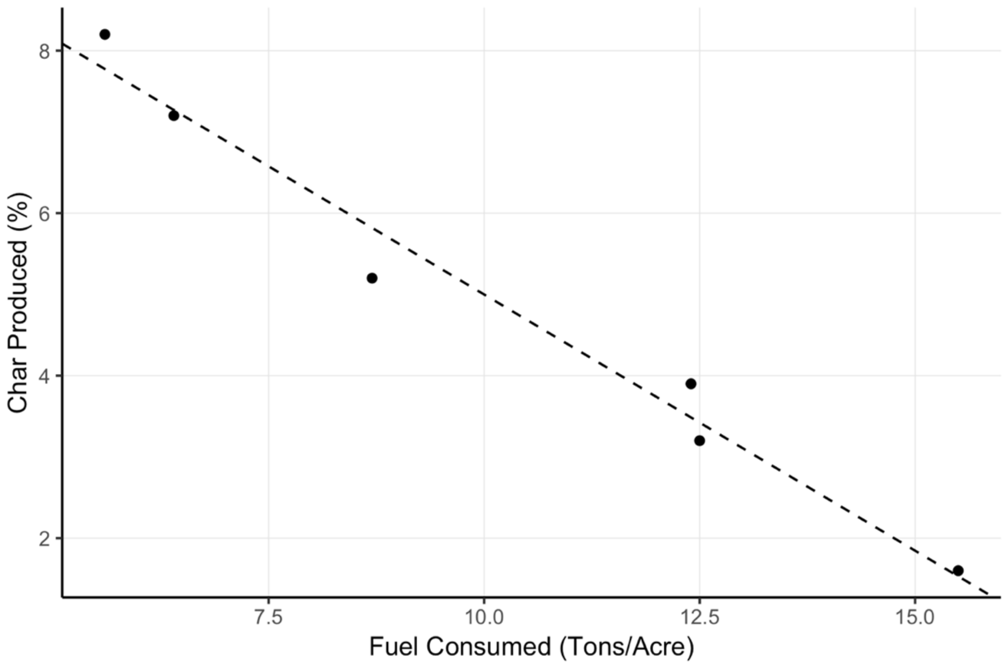

Figure A5: Wind Adjustment Factors for Site Characteristics