Report

California Biomass Residue Emissions Characterization (C-BREC) Model Framework

Version 1.2.1

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CHAPTER 1
Introduction

The California Biopower Impacts (CBI) Project is supported by the California Energy Commission under Grant Funding Opportunity 16-306. This multi-year project – begun in the summer of 2017 - investigates many of the greenhouse gas (GHG) and other environmental considerations associated with utilization of forest-derived woody biomass and agricultural residues for electricity and process heat generation, as well as investigating project economics and developing policy recommendations.

California's Forest Carbon Plan (Forest Climate Action Team, 2018) identifies insufficient forest management activity rates, limited biomass processing and utilization infrastructure, and unprecedented deterioration of forest health as a few of the critical barriers to managing forests for resilience and net carbon sequestration. In his October 2015 proclamation of a State of Emergency, Governor Brown emphasized that California utilities and state agencies should cooperate to address this emergency. At the same time, residues generated by forest thinning and fuels treatment as well as conventional forestry and agricultural activities have the potential to be transformed from a waste stream into a renewable energy resource.

If managed properly, bioenergy can support sustainable forest management activities while also advancing California's Renewable energy goals. However, there are legitimate concerns surrounding climate, air quality, and ecosystem health implications of improperly managed bioenergy systems. The CBI Project seeks to firmly and transparently establish the environmental performance of bioenergy from forest and agricultural residues.

The key project goals are to:

1. Assess and map technically recoverable forest and agricultural biomass residue in California that could be utilized for electricity and heat generation.
2. Conduct a landscape-level assessment of the fire emission implications of forest residue removal.
3. Develop and implement the California Biomass Residue Emissions Characterization (C-BREC) Tool.
4. Characterize and report on key positive and negative environmental impacts of residual biomass mobilization such as changes to soil nutrient balance and carbon stock, and air quality effects from altered black carbon and criteria air pollutant emission profiles.
5. Assess the potential to offset residue mobilization costs for forest management activities through value added supply chains, post-harvest processing, payments for ecosystem services and similar schemes.
6. Consolidate project results into actionable policy recommendations, and disseminate these recommendations to California stakeholder groups.

This document lays out the framework and methodologies developed for the C-BREC tool, laying out in detail the datasets, assumptions, and methods that went into this spatially-discrete emissions accounting tool for electricity and process heat from California residual biomass. Chapter 2 of this document describes the California Biomass Residue Emissions Characterization (C-BREC) modeling framework at a high level, defining key terms as they apply to this framework, and explaining key methodological choices that underpin the model. Chapter 3 lays out the parameters that must be defined for a given model scenario and the options that are available for each. Subsequent chapters offer detailed information on the different elements of the life cycle assessment framework - namely biomass resource base assessment (Ch. 4), decay (Ch. 5), emissions from fire (Ch. 6), emissions from soil (Ch. 7), emissions from the bioenergy supply chain (Ch. 8), emissions from electricity and process heat production (Ch. 9), and aggregate climate impact metrics (Ch. 10).

CHAPTER 2
The California Biomass Residue Emissions Characterization (C-BREC) Framework

Almost a half-century of literature has established life-cycle assessment (LCA) as an effective tool for evaluating the total resource impact of a product or action. The CBI Project has developed an LCA framework specific to the use of California forest and agricultural residues for electricity generation and heating applications. This chapter describes the goal, scope, and intended applications of this framework.

2.1 Goal of this Framework

The goal of this framework is to develop and describe a carbon footprint methodology for exploring the life cycle climate impacts of different bioenergy pathway scenarios. The framework is being implemented via the California Biomass Residue Emissions Characterization (C-BREC) model, a transparent and customizable LCA tool allowing stakeholders in California to evaluate the impacts of different residual biomass energy policy and technology pathways in the state.

There are many target audiences for this framework and for the C-BREC model. Biomass energy industry stakeholders and forest managers may use it to inform decisions and the evaluate potential supply-chain changes that could improve the environmental performance of their operations. LCA researchers will find methodological innovations and results that may be of use in other contexts. Finally, policymakers in California and beyond may find that the C-BREC framework and model provide useful insights in shaping policy at the nexus of forest management and renewable energy.

This framework was commissioned by the California Energy Commission under the Electric Program Investment Charge program's Grant Funding Opportunity 16-306. This program has the stated objective to "reduce the environmental and public health impacts of electricity generation and make the electricity system less vulnerable to climate impacts."

2.2 The C-BREC Model

The C-BREC model enables robust, transparent accounting for the GHG and air pollutant emissions associated with residual biomass energy systems in the state. This entirely open-source tool is being built using the R programming language, and implemented online using Python. Users specify the following key project characteristics to begin using the tool:

- Location of residue generation
- Type of forestry or agricultural activity being conducted
- Location of residue use

- Counterfactual fate (reference case) of unremoved biomass (piled, scattered, burned)
- Key supply chain characteristics such as any post-harvest treatment, end-use technology, etc.

For a given project profile, The C-BREC model generates an emissions time-series, reporting net emission values for several different time-explicit climate metrics. This modeling approach will enable us to evaluate the sensitivity of the results to various key input parameters.

What C-BREC *cannot* do at this stage is evaluate the statewide implications of biomass policy design. The model informs a user of the emissions associated with biomass mobilization at a given site and through a given supply chain as well as enabling the user to evaluate the impact of feasible changes to the system design. It does not tell a user the aggregate emission from statewide deployment of biomass power or from constructing a biomass power plant in a given location. Our framework could be applied to this type of analysis, but does not have these capabilities at present.

2.3 Reference and Use Cases

For a given biomass utilization scenario, details of both the reference and use cases must be defined. The use case refers to the scenario in which biomass residue is mobilized from the field for use in a biomass energy supply chain. For a given use case, the C-BREC model calculates emissions of criteria pollutants and GHGs (including biogenic carbon) across the supply chain, including mobilization, transportation, and end-use.

The net emission associated with mobilization and use of the biomass is the difference between these use-case emissions and a baseline, or "reference" case in which they are not mobilized. Because the biomass resource base in question for this research is residue from primary harvest and forest management activities, the baseline against which the use case must be compared is that in which those materials are cut and left on the forest floor or farm field. The reference case in our model is therefore made up of three distinct processes, applied in probabilistic fashion to any given tonne of biomass:

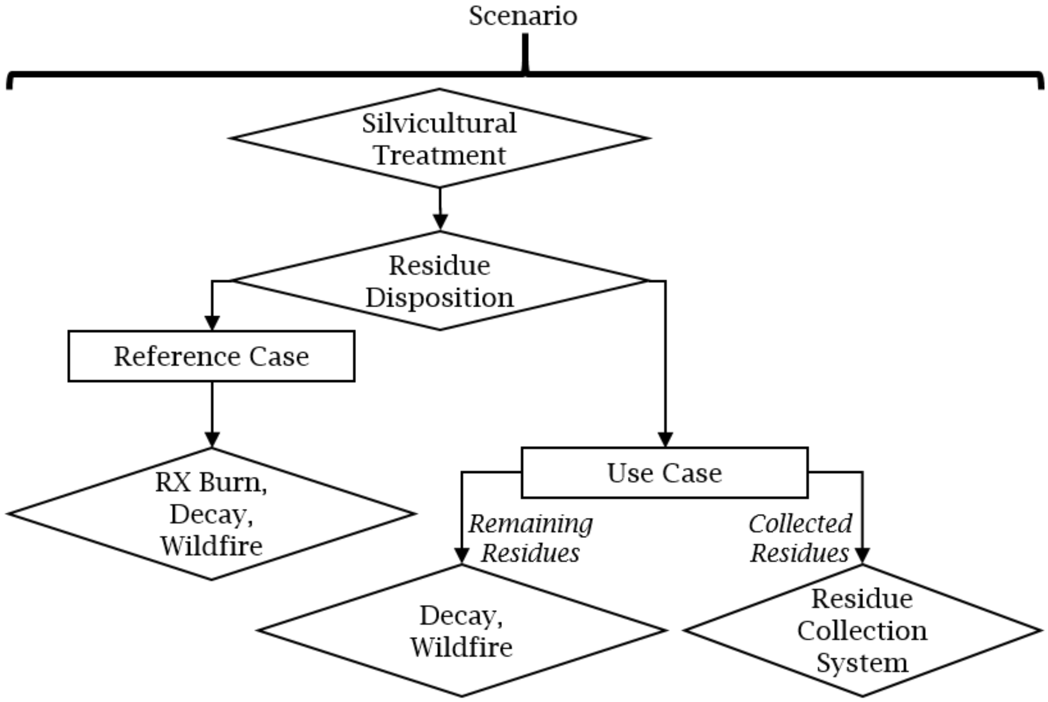
- Pile or broadcast burning of residues in year 1
- Decay extending for 100 years of material piled/scattered on the forest floor (forest residues) or scattered/incorporated into the soil (agricultural residues).
- Ongoing exposure to wildfire over a 100-year period (forest residues)

Since emissions are fully characterized in both cases, it is also possible to compare two different use cases or two different reference cases and to evaluate the sensitivity of the life-cycle emissions to specific decisions along the supply chain.

2.4 Definitions of Key Terms

To facilitate clear comprehension of the remainder of this framework document, we need to define a set of key terms that will be used throughout. These terms are related via the flow diagram in Figure 1.

Figure 1: Relationship of Definitions



- ***Reference case*** is the fate of the residues in question if they are not removed from the field for use in energy systems. Some LCA studies refer to this as the "counterfactual" case. However, we use "reference" case as this does not imply a deterministic counterfactual outcome (Giuntoli et al., 2016), but instead the outcome used as the reference for our analysis. The reference case includes ongoing decay of residues as well as exposure to prescribed burns and wildfire.
- ***Residue management method*** refers to what is done with residues in the reference and use case after silvicultural treatment activity. This includes pile burn, broadcast burn, and in-field decay. The reference and use cases can have different residue management methods.
- ***Residue collection system*** refers to the system of equipment used to collect, process, and mobilize residues in the use case.
- ***Residue disposition*** refers to the physical placement of residue following the silvicultural treatment. Depending on the harvest system and silvicultural treatment, varying fractions of gross residue are either piled or scattered. This affects the residue collection system in the use case, and decay and fire dynamics in the reference case.
- ***Scenario*** is the term used to describe the comparison between reference and use case characteristics. Net scenario emissions are the difference in emissions between reference and use cases. In other words, the use case represents the actual activity being modeled and the reference case represents the counterfactual fate if the activity didn't happen.
- ***Silvicultural treatment*** refers to the type of primary harvest involved in the scenario being investigated. The silvicultural treatment is what generates the residues. For forestry feedstocks, this can be harvest or thinning at different levels, fire management, or dead tree removal. This affects the amount of residue present, where that residue is left on the landscape, and how it would be collected for mobilization.

- ***Use case*** refers to the case in which the residues are removed from the field for biomass energy use. A given use case will have numerous supply-chain characteristics, including transport distance, equipment utilization, and end-use facility technology.

2.5 Primary Mass Balance Equations

The core of the C-BREC model consists of calculating use case and reference case emissions using an attributional approach. Emissions are time-explicit on an annual basis. For each gas species g the use case emissions are calculated with the following basic structure:

$$E_{use,g}(t) = \left(E_{supply,g} + E_{energy,g} + E_{RX,g}\right)\delta(0) + E_{decay,g}(t) + E_{wf,g}(t) \cdot \Pi_f,$$

where E_{supply} represents emissions associated with residue collection and mobilization, E_{energy} represents emissions from energy production, $E_{decay}(t)$ includes both decay of collected material at the power plant and in-field decay of remaining residue, and E_{RX} and $E_{wildfire}(t)$ represent emissions associated with in-field prescribed burning and exposure to wildfire respectively of remaining residue not mobilized. The term $\delta(0)$ represents the delta function at time $t = 0$ indicating that the cumulative emission from mobilization, energy production, and prescribed burning occur in year 0. The term Π_f represents a scaled rectangle function that annualizes wildfire by applying a probability that varies in time.

The reference case emissions are calculated with the following equation:

$$E_{ref,g}(t) = E_{RX,g}\delta(0) + E_{decay,g}(t) + E_{wf,g}(t) \cdot \Pi_f.$$

Emissions associated with a scenario are calculated as the difference between the use and reference cases, which introduces a consequential element to this framework:

$$E_{scenario,g}(t) = E_{use,g}(t) - E_{ref,g}(t).$$

The data used to calculate each of the emissions terms in the above equations depend on spatially-variable inputs, and the time-dependent terms also vary in time. Chapters within this framework discuss the methods used to calculate each of the terms.

Well-mixed greenhouse gas emissions are used to quantify climate change impact metrics. Climate change impacts are conveyed using a time-explicit approach to derive the well-known CO_2 equivalent metric.

2.6 Key LCA methodological choices

For clarity and transparency, this section details key methodological choices that have been made in structuring the C-BREC model analytical framework as well as the logic and decision factors underpinning those choices. This is broadly considered a best practice in LCA, as some of these subjective methodological decisions can have a significant impact on results (Wolf et al., 2010).

The CBI Project analysis takes an adapted attributional approach to Life Cycle Assessment following other key analyses in this space (Giuntoli et al., 2015). Some researchers (Plevin et al., 2014) prefer a consequential approach, citing reasonable concerns about the use of attributional LCA for policymaking, indicating that these approaches typically ignore – or poorly characterize – complex interactions such as market-mediated land use and land management effects, emission of short-lived climate forcing agents, and biophysical changes at the landscape level. The fact that the systems under consideration in this study are making use of waste and residue feedstocks avoids most market-mediated effects such as indirect land use change as well as the many biophysical effects caused by cutting of biomass that would otherwise have remained living (Cherubini et al., 2013; Giuntoli et al., 2015). This does not mean that there are no biophysical consequences associated with biomass removal, which is why the C-BREC modeling framework employs some key consequential elements in tracking not only the use-case of the material, but also the reference-case in which that material is left on-site.

2.6.1 System boundary

Life cycle inventory for the use case includes:

1. Direct emissions from collection, transportation, and conversion of biomass residues into electricity and process heat, and
2. Emissions resulting from changes in wildfire dynamics strictly associated with the absence of residues.

Life cycle inventory for the reference case includes emissions over time from residues scattered or piled in the field, including:

1. Prescribed burn of residues,
2. Decomposition out to 100 years following treatment, and
3. Emissions from residues due to wildfire.

Figure 2 and Figure 3 below detail the overall life cycle accounting framework deployed in the C-BREC model for forest and agricultural residues respectively.

2.6.2 “Upstream” emissions

A central assumption underpinning the C-BREC analytical framework is that the residual material being utilized is a *true waste* in that it would not have been used at all were it not for the bioenergy system being evaluated. As such, it is assumed that the residues are not a driver of the primary forestry or agricultural activity, and therefore the utilization of the residues is not allocated any of the upstream emissions associated with those activities. This approach is well supported in LCA literature and is the same approach taken by other key analyses focused on energy from residual biomass (Giuntoli et al., 2016; Gustavsson et al., 2015).

For example, commercial harvest activities are often conducted for the purpose of saw timber extraction. The branches and treetops that comprise the harvest residue base are typically left to decay or are burned on site. As such, we do not allocate any of the primary harvest emissions – nor any of the forest carbon cycling implications of the primary harvest – to the bioenergy pathway. Similarly, where fire management is conducted in California, the residue is a true waste product, with the fire management being the primary "product" of that activity. If the residues bore some current fair market value, conventional LCA methodology would assign them a portion of the upstream emissions through coproduct allocation. However, in this case, they are typically left or burned on site. Where they are mobilized, it is typically through systems that are subsidized as a means of waste/residue management. If this situation were to change, and the biomass electricity industry in California were to evolve to the point at which forest and agricultural residues have a sufficient positive value to drive forest management and cultivation decisions, this assumption would no longer be valid. This framework could be integrated with an LCA of the primary harvest activities to obtain a broader perspective on the environmental implications of forest management and agricultural activities.

2.6.3 Biogenic emissions

The biomass LCA literature is split as to whether biogenic emissions should be considered in life cycle GHG accounting. Some analysts assume that since they are part of a "closed loop" of sequestration and emission, they should be counted as zero. Others argue that not counting biogenic carbon potentially misses an important emissions source, as it can't be assumed *a priori* that all carbon emitted through a biomass energy supply chain is being re-sequestered at the source of the biomass. If bioenergy systems lead to a net loss in biosphere C stock, these emissions must be counted.

As the biomass under consideration is residue, and the activity generating the residue is assumed not to be driven by the residue market, this question is simpler than in other biomass LCAs. There is no change in on-site C pools beyond the presence/absence of the biomass residue itself, so by tracking the full emission profile of the use case, net of the emissions from fire and decay in the reference case, we are able to account for all net emissions biogenic and otherwise.

2.6.4 Functional Unit

Three different functional units are considered, as each is useful to different stakeholder groups.

- Emissions per Bone Dry Tonne (BDT) of residue collected
- Emissions per Bone Dry Tonne (BDT) of residue delivered to a power plant gate
- Emissions per kWh of electricity delivered at the utility point of connection

Throughout this project, tonnes are measured as metric tons (e.g. BDT is bone dry metric tons and tonnes of CO_2e is metric tons of CO_2 equivalent). Biomass moisture content is reported on a wet basis, that is the moisture content as a fraction of the original wet mass of the material.

Figure 2: Forest Residue Mass Flow Boundary

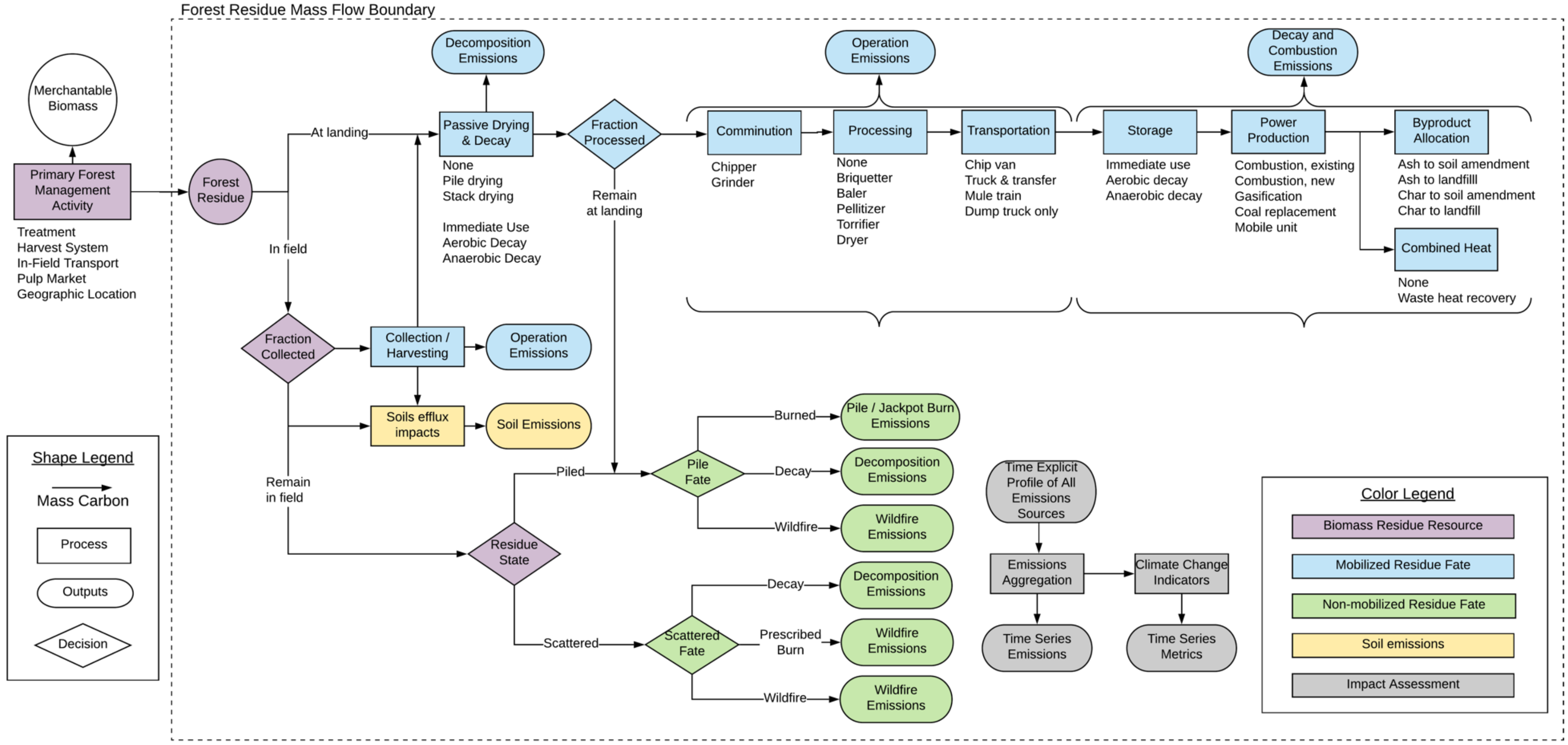
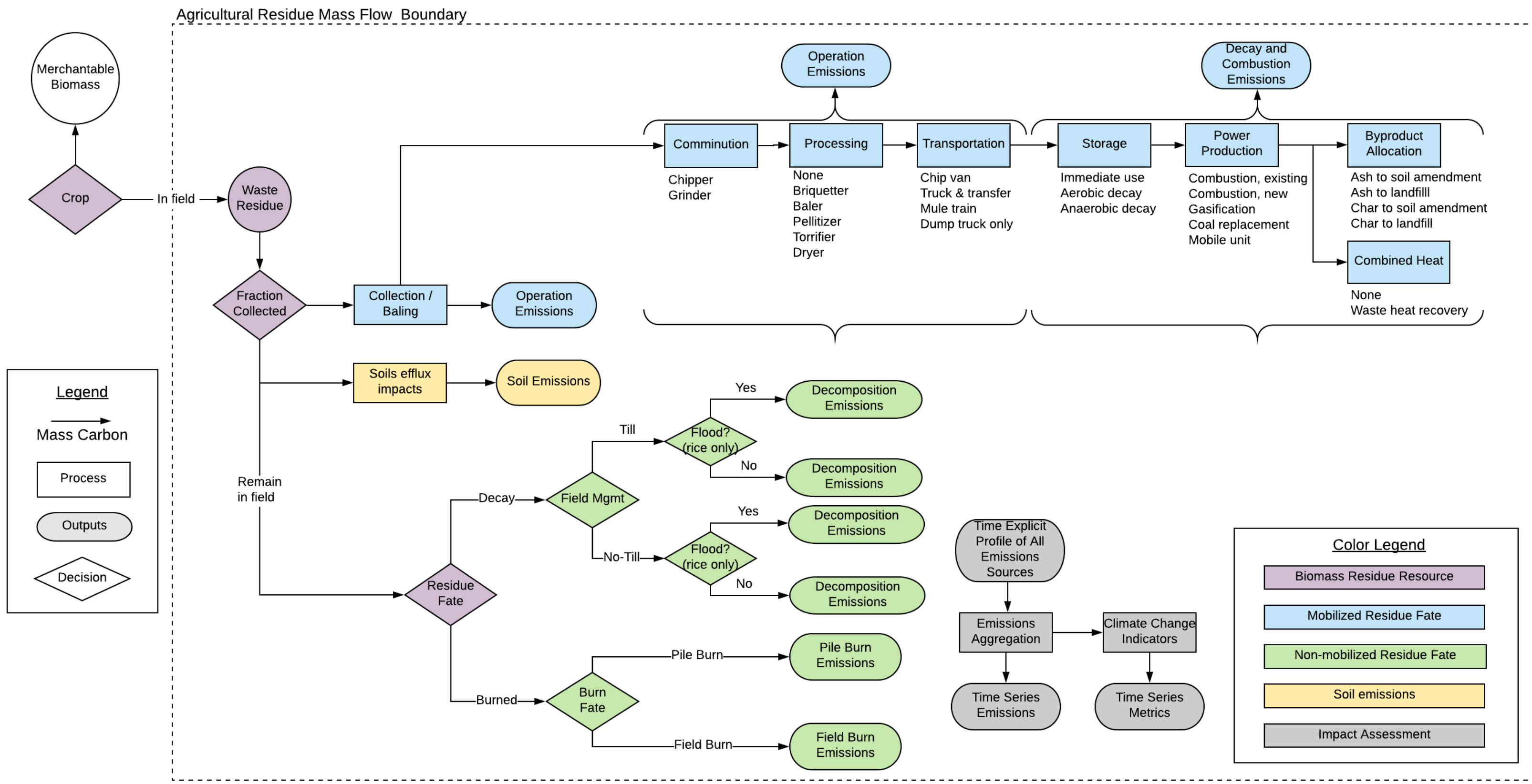


Figure 3: Agricultural Residue Mass Flow Boundary



2.6.5 Emission Species Considered

This analysis evaluates and reports gross (for both use and reference cases) and net emissions of key greenhouse gases and criteria air pollutants. Pollutant species quantified include the following:

- CO_2 – carbon dioxide
- CH_4 – methane
- N_2O – nitrous oxide
- VOC – volatile organic compounds (for sources that report non-methane hydrocarbons (NMHC) or non-methane volatile organic compounds (NMVOC), these are aggregated under VOC)
- NO_x – nitrogen oxides
- SO_x – sulfur oxides (for sources that report SO_2, these are aggregated under SO_x)
- PM_{10} – particulate matter less than 10 microns in diameter
- $PM_{2.5}$ – particulate matter less than 2.5 microns in diameter
- BC – black carbon as a fraction of $PM_{2.5}$

2.6.6 Life Cycle Impact Assessment Impact Categories and Indicators

This framework inventory specifically quantifies air emissions only, and ignores other categories such as water pollutants. It limits the air emissions to those species listed above. We aggregate three greenhouse gas species (CO_2, CH_4, and N_2O) into two midpoint climate change indicators: absolute global warming potential and the absolute global temperature potential. We use an "Emissions Scenario" methodology to calculate these two indicators in a time-explicit way. This methodology has only recently been applied in published LCAs (Giuntoli et al., 2015), and is documented in the Intergovernmental Panel on Climate Change (IPCC) 5th Assessment Report (Myhre et al., 2013). We describe the approach in detail in CHAPTER 10.

The framework does not aggregate criteria pollutant emissions into any impact indicators. Rather it directly reports the mass quantity of these emissions per unit of biomass/bioenergy production. This will enable investigation of both the net emission and the spatial distribution of these pollutants in reference and use cases. In addition, it does not quantify any endpoint indicators that estimate the impacts associated with the emissions (e.g. sea level rise or human health impact).

2.7 Alignment with Key Existing Frameworks

Discussed here are key reference documents that this framework uses for guidance and/or are important for understanding how this framework relates to important state policies.

2.7.1 International Reference Life Cycle Data (ILCD) Handbook

The design of this framework follows the ILCD Handbook General Guide for Life Cycle Analysis - First Edition (Wolf et al., 2010) in scoping and development of the four main LCA steps: 1) goal and scope definition; 2) life cycle inventory analysis; 3) life cycle impact assessment and 4) interpretation. These guidelines build upon, are compliant with, and exceed ISO 14044:2006 requirements. Note that the CBI Project framework does not seek ILCD compliance.

The ILCD handbook requires that LCA frameworks clearly define their goals and target audience. Section 2.1 above describes both in detail. It also identifies the funder and funding program responsible for this research in the interest of transparency.

Per the ILCD handbook, this document is also explicit about the limitations of the C-BREC modeling framework. As described in Section 2.6.1 above, C-BREC enables rigorous calculation of the emissions impact of various biomass-residue-to-energy supply chains in California. However, it is a project-based analysis and does not characterize statewide dynamics. As such, it cannot be used directly to evaluate the statewide implications of biomass policy design or to calculate the aggregate emission from statewide deployment of biomass power. Furthermore, the C-BREC system boundary excludes the emissions impacts of primary treatment decisions. It can be used to evaluate the impact, for example, of removing residues from fire risk management activities. However, it does not assess the efficacy or emissions implications of conducting those treatments in the first place. Integrated land-use assessment of this type would require coupling C-BREC with another land-use modeling framework.

The key objectives of this framework are:

- To integrate and aggregate data associated with processes along the residue biomass supply chain within the framework boundary.
- To align framework design with relevant policy priorities in California such that the comparative LCIA results can inform policy decisions to the extent possible.
- To enable transparency in biopower LCA by evaluating the sensitivity of results to key input assumptions

The target deliverables of this framework are the following compared between the reference and use cases for biomass residue:

- Greenhouse gas and criteria pollutant emissions per bone dry tonne of residue, and
- Two climate change midpoint indicators associated with the greenhouse gas emissions per bone dry tonne of residue: global warming potential and integrated global temperature potential.

2.7.1.1 Decision Context

The ILCD Handbook breaks down LCA studies into the following set of what it terms “goal situations”

- Situation A ("Micro-level decision support"): Decision support on micro-level, typically for product-related questions. “Micro-level decisions” are assumed to have only limited and no structural consequences outside the decision-context, i.e. do not change available production capacity. The effects are too small to overcome the threshold to be able to cause so called large-scale consequences in the background system or other parts of the technosphere.
- Situation B ("Meso/macro-level decision support"): Decision support at a strategic level (e.g. raw materials strategies, technology scenarios, policy options, etc.). “Meso/macro-

level decisions" are assumed to have also structural consequences outside the decision-context, i.e. they do change available production capacity. The analyzed decision alone results in large-scale consequences in the background system or other parts of the technosphere

- Situation C ("Accounting"): Purely descriptive documentation of the system under analysis (e.g. a product, sector or country), without being interested in any potential consequences on other parts of the economy. Situation C has two sub-types: Situation C1 that includes existing benefits outside the analyzed system (e.g. credits existing recycling benefits) and Situation C2 that does not do so.

Based upon this typology, the CBI Project and C-BREC modeling tool should be considered a Situation A tool - capable of evaluating in detail the impacts of a given biomass-to-energy system given spatial and supply-chain specifics of that system. It can be used to evaluate sensitivities of life cycle emissions to various system decisions and characteristics and to aid in system design to improve environmental performance.

2.7.2 EPA Framework for Assessing Biogenic CO2 Emissions from Stationary Sources

The US Environmental Protection Agency published a 2014 framework for biogenic emissions accounting in LCA (US EPA, 2014). This framework hinges on a) comprehensive accounting for avoided emissions, b) leakage from the supply chain, c) sequestered carbon content in the final product, and d) change in non-feedstock carbon pools in the source location. C-BREC accounts for avoided emissions from biomass mobilization as well as leakages/mass loss along the supply chain. It defines as sequestered any carbon created through incomplete combustion in the field or in a power plant as well as any biomass remaining after 100 years of exponential decay. Because the system boundary assumes that the residues in question are true wastes, any landscape-level carbon pool changes resulting from primary treatment are not allocated to the bioenergy system.

2.7.3 CARB Quantification Methodology for CAL FIRE Forest Health Program

The California Air Resource Board (CARB) developed a Forest Restoration and Management Quantification Methodology (FRMQM) for the Forest Health Program (California Air Resources Board, 2021). Our framework differs from the FRMQM in the boundary of the emissions assessment. Our framework boundary is analogous to the "project boundary" as defined by the FRMQM. Furthermore, whereas the FRMQM aims to evaluate the climate impact of primary treatment, the C-BREC framework aims to evaluate the climate impact of waste/residue mobilization. As such, C-BREC does not account for forest re-growth, emissions from primary treatment, or landscape-scale fire impacts (i.e. "impact boundary" as defined in the FRMQM) as these are considered exogenous. However, in areas of system boundary overlap, we align with the following methods specified in the FRMQM:

- Residue resource tree list: our resource database was modeled using 2012 Gradient Nearest Neighbor (GNN) dataset made available by the Landscape Ecology, Modeling, Mapping, and Analysis group at Oregon State University (Ohmann & Gregory, 2002) which draws on the FIA database and other resources,

- Forest Fire Model: we use the Fire and Fuels Extension to the Forest Vegetation Simulator (FVS FFE) and the Consume model to estimate emissions from pile burns, prescribed burns, and wildfire,
- We annualize the wildfire probability using the same method as that shown in Equations 8 and 9 in the FRMQM, and
- We determine a net GHG impact via the difference between a reference and use case.

CHAPTER 3
Defining LCA Scenario Parameters

This framework enables the exploration of and comparison between a large number of pathways that specify different use and reference fates for forest and agriculture residues. It is designed to calculate and compare time-explicit emissions profiles between a specified reference and use case for residues to evaluate the net emissions impact of residue mobilization. To evaluate a scenario for LCA, the following set of parameters must first be defined, characterizing the system under consideration:

- Location, source, and characteristics of the biomass resource base under consideration
- Residue fate in both reference and use cases
- Characteristics of the processing, transportation, and end-use systems deployed in the use case

These three sets of parameters are described in the following sections. Further detail on methodology, assumptions, and resultant calculations can be found in the remaining chapters of this document.

3.1 Identify the Biomass Residue Resource

The first parameter requiring definition in the C-BREC framework is the biomass residue base being evaluated. This requires establishing a study area location and primary treatment operational characteristics. There are numerous combinations of the system properties such that many pathways can be evaluated using the C-BREC framework. The following characteristics of the biomass resource base vary from scenario to scenario:

- Total and per-acre technically available residue mass in the study area (CHAPTER 4),
- Residue disposition (CHAPTER 4), including
    - Species and size class distribution,
    - Whether residues are piled or scattered, and
- Decay constants that are applied to the reference case (CHAPTER 5).

The following system characteristics must be established for a given biomass residue scenario:

- Resource sector: either forest or agricultural residues
  a) Forest
    i) Primary treatment: this partially determines total volume and spatial density of residues (CHAPTER 4)
        - One of 14 modeled primary treatment options
    ii) Whether market exists for pulp logs in the region: this determines if pulp logs are included in the residue base.
        - Yes or no
    iii) Specify geographic location and study area: this partially determines total volume and spatial density of residues (CHAPTER 4), indicates species

composition, and determines applicable decay constants (CHAPTER 5) and wildfire probability (CHAPTER 6).

b) Agriculture
   i) Crop type: Affects the decay rate for in-field residues and partially determines total volume of residues
      - one of seven major California crops
   ii) Post-harvest field management: Affects the decay rate for in-field residues
      - Till or No-Till
   iii) Specify geographic location and study area: this partially determines total volume of residues

3.2 Define the Residue Fate for the Reference and Use Cases

The next step in the LCA process is to define the fate of the residues in both reference and use cases. Different fates are possible for forest and agricultural residues. This choice determines the following system characteristics:

1. Mass fraction of residues that can be collected (CHAPTER 4)
2. Decay emissions over time from residue left in the field as applicable (CHAPTER 5)
3. Combustion emissions from wildfire and prescribed burn as applicable (CHAPTER 6)
4. How the residues are collected, and the emissions associated with collection equipment (CHAPTER 8)
5. Combustion of residues in a power plant (CHAPTER 9)

3.2.1 Forest Residue Fates

Each LCA scenario for forestry residues is characterized by defining both a reference and a use-case fate for the residual biomass under consideration. For each reference and use case, the silvicultural treatment and residue disposition must be specified. In addition, the reference residue management method must be specified for the reference case, and the residue collection system must be specified for the use case.

For any given silvicultural treatment, the different permutations of reference residue management method options and residue collection system options are defined in Table 1. Note that not all possible reference and use cases can be compared in a scenario because the residue disposition must be the same for both cases (as shown in Figure 1). See Section 4.2 for a description of the technically recoverable biomass in different cases. Furthermore, some options that are allowed are not commonly practiced.

Table 1: Definition of Reference and Use Cases for Forest Residues

F-R1. Biomass Left On-Site All residues are left on-site to decay and are subjected to annualized wildfire probability.
F-R2. 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.
F-R3. 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.
F-R4. 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.
F-U1. Collect All Piles All piled residues are collected. Residues that remain are subjected to decay and annualized wildfire probability.
F-U2. Collect All Piles and/or Technically Recoverable Scattered 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.

Different activities are applied in the following temporal order:

- Year 1: Collection -> Prescribed Burn -> Decay -> Wildfire
- Remaining Years: Decay -> Wildfire

3.2.2 Agricultural Residue Fates

Each LCA scenario for agricultural residues is characterized by defining both a reference and a use-case fate for the residual biomass under consideration. Some options will be limited by whether the residue is a straw residue, such as corn, cotton, rice, or wheat, or a woody residue, such as almond, walnut, or grape residues. These residue classes are discussed in greater detail in CHAPTER 4. Each reference and use case is defined in Table 2. See Section 4.2 for a description of the technically recoverable biomass in different cases.

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

A-R1. Biomass Left Scattered On-Site Residues are left scattered in-field to decay. Decomposition dynamics depend on the crop (in the case of rice, depending also on whether the field is flooded post-harvest). A-R2. Residues Incorporated Into Soil (Straw Only) Residues are tilled into the soil in the field in which they were grown during year 1 – the same year as the primary harvest activity.. This option is limited to straw residues (corn, cotton, rice, and wheat). Decomposition dynamics depend on the crop (in the case of rice, depending also on whether the field is flooded post-harvest). A-R3. Residues Burned On-Site All residues are control-burned during year 1 – the same year as the primary harvest activity.
A-U1. Collect Residues Biomass residues are collected. Residues that remain are subjected to above-ground decay.

Different activities are applied in the following temporal order

- Year 1: Collection -> Prescribed Burn -> Decay
- Remaining Years: Decay

Note that wildfire is not applied to agricultural residue pathways as we assume agriculture lands are not exposed to significant wildfire risk.

3.3 Define Processing, Transportation, and End-Use Systems Deployed in the Use Case

For the use-case in a given scenario, characteristics of the biomass energy supply chain have significant impact on life cycle emissions profile. The parameters must be defined regarding biomass residue processing equipment, transport equipment and distance, and end-use technology (CHAPTER 8 and CHAPTER 9).

3.3.1 Forest residue collection and post-harvest treatment

Residue collection equipment systems are defined based on the following parameters:

- Project size: cumulative amount of technically available residue for a specified project. This is calculated when the residue resource and geographic location are specified as described in Section 3.1.
    - Large: residue volume >= 1,000 BDT, and residue density is >= 13 BDT per acre
    - Small: any project that does not meet the conditions of a large project
- Moisture and dirt content
    - Clean and green: low dirt content, 63% moisture content (wet basis)
    - Dry and/or dirty: high dirt content, 50% moisture content (wet basis)
- Chip or grind
    - Chipping is only allowed for clean and green material generated from a large project

    - All residues are assumed to be chipped or ground in-field
- Residue disposition and collection: piled or scattered already specified when the residue resource and geographic location are specified as described in Section 3.1. Identification of whether piles and scattered material will be collected is already specified by the use case as described in Section 3.2
- Slope: determined by the slope of each raster cell in the project area
    - slope <= 10%
    - 10% < slope <= 35%
    - slope > 35%

Equipment systems defined for each of the permutations of the above variables are described in CHAPTER 8.

3.3.2 Agricultural residue collection and post-harvest processing

It is assumed that 5% of residue mass is lost during the collection process. This then becomes a part of the residue mass that is left in the field. Static options for processing are as follows:

- All woody material
    - Chip or grind
- All straw material
    - Baler

3.3.3 Define Residue End-Use Location

For a given scenario, a location for biomass residue end-use must be established, along with the conveyance type used for material transport. We model all current and proposed wood aggregation points (including power plants and mills) in California and limit transport distance to 4-hour one-way or less drive-time. While some transport methods (namely the mule train) would not be appropriate for agricultural residues, there is no anticipation of uniquely agricultural equipment needed for transportation to an end-use location. The options for transport are as follows:

- Chipvan
- Truck and Transfer
- Mule Train
- Dump truck only

3.3.4 Define Residue End-Use Pathway

Once residues have been collected, processed, and transported to the power plant, there are various end-use pathways that can be specified. These are as follows:

- Biomass stoker
- Cyclone combustor
- Fluidized bed combustor
- Gasifier

Each of the above technologies can be deployed with or without a combined heat and power (CHP) system. Either existing power plant locations (and associated technology) can be chosen, or a generic technology and static haul distance can be specified. Details are described in CHAPTER 9.

CHAPTER 4
Biomass Residue Resource Assessment

While this framework reports emissions on a per bone-dry tonne of residue basis, derivation of residue availability requires gross carbon stock estimates. This section describes the input datasets and methodology used to calculate the gross carbon stock, derive gross residue amounts, and estimate technically recoverable residue amounts.

4.1 Gross Resource Estimation Methodology

The gross biomass residue available from forestry and agricultural activities was estimated within California. These estimates comprise the available supply of residues that can be collected for electricity and process heat production.

4.1.1 Forest

Biomass residues from forestry activities are a byproduct of a primary forest treatment. We define residues as those parts of the tree remaining after a primary treatment that do not have a market pathway (i.e. forest slash). The biomass resource base comprises trees and the forest overstory, but does not include shrubs or understory. A species list is included in APPENDIX A, Table 47.

In order to estimate the amount of residues that can be transported out of the forest to a bioenergy facility, three major steps are required:

1. Define the initial structure and stocking of California's forests,
2. Describe the type, extent, and impact of different silvicultural treatments, and
3. Evaluate the gross amount of residues generated by the silvicultural treatments.

The following sections provide details on how we assess the amount of residue that would be available from a variety of treatments on California's forest landscapes.

4.1.1.1 Forest Characterization

The initial forest conditions for all of California are characterized by updating the 2012 Gradient Nearest Neighbor (GNN) dataset (Ohmann & Gregory, 2002) to 2018 conditions.[1] This work was conducted by the Natural Resources Spatial Informatics Group (NRSIG) at University of Washington. The 2012 forest conditions characterized in the GNN dataset were projected forward to 2018 using the U.S. Forest Service Forest Vegetation Simulator (FVS) and updated to

[1] To align with the wildfire and decay modeling data sets, forested areas in the GNN dataset that were not also classified as a forest land type by the Fuel Characteristic Classification System (FCCS) data set were removed. In addition, remaining forested areas where there was an absence of meteorological data in the Gridded Surface Meteorological Dataset (GRIDMET) were also removed.

account for disturbances from known timber harvest, fire, and mortality events. Timber harvests were identified using Timber Harvest Plans (California Department of Forestry and Fire Protection, 2019b), categorized into silvicultural treatments and applied to the landscape using the silvicultural treatments described in the California Forest Practices Rules (California Department of Forestry and Fire Protection, Resource Management, Forest Practice Program, 2017). Disturbances from fire were added using data from the Monitoring Trends in Burn Severity Program (United State Geological Survey, 2017), the U.S. Forest Service (United States Department of Agriculture, Forest Service, 2017), and U.S. Geological Survey (United State Geological Survey, 2018). Forest Spatial datasets from the California Department of Forestry and Fire Protection Tree Mortality Mapper (California Department of Forestry and Fire Protection, 2018) were used to estimate tree mortality across the state between 2012 and 2017. The revised forest characteristics are provided in a spatially-explicit raster with data for species and structure composition on 30x30 meter grid cells.

Each silvicultural treatment from a set of 14, as described in Table 3, were applied to each forested 30x30 meter grid cell. Treatments were selected to cover a range of silvicultural activities including commercial timber harvest, thinning, forest health, fuels reduction, and salvaging snags. The treatments vary by tree size and fraction of basal area removed from the stand. The set of prescriptions were set using a basal area targeted after treatment in order to align with the California Forest Practice Rules that set requirements for residual standing basal area.

Table 3: Description of Forest Silvicultural Treatments

Treatment	Label	Description
Remove 100%	RM100	Clear-cut 100% of standing trees
Snags	Snags	Remove 100% standing dead wood
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%	TP20	Remove 20% of basal area proportionally across all tree sizes
Proportional Thin by 40%	TP40	Remove 40% of basal area proportionally across all tree sizes
Proportional Thin by 60%	TP60	Remove 60% of basal area proportionally across all tree sizes
Proportional Thin by 80%	TP80	Remove 80% of basal area proportionally across all tree sizes

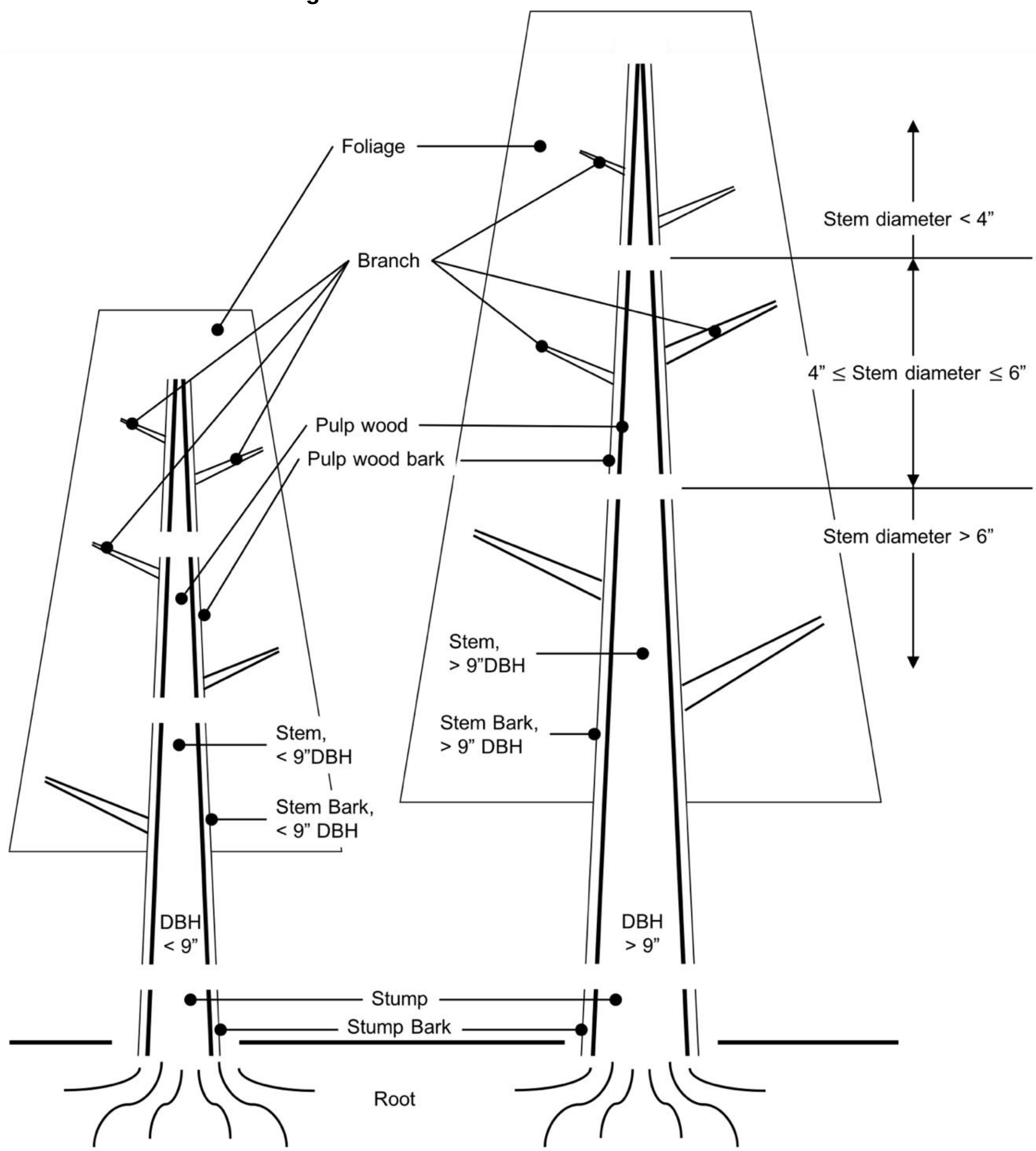
Each treatment is simulated on every forested location in California to calculate the amount of biomass cut and remaining after the silvicultural activity, as described in APPENDIX A. Post-treatment conditions are summarized by reporting the stand structure and mass by size class.

To facilitate the development of residue collection systems (see CHAPTER 8), all forest types in the state were also grouped into 177 representative stands by k-means clustering (MacQueen, 1967). For more information about the initial resource characterization and representative stands, see APPENDIX A.

4.1.1.2 Forest Biomass Size Classification Systems

The size classes from the biomass resource assessment are grouped into the categories illustrated in Figure 4, which are referred to henceforth as the resource size classes.

Figure 4: Forest Biomass Resource Size Classes



There are multiple models that are deployed for other elements of this framework, such as decay and fire modeling, that depend on the size class of the biomass material. The resource size classes are converted and subdivided into different size class bins used in decay and wildfire modeling. Table 4 is used to translate the size classes between the resource database and the different models employed in this framework.

Table 4: Forest Biomass Resource Size Classifications

Resource Size Class	Fuel Characteristic Classification System (FCCS)	Consume	C-BREC Decay Model
Stem, >9” DBH to 6” top & Bark, >9” DBH to 6” top	Ø > 20”	>10,000 hr	Coarse Woody Debris (CWD)
Stem, >9” DBH to 6” top & Bark, >9” DBH to 6” top	9” < Ø ≤ 20”	10,000 hr	Coarse Woody Debris (CWD)
Stem, ≤9” DBH to 6” top & Bark, ≤9” DBH to 6” top	3” < Ø ≤ 9”	1,000 hr	Coarse Woody Debris (CWD)
Pulp Wood, 4” ≤ Ø < 6” & Bark, 4” ≤ Ø < 6”	3” < Ø ≤ 9”	1,000 hr	Coarse Woody Debris (CWD)
Branches + tops (Ø < 4”) & Bark, Ø < 4”	1” < Ø ≤ 3”	100 hr	Fine Woody Debris (FWD)
Branches + tops (Ø < 4”) & Bark, Ø < 4”	0.25”< Ø ≤ 1”	10 hr	Fine Woody Debris (FWD)
Branches + tops (Ø < 4”) & Bark, Ø < 4”	Ø ≤ 0.25”	1 hr	Fine Woody Debris (FWD)
Foliage	Litter	Litter	Litter
--	--	Duff	Duff
Stump	N/A	N/A	N/A
Stump Bark	N/A	N/A	N/A
Root	N/A	N/A	N/A

4.1.1.3 Gross Forest Residue Base from Live Trees

Only a fraction of the biomass resource is considered part of the residue base. The size classes are considered to be residues based on the conditions listed in Table 5. Note this does not represent the technically recoverable resource.

Table 5: Gross Forest Residues from Live Trees by Size Class

Resource Size Class	C-BREC Decay Model	Fraction of Mass Assigned as Potential Residue
Stem, >9” DBH to 6” top	Coarse Woody Debris (CWD)	15.5% [a,b]
Stem Bark, >9” DBH to 6” top	Coarse Woody Debris (CWD)	15.5% [a,b]
Stem, <=9” DBH to 6” top	Coarse Woody Debris (CWD)	15.5% [a,b]
Stem Bark, <=9” DBH to 6” top	Coarse Woody Debris (CWD)	15.5% [a,b]
Pulp Wood (< 4” ∅ < 6”)	Coarse Woody Debris (CWD)	15.5% / 100% [a,c]
Pulp Wood Bark (< 4” ∅ < 6”)	Coarse Woody Debris (CWD)	15.5% / 100% [a,c]
Branches	Fine Woody Debris (FWD)	100%
Tops (∅ < 4”)	Fine Woody Debris (FWD)	100%
Foliage	Litter	100%
--	Duff	0%
Stump	--	0%
Stump Bark	--	0%
Root	--	0%

a: Average of 14% for ground and 17% for cable yarding systems, from (Kizha & Han, 2015).

b: These size classes are considered merchantable timber. This percentage is available due to stem breakage.

c: With a pulp market, this size class is considered merchantable timber and therefore 15.5% is available due to stem breakage. However, if there is no pulp market, than 100% is considered available.

4.1.1.4 Gross Forest Residue Base from Standing Dead Trees

The mass of standing dead material (a.k.a. snags) in the forest is quantified for all of the same size classes as live trees (Table 4) with the exception of foliage. All above-ground material is considered part of the residue base as described in Table 6 (i.e. none of the stemwood is considered merchantable). In the biomass resource database, the mass of snags is considered sound wood and is classified as decay class 1 as described by the Forest Inventory Analysis (Battles et al., 2014; United States Department of Agriculture, Forest Service, 2010). It is assumed that snags which have degraded to other decay classes are too difficult or dangerous to harvest and collect. Therefore, all snags are assumed to include all stemwood, branches, and bark that were present when alive, but no foliage is included. Harvest and collection equipment is selected based on harvesting sound snags.

Table 6: Potential Forest Residues from Snags by Size Class

Resource Size Class	C-BREC Decay Model	Fraction of Mass Assigned as Potential Residue
Stem, >9" DBH to 6" top	Coarse Woody Debris (CWD)	100%
Stem Bark, >9" DBH to 6" top	Coarse Woody Debris (CWD)	100%
Stem, <=9" DBH to 6" top	Coarse Woody Debris (CWD)	100%
Stem Bark, <=9" DBH to 6" top	Coarse Woody Debris (CWD)	100%
Pulp Wood (< 4" ø < 6")	Coarse Woody Debris (CWD)	100%
Pulp Wood Bark (< 4" ø < 6")	Coarse Woody Debris (CWD)	100%
Branches	Fine Woody Debris (FWD)	100%
Tops (ø < 4")	Fine Woody Debris (FWD)	100%
Foliage	Litter	0% (not present for snags)
--	Duff	0%
Stump	--	0%
Stump Bark	--	0%
Root	--	0%

4.1.1.5 Forest Residue Disposition

After each primary treatment, the residues are distributed across the landscape and categorized as fraction of gross residues that are piled or scattered. The disposition of gross residues (not technically recoverable) is specified by the user. The following four disposition options are provided for all silvicultural treatments:

Table 7: Residue Disposition Options

	Fraction Scattered	Fraction Piled
RD1	100%	0%
RD2	70%	30%
RD3	50%	50%
RD4	30%	70%

We do not allow 100% of gross residues to be piled as this is technically not possible. The maximum piled fraction of 70% is based on an estimate of maximum technically recoverable residues of 70% (U.S. Department of Energy, 2011).

4.1.2 Agriculture

Biomass residues from agricultural activities emerge following the primary crop harvest. We define these residues as any material remaining in-field following the harvest of an annual crop, or trimmings, dead material, and plant waste from perennial crops. As the primary cultivation activities occur regardless of residue fate, any emissions associated with the cultivation or harvest of the primary crop are the same in both reference and use cases, and are therefore not a focus of this study.

4.1.2.1 Gross Agricultural Residue Base

Agricultural residue production quantities were derived from research by the California Biomass Collaborative (Williams et al., 2015), which estimated both the gross annual resource production (the total crop residue generated by a given harvest) as well as the technically recoverable annual resource production (the crop residue that could potentially be collected). With California farmers growing dozens of different crop varieties, some simplification was necessary to focus the study scope on only significant residues sources. The agricultural residues evaluated for this project are limited to the seven crop types with the highest gross residue production (see Table 8) – accounting for roughly 80% of California agricultural residues in total.

Table 8: Gross Residues Amounts from Agricultural Crops Considered

Crop	2013 Gross Residue (BDT/yr)	% of All Crop Residues in CA
Almonds	794,400	11%
Corn	957,330	13%
Cotton	374,530	5%
Grape Vines	1,136,100	15%
Rice	1,782,400	24%
Walnuts	219,900	3%
Wheat	677,760	9%
Top Seven Crops	5,942,420	80%

Data from (Williams et al., 2015)

Many agricultural products generate additional residues post-harvest as these products are processed for consumption (for example, nut shells, rice hulls, and grape pomace). We do not consider such food processing residues in this framework, and they are not considered in the data in Table 8. Many food processing residues have market pathways, or are more likely to see market pathways in the future given state goals for diverting food waste from the landfill.

Because of the similarities between certain crop residues considered for this framework, agricultural residues are classified into two categories:

- Straw: corn, cotton, rice, and wheat residues
- Woody: almond, walnut, and grape vine residues

Each category generates residues from different agricultural activities, requires different processing approaches, and will have different decay dynamics.

4.1.2.2 Agricultural Residue Disposition

Straw Agricultural Residue

Straw residues consist of plant stalks and leaves, and for the purposes of this framework, bolls from cotton plants. Straw residues are generated at the time of the primary harvest. The primary harvest system (typically a combine harvester) will extract the full stalk, separate the primary product from the waste straw, and leave the waste straw on the ground. Currently, no combine harvester is able to collect straw residues during primary harvest activities, so the straw residues are assumed to be scattered throughout the field post-harvest.

Woody Agricultural Residue

Woody residues consist of branches, vines, and whole trees. They are not generated at the time of harvest, but throughout the year during orchard/vineyard maintenance or turnover. Branches and vines will be periodically pruned to maintain plant health and productivity, and entire vines or trees will be removed when advanced age hinders harvest yield. These residues are large enough that they must be chipped upon collection.

Residue Fate

While there are some differences in the fate pathways between straw and woody residues, there is significant overlap. Where residues are collected, the first characteristic that must be evaluated is collection efficiency. As with forestry residues, collection is not 100% efficient and some quantity of residue will remain in-field. We rely on reported technically recoverable data to represent collection efficiency. See Section 4.2.2 for details.

As in the forest residue case, residues that remain in the field will face one of two fates: combustion in a controlled burn, or in-field decay over time. For straw crops, we assume that the burning is done under scattered conditions as harvest leaves these residues in the field. In-field burning poses too great a risk to healthy perennial plants in an orchard or vineyard, so woody residues are assumed to be pile burned.

Where residues are not burned, they will be subject to decay. The dynamics of this decay are not uniform, however, as they are significantly affected by management decisions in the field. As fields, orchards, and vineyards are in continuous use, remaining residue must be managed in such a way that normal operations can continue. Straw residues can be incorporated into the soil (till), operations can be adjusted to allow the residue to remain on the ground (no-till), or soil incorporation can be carefully managed to preserve ground cover (reduced till). Rice straw residues may also undergo winter flooding to aid in decomposition and weed management. Woody residues that are not burned are assumed to be chipped and scattered.

4.1.2.3 Agricultural Residue Size Classification Systems

Straw crop residues are not disaggregated into size classes. Although there are some size differences between different straw crops (for example, corn stalks are generally a larger diameter than wheat stalks), we do not find variability in decay or combustion parameters by size of straw residues in published literature.

Woody crop residues are similarly contained within a single size class. While walnut and almond trees generate residues ranging from branches to whole trees, unlike the forestry scenarios, an orchard undergoes continuous use throughout the year. Any large residues would hinder operation, so residues must either be removed, or chipped and scattered over the orchard floor. Likewise, residues that are removed for utilization would require similar processing for ease of transport. Given these constraints, all woody residues are assumed to be chipped following primary harvest activities, and can be assumed to fall within the “Fines” size class of the C-BREC decay model.

Table 9: Agricultural Biomass Resource Size Classifications

Agriculture Category	C-BREC Decay Model
Straw	Literature values by crop
Wood	Fines

4.2 Technically Recoverable Resource Estimation Methodology

The amount of biomass residues that can be recovered following harvest activities is limited by technical constraints such as accessibility, slope, and biomass disposition. This section describes how the technically recoverable biomass is estimated from the gross biomass resource.

4.2.1 Forest Residues

Using the residue disposition described in Section 4.1.1.5, the fraction of residues that are technically recoverable are determined using the assumptions shown in Table 10.

Table 10: Technically Recoverable Forest Residue Assumptions

Description	Slope Constraint	Value [a]	Source
Maximum technically recoverable ($\%_{max}$)	< 40%	70%	(U.S. Department of Energy, 2011)
Maximum technically recoverable ($\%_{max}$)	>= 40%	60%	(U.S. Department of Energy, 2011)
Maximum technically recoverable ($\%_{max}$)	>= 80%	0%	(U.S. Department of Energy, 2011)
Fraction of piles that can be recovered ($\%_{pile\ recover}$)	None	95%	(Cai et al., 2018)
Processing efficiency of collected residues ($\%_{processing}$)	None	95%	(Cai et al., 2018)

a: All values are fractions of gross BDT.

Using the above assumptions, the technically recoverable residue is calculated as

$$M_{tech}^{piles} = \begin{cases} M_{gross}^{piles} \cdot \%_{pile\ recover} \cdot \%_{processing} & if\ \dfrac{M_{tech}^{piles} + M_{tech}^{scattered}}{M_{gross}^{piles} + M_{gross}^{scattered}} \leq \%_{max} \\ M_{gross}^{piles} \cdot \%_{max} & if\ \dfrac{M_{tech}^{piles} + M_{tech}^{scattered}}{M_{gross}^{piles} + M_{gross}^{scattered}} > \%_{max} \end{cases}$$

$$M_{tech}^{scattered} = \begin{cases} M_{gross}^{scattered} \cdot \%_{processing} & if\ \dfrac{M_{tech}^{piles} + M_{tech}^{scattered}}{M_{gross}^{piles} + M_{gross}^{scattered}} \leq \%_{max} \\ M_{gross}^{scattered} \cdot \%_{max} & if\ \dfrac{M_{tech}^{piles} + M_{tech}^{scattered}}{M_{gross}^{piles} + M_{gross}^{scattered}} > \%_{max} \end{cases}$$

The maximum technically recoverable constraint overrides any other possible option that conflicts with this. For example, if 70% of gross residues are piled and the total effective slope for the project is greater than 40%, the maximum recoverable of 60% overrides the calculated value of 70% * 95% * 95% = 63.2%.

4.2.2 Agriculture

The California Biomass Collaborative estimated the technically recoverable residue availability as a fraction of the gross resource availability. This fraction accounts for collection losses as well as residues deliberately left in-field to maintain soil fertility, and is determined on a crop-by-crop basis. For the woody residue crops (almond, walnut, and grape) 70% of the gross residue production is considered technically recoverable (Williams et al., 2015). For straw residue crops (corn, cotton, rice, and wheat), the technically recoverable residues were estimated to be 50% of the gross residue production (Williams et al., 2015). The technically recoverable residue totals are given in Table 11. While the technically recoverable portion can be collected and utilized, the remainder of the gross resource is still subject to in-field decay.

Table 11: Technically Recoverable Residue and Harvest Acreage for Agriculture Crops

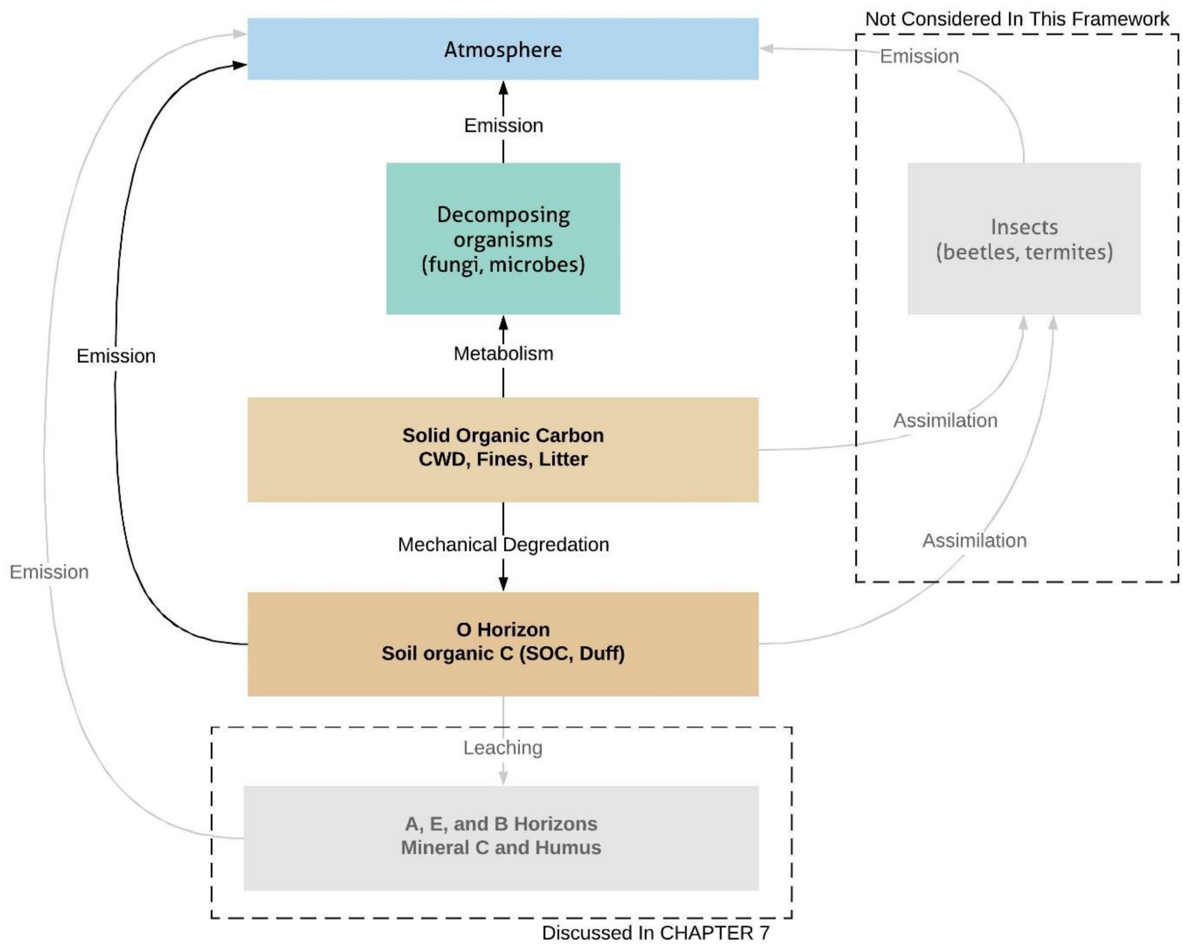
Crop	2013 Residue Totals (BDT/yr)	2013 Acres Harvested	2013 Residue Totals (BDT/acre-yr)	% of All Crop Residues	% of All Acres Harvested
Almonds	556,200	850,000	0.654	13%	9.1%
Corn	478,665	180,000	2.66	12%	1.9%
Cotton	187,265	278,000	0.674	5%	3.0%
Grapes	795,200	875,000	0.909	19%	9.4%
Rice	891,200	562,000	1.59	21%	6.0%
Walnuts	153,900	280,000	0.550	4%	3.0%
Wheat	338,880	394,000	0.860	8%	4.2%
Top Seven Crops	3,401,310	3,419,000	0.995	82%	37%

Data from (United States Department of Agriculture, 2018; Williams et al., 2015)

CHAPTER 5
Decay of In-Field Residues

The following sections detail the methods used to quantify emissions from decaying biomass. Decay is quantified for in-field forest residues, in-field agricultural residues, and processed material piled at the power plant. All of the methods described here address decay of surface biomass, including soil organic carbon (which includes the duff size class as described in CHAPTER 4). Potential emissions from insect assimilation are not included as discussed in Section 5.3.1.2. Additional potential emissions from soil below the O Horizon are not included for reasons described in CHAPTER 7. Figure 5 shows the carbon mass flows from surface biomass that are addressed.

Figure 5: Decay Emissions Mass Flow Boundary



The carbon contained in residues can follow a variety of pathways over the course of decomposition (Cornwell et al., 2009). This framework specifically considers the following, as shown in Figure 5, applied to all size classes:

- Microbial facilitated decomposition of carbon mass, which results in the transformation of solid organic C into gaseous emissions.
- Physical degradation (or fragmentation) of carbon mass due to mechanical breakdown (including from xylophagous insects) or weathering.

Emissions from decay are calculated as

$$E_{decay,g}(t) = E_{g,pd}(t) + E_{g,sd}(t),$$

where

$$E_{g,pd}(t) = \sum_{x,y=piled,i} Ef_g \cdot \left(M_{t-1_{x,y,i}} - M_{t_{x,y,i}}\right) = \text{emissions for decay of in-field piles}$$

$$E_{g,sd}(t) = \sum_{x,y=scatterd,i} Ef_g \cdot \left(M_{t-1_{x,y,i}} - M_{t_{x,y,i}}\right) = \text{emissions for decay of in-field scattered material}.$$

The term $M_{t-1_{x,y,i}} - M_{t_{x,y,i}}$ represents mass of decaying in-field residue released to the atmosphere at time t for each residue size class x, disposition y, and spatial location i, and Ef_g are emissions factors for in-field residues for each gas species g.

The following sections describe the methods for calculating the mass terms and emissions factors. Further details can be found in APPENDIX B and in (Blasdel, 2020) which also documents many details of the C-BREC decay model.

5.1 Mass Loss and Recruitment of In-Field Forest Residues

We directly model decay of solid residues to atmospheric emission. The dynamics of residue decay as modeled varies by size classes, location/climate characteristics, and physical state of the residue.

For forest residues, we apply a simple exponential decay function to calculate the mass lost over time. For the duff class, which both decays and accumulates mass over time, a first order linear approximation of the exponential function is used; consistent with Forest Vegetation Simulator Fire and Fuels Extension (FVS FFE) (Section 2.4.5 in (Rebain, 2015)). Mechanical degradation results in the accumulation of soil organic matter (duff) on the forest floor. Therefore, mass movement from CWD, FWD, and litter size classes into the duff size class is included. Also consistent with FVS FFE, we assume that 2% of the total carbon lost from all size classes in a given year will transfer into the duff size class (Table 2.4.6 in (Rebain, 2015). See APPENDIX B for details).

In addition, this framework recognizes that as forest litter decomposes it becomes increasingly hard to distinguish from duff at it enters the soil column. Therefore, once the litter size class has decayed to 50% of the original mass, the remaining mass is moved to the duff size class (see Section 5.1.3). This assumption follows field observations of forest litter interactions on annual time steps (Personal Communication, Jeffery Kane).

The decay equations for forest and agriculture residues are described in detail in APPENDIX B. Further detail on the methods used to derive the decay constants used in the decay functions are described in the following sections.

5.1.1 Development of In-Field Decay Constants and Climate Multipliers

The decay model for in-field woody residues is built on a simple negative exponential decay model (Olson, 1963). Decomposition mechanisms are characterized through a single decay constant $k_{x,y,i}$ for each residue size class x, disposition y, and spatial location i, which are adjusted with a climate modifier α_i:

$$M_{t_{x,y,i}} = M_{0_{x,y,i}} e^{-k_{x,y,i}t}$$

where M_o is the original mass, time t is calculated on annual time steps, and M_t is the mass remaining at time t. The decay constants are modified by a climate multiplier which acts as a scalar to account for the effects of temperature and moisture on decay rates. This is discussed in Section 5.1.6.

The decay constant $k_{x,y,i}$ and the climate multiplier α_i are spatially explicit and therefore contained in a spatial layer created for the C-BREC framework. As described in more detail in the following sections, decay constants vary based on the following characteristics:

- Species composition: decay constants vary by species, and species composition varies by location. We established the baseline decay constant for each 30m x 30m spatial grid cell (or FCID as is used in the GNN data set) by taking the average of the decay constants for the species present at that site weighted by their proportional abundance on a DBH basis.

$$k_{x,y,i} = \sum_{species\ s} \frac{\sum DBH_s}{\sum DBH} k_{x,y,i,s}$$

  where $\sum DBH_s$ is the sum DBH for a given species in an FCID numbered cell, $\sum DBH$ is the sum total DBH for all species in the same numbered cells, and $\sum_s \frac{\sum DBH_s}{\sum DBH} = 1$.

- Residue size class: material is divided into CWD – standing (CS), CWD – down (CD), fines (F), litter (L) and duff. Note that the decay constant for duff is not spatially explicit and is held constant at 0.002 (Rebain, 2015).
- Residue disposition: material is divided into piled (p) and scattered (s) portions

Therefore, each geographic location (subscript i) has an attribute table with the information shown in Table 12, where "x" indicates whether that value is associated with an FCID or a climate raster. Note that a single decay constant for duff of $k_D = 0.002$[2] (Rebain, 2015) is used

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[2] Note that the value is from the FVS FFE which does not have units of $[{}^{1}/_{yr}]$. FVS FFE assumes the first order series approximation of an exponential $(1 - k_D) \approx \left(\sum_{i=0}^{\infty} \frac{(-k_D)^i}{i!} = e^{-k_D} = \frac{M_{t+1}}{M_t} =\right.$

and is therefore not spatially explicit. It is show in Table 12 for completeness, but the same value is used for all locations.

Table 12: Decay Constant Spatial Layer Attribute Table

Location i	Piled			Scattered			k_D	α_i
	$k_{CD,p,i}$	$k_{F,p,i}$	$k_{L,p,i}$	$k_{CD,s,i}$	$k_{F,s,i}$	$k_{L,s,i}$		
FCID	x	x	x	x	x	x	N/A	
Climate Raster							N/A	x

5.1.2 Tree Species Decay Constants

A literature review was conducted to gather data from past studies on decomposition of coarse and fine woody debris. Information on species, size class, location, and other notes on the studies were recorded and a dataset of values was created (see APPENDIX B for a table of values by species).

The biomass resource data (see CHAPTER 4) reports residual trees post-harvest for every defined treatment. The pre-treatment tree list provides a list of all modeled trees for the study area. The sum DBH for each species in each FCID raster cell ($\sum DBH_s$) was calculated from the residual tree list. Dividing a species aggregate DBH by the sum DBH for each cell ($\sum DBH$) gives the proportional abundance of that species. This was done on a DBH basis rather than by total tree count because DBH is a better proxy for overall woody biomass.

The species listed in the NRSIG data were matched to applicable decay values from the compiled decay dataset based on taxonomic order. Species that did not have literature values were placed in an “other hardwood” category. All species in the NRSIG data were categorized into a species, genus, family, or other taxonomic category to correlate with decay literature. While the “other hardwood” category represents incomplete data, the major forestry species are the best represented in the literature. All of the species placed in “other hardwood” represent a small overall proportion of potential residues. The result is a set of decay values for every species of every FCID raster cell that has biomass resources.

5.1.3 Litter Decay Constants

Values for foliage and litter were extracted from literature (Section 5.1.2) and their mean values calculated based on angiosperm/gymnosperm distinctions. The proportional k values for foliage were calculated for each FCID number based on the relative proportions of angiosperm and gymnosperm species by DBH. Decomposition of leaf litter has been found to vary significantly between angiosperms and gymnosperms, with much less variation within taxonomic families (Pietsch et al., 2014). Using angiosperm and gymnosperm designation in litter values therefore provides sufficient resolution of this residue class.

$\frac{M_0 e^{-k_D(t+1)}}{M_0 e^{-k_D t}}\Big)$. However, the deviation between the exponential form and the series approximation form is negligible in this context, and k_D is used in both forms.

While the movement of material from foliage to duff is poorly defined, foliage is observed to have a much faster recruitment rate into duff than woody materials (Personal Communication, Jeffrey Kane). For this model, when the mass of foliage drops below 50% of its original mass, the remaining amount is moved to the duff category of materials.

5.1.4 Size Class Comparison

As part of the NRSIG species database, approximate sizes of the coarse woody debris were binned according to the fire class distinctions (Table 4). This was done to maintain consistency with fuel classifications used for fire modeling (CHAPTER 6).

We grouped values in the decay dataset by size class, genus, and species to calculate mean decay constant values. We classified the data into categories of fine woody debris (FWD) and coarse woody debris (CWD) to differentiate size classes (see APPENDIX B). This produced genus- or species-specific decay values based on size class of the material.

Decay values for all species of size class CWD and FWD were not available from the literature. Therefore, we linearly interpolated missing values using a linear regression based on CWD and FWD decay rates. Species that had literature values for CWD and FWD were plotted against each other and a linear model was fit using R statistical software (see Table 13 and APPENDIX B).

Table 13: Equations for Interpolating CWD and FWD Decay Rates

Regression Equation	To derive FWD values	To derive CWD values
$y = 0.0393 + 1.2535x$	$\mathrm{FWD_i} = 0.0393 + \mathrm{CWD} * 1.2535$	$\mathrm{CWD_i} = \frac{\mathrm{FWD} - 0.0393}{1.2535}$

5.1.5 Impact of Residue Disposition on Decay Rates

Residue is considered to either be piled or scattered. Scattered material is classified as ground-contact (GC), and piles are considered to have a mix of GC and above-ground (AG) material. Our baseline k values derived from literature, as described above, are for GC material (i.e. scattered), which decays more rapidly than AG material because it is exposed to soil organisms and conditions. The decay constant for piled material is modified using the following equation:

$$k_{x,y=pile,i} = k_{x,y=scattered,i}\left[\left(AG_c \cdot \frac{m_{AG}}{m_{pile}}\right) + \frac{m_{GC}}{m_{pile}}\right]$$

for each residue size class x and spatial location i, where $k_{x,y=scattered,i}$ is the baseline decay constant derived from literature, $AG_c = \frac{k_{AG}}{k_{GC}}$ is the ratio of AG to GC decay constants (the value of which is described below), $\frac{m_{AG}}{m_{pile}}$ is the fraction of mass in a pile that is above ground, and $\frac{m_{GC}}{m_{pile}}$ is the fraction of mass in a pile that is ground contact.

5.1.5.1 Determining the Above-Ground Coefficient

To develop a value for the above-ground coefficient (AG_c) a literature review was conducted focusing on studies that explicitly measured aboveground (AG) and ground contact (GC) material (Barber & Van Lear, 1984; Edmonds et al., 1986; Erickson et al., 1985; Garrett et al., 2010; Næsset, 1999; Swift, 1977). These studies were similar in all other variables that would affect the decay rates of the material since they measured the same species of similar size classes in the same climates, isolating the structural variable of height above the ground.

For each study, the mean observed decay rates were put into a ratio of AG/GC and then averaged together to find a single coefficient (Table 14). The resultant coefficient can be used in an exponential decay equation as a multiplier to the decay rates of debris to capture the decay rate effect piling slash. This coefficient, 0.721, only applies to the AG portion of piled material.

Table 14: Above-Ground to Ground-Contact Ratios for Piled Forest Residues

Reference	AG/GC
(Garrett et al., 2010)	0.691
(Mattson et al., 2011)	0.709
(Swift, 1977)	0.664
(Edmonds et al., 1986)	0.741
(Erickson et al., 1985)	0.721
(Barber & Van Lear, 1984)	0.775
(Næsset, 1999)	0.748
Mean = $\mathrm{AG_c}$	0.721

5.1.5.2 Establishing Amounts of Above Ground and Ground Contact Material

To apply the above ground coefficient (AG_c), the slash piles need to be differentiated into AG and GC portions. This number can be defined by estimating an average pile size and calculating proportions based on an assumed pile shape.

Using field measurement data of slash piles (C. Miller & Boston, 2017) and an assumed paraboloid shape (Wright et al., 2017), the average pile height is assumed to be 3.1 meters. This number is in line with previous research concerning typical maximum pile heights for forestry practices (Winterbourne, 2016).

Under the assumption that material within a given height above the forest floor is considered GC, a shorter paraboloid can be subtracted from a larger paraboloid to yield the relative volumes of material. For this model, material that is within one foot (0.305 meters) of the ground is considered GC with all other material treated as AG.

Using these assumptions we arrived at a value of $\frac{m_{AG}}{m_{pile}} = 89.2\%$ for material in the AG category and $\frac{m_{GC}}{m_{pile}} = 10.8\%$ in the GC category. This is in line with a previous study that used a rough estimate of 20% GC and 80% AG based on a visual inspection (Barber & Van Lear, 1984). These proportions are dependent on the chosen value of how close material can be to the ground to be considered GC (see APPENDIX B).

Since the above ground coefficient only effects the AG material, each pile has two classes of material. GC material is treated the same as scattered material for the decay portion of this model, while AG material will decay at a different rate. This approach would create piles with changing proportions of AG/GC material overtime. Modeling pile dynamics and adjusting the proportions of AG/GC material as they decay over time is beyond the scope of this study. As a simplification, a weighted average decay value is taken for piled materials based on the proportion of materials in each AG and GC class.

5.1.5.3 Assumptions

The design of the decay model makes several simplifying assumptions that should be noted. By using a single AG/GC ratio for all piled material, we are effectively assuming that all piles are the same size. It also implies that piles hold the same shape and GC ratio as they decay. In reality, the ratio of ground contact material would most likely increase overtime as the piles become more compacted. This work simply classifies material as piled as opposed to creating and modeling piles over time and as they change.

Taking a weighted average approach for the piled materials is a mathematical approximation as there is no method for summing exponentials. The weighted average approach differs from tracking the sum of AG and GC materials, but the percent difference in these approaches is never greater than 0.5% (see APPENDIX B).

We also do not characterize the effect of applying tarps to slash piles, which can have significant effects on the moisture content of the piled material (Afzal et al., 2010). Further, the simple act of piling materials may create a moisture insulating environment that may affect decomposition dynamics, such as the creation of methane hotspots.

5.1.6 Climate Multiplier

Climate modifiers are applied to the species-specific decay rates for all of California. The basic structure of the climate modifier models are a set of functions representing environmental variables that affect decomposition constants. This is expressed through the decay function as a factor that multiplies the k constant.

$$k_{x,y,i,s} = \alpha_i \cdot k_{s,norm}$$

where $k_{x,y,i,s}$ is the climate-modified decay rate and α_i is the climate modifier, which is a function of temperature($f(T)$) and available moisture ($f(M)$) (Sierra et al., 2015) as shown below.

$$\alpha_i = f(T) * f(M)$$

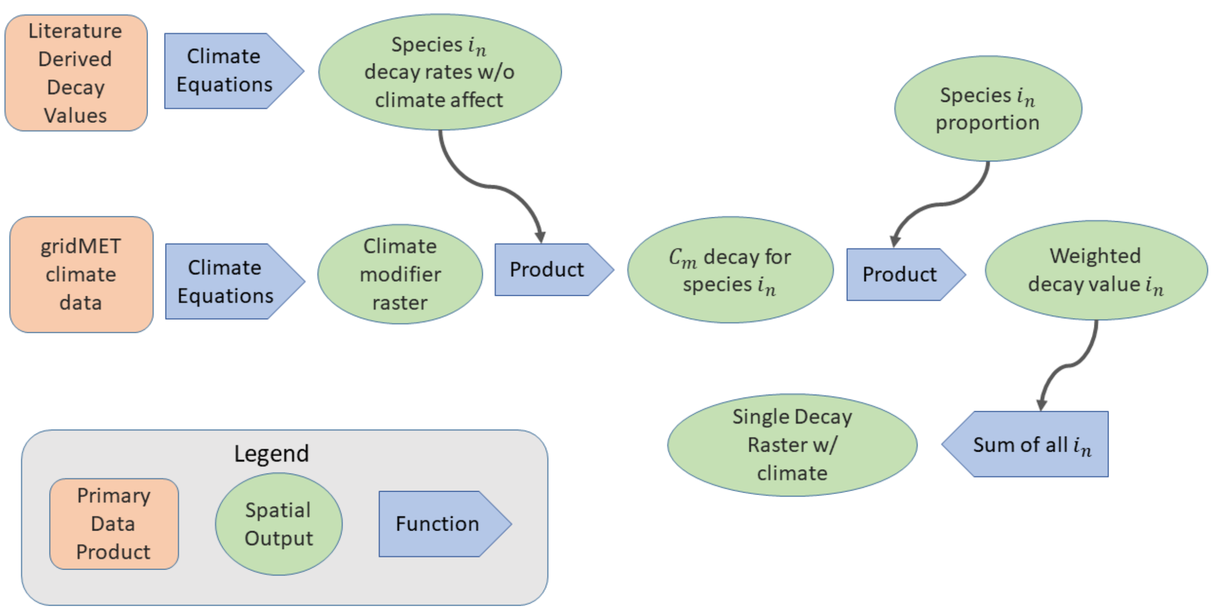
The climate modifier is included to reflect the spatial variability of climate that is known to alter the rates of biological decay (Lloyd & Taylor, 1994). A variation to the approach described in (Adair et al., 2008) was used for the temperature and moisture function. The climate equations create a raster of unitless values which are then applied to alter species-specific decay rates. (see APPENDIX B).

To account for the fact that the literature derived decay constants already reflect the climate associated with the study region they were obtained from, we normalize the decay constants to the climate equations used to derive α_i (see Section 5.1.6.1). For each species s, the reported climate values from the literature studies were used to determine the $\alpha_{literature}$ value associated with the decay constant $k_{s,literature}$ from each study. They were then normalized using the following equation:

$$\frac{k_{s,literature}}{\alpha_{literature}} = k_{s,norm}$$

For each raster cell i, the climate modifier is calculated with ten-year averages for the State of California and applied to the decay constant for each species. The full climate modifier approach is summarized in Figure 6.

Figure 6: Climate Modifier Methodology



All climate variables used in the α_i equations are taken from the gridMET data products (Abatzoglou, 2013). The data used represents a 10-year average from 2007 through 2017 for mean annual temperature, potential evapotranspiration, and annual precipitation. The mean temperature metric was derived by averaging daily minimum and daily maximum temperatures since no daily mean is given in the gridMET data.

5.1.6.1 Climate Equations

The effect of temperature on decay was quantified with the equation:

$$f(T) = \exp\left[308.56 * \left(\frac{1}{56.02} - \frac{1}{(273 + T) - 227.13}\right)\right]$$

where T is the mean annual temperature in Celsius (Adair et al., 2008). This equation is a variation on the Lloyd and Taylor model to describe temperature effects on decomposition (Lloyd & Taylor, 1994). This equation produces a values of 1 with an input of roughly 16.2˚C, meaning $f(T)$ has no impact on decomposition rate at this temperature.

The effect of moisture on decomposition is quantified with the equation:

$$f(M) = (PPT, PET) = \frac{1}{1.0 + 30 * \exp\left(-8.5 * \frac{PPT}{PET}\right)}$$

where PPT is the annual precipitation and PET is the potential evapotranspiration. The $f(M)$ function is based on the CENTURY model to show the effect of water stress on decomposition (Follett et al., 2001). PET is a derived variable calculated from gridMET using the Penman-Monteith method (Abatzoglou, 2013). Climate equations were calculated on monthly means for each climate metric (Adair et al., 2008). In this application decay is calculated on annual time steps so annual means are used instead.

5.1.6.2 Assumptions

This process makes the assumption that $f(T)$ and $f(M)$ affect decay independent of one another. This is an important assumption as temperature and moisture work in conjunction to affect decomposition, but would require much more complex equations to capture. The climate equations used were tested against the LIDET dataset, which is a spatially extensive long-term study of decay which isolated climate effects by using a consistent size and tree species in the study (Long-Term Intersite Decomposition Experiment Team (LIDET), 1995).

5.1.7 Mass Loss and Recruitment of Standing Dead Tree Residue

Although there is loss of standing dead tree mass through decay, and recruitment of mass from snags into the fuel bed, these pathways are outside the boundary of this LCA. Only the decay of residues generated from the primary silvicultural treatment are considered. The spatially explicit decay rates associated with CWD and FWD are applied to snag residues, as described in Section 5.1.

5.2 Mass Loss of Agriculture Residues

Decay equations for agricultural residues in the C-BREC framework do not vary spatially. While there is significant climate variability across the state, there is less variability across the geographic spread of a given crop. Furthermore, non-woody residues have relatively quick decay rates such that climate modifiers would likely be less significant.

Several key assumptions can be made about farming operations that simplify the agricultural decay characterization. Each of the seven crops investigated has an annual harvest, ensuring essentially constant field/orchard/vineyard utilization – so there is immediate need to either remove or incorporate residues into existing operations. Therefore, it is assumed that residues that will be mobilized are done so immediately and are not left to decay prior to mobilization.

Both straw and woody residues follow a similar decay framework. A decay function is applied to calculate the mass lost over time, with some fraction of the original mass assumed to be recalcitrant and the remainder assumed to be volatile. The volatile mass will eventually decay completely to the atmosphere, and the recalcitrant mass will be incorporated into the soil organic carbon content upon decay of the volatile component.

The decay equations for forest and agriculture residues are described in detail in APPENDIX B. Further detail on the methods used to derive the decay constants used in the decay functions are given in the following section.

5.2.1 Size Classes

As discussed in Section 4.1.2.3, agricultural residues are broken into two categories - woody and straw. A given crop type falls into one or the other class, so there is no breakdown of a given residue base into varying size classes. Woody residues are all assumed to be chipped.

5.2.2 Impact of Residue Disposition on Decay Rates

Straw residues can either be left on the ground surface (no-till), incorporated into the soil (till) or partially incorporated to leave some degree of soil cover (reduced-till). Each disposition has a unique, crop-specific decay rate. Rice residue may additionally undergo winter flooding, which also results in a different decay rate.

As previously mentioned, woody agricultural debris is assumed to be chipped upon collection. Wood chips are assumed to be scattered on the surface. We do not consider tilled wood chips as this is uncommon. We also do not considered piled wood chips, since piled residues are not retained in the field; residues are piled with the intent to mobilize to a specific end-use. Decay from the storage of wood chips prior to use is addressed in Section 8.2.

We use the three different decay equations shown in Table 15 depending on the crop:

Table 15: Agricultural Residue Decay Equations

	Equation	Description of Variables	Source
1	$M_t = M_0 e^{-kt}$	M_t = mass remaining at time t M_0 = initial mass k = decay rate	(Yadvinder-Singh et al., 2010)
2	$M_t = M_0 \left(\begin{matrix} C_{0,1} e^{-k_{C_1} t} + \\ C_{0,2} e^{-k_{C_2} t} \end{matrix} \right)$	M_t = mass remaining at time t M_0 = initial mass C_t = fraction of carbon remaining at time t $C_{0,1}$ = initial carbon fraction of labile carbon $C_{0,2}$ = initial carbon fraction of recalcitrant carbon k_{C_1} = decay rate for component 1 k_{C_2} = decay rate for component 2 t = time (years)	(Beyaert & Paul Voroney, 2011)
3	$M_t = M_0(1 - k\tau)^2 \quad 0 \le t \le 730$ $M_t = 0 \quad t > 730$	M_t = mass remaining at time t M_0 = initial mass τ = A time-weighted variable accounting for moisture index and carbon/nitrogen ratios k = Decay constant t = time in days	(Ghidey & Alberts, 1993)

Equation 2 in Table 15. follows a basic exponential decay function, but applies separate decay constants for different components – the readily-decaying labile component, and the more persistent recalcitrant component.

Unlike equations 1 and 2, equation 3 is a polynomial function and represents a fundamentally different type of decay behavior. Furthermore, it is assumed that all mass loss occurs in the first year. The equation for the τ variable is as follows:

$$\tau = \frac{T_a a_m}{C_n}$$

Where T_a is the average daily temperature for the time step being considered, a_m is the antecedent moisture index (and is derived from precipitation data), and C_n is the carbon to nitrogen (C/N) ratio. In this work, τ is spatially explicit. Regional temperature and precipitation data from 2017 are loaded in from gridMET when evaluating a location for a specific project. Note that the value of T_a must be greater or equal to 0 ˚C to prevent against mass gain (i.e. $\frac{M_t}{M_{t-1}} > 1$). C/N ratios were informed by values provided in (Ghidey & Alberts, 1993).

Crop-specific decay coefficients and carbon fractions (when applicable) given in Table 16, although some values must still be determined. Decay rates are derived from the same literature source as the equations. Note that values are also organized by residue disposition method (e.g. till, no till, and reduced till). Refer to Section 4.1.1.5 for more information on these methods.

Table 16: Straw Residue Decay Constants

Crop	k_{Till}		$k_{No\ Till}$		$k_{Reduced\ Till}$	
	Constant	Equation	Constant	Equation	Constant	Equation
Corn	Year 1: k=1.03 [a] Year 2: k=0.328 [a]	3	Year 1: k=0.730 [a] Year 2: k=0.459 [a]	3	$C_{0,1}$=79.64% [b] k_{C_1}=1.2933 [b] $C_{0,2}$=20.36% [b] k_{C_2}= 0.077467 [b]	2
Cotton	Year 1: k=0.823 [a] Year 2: k=0.243 [a]	3	Year 1: k=0.504 [a] Year 2: k=0.318 [a]	3	N/A	N/A
Rice	Dry: 0.000052 [c] Flooded: N/A	1	Dry: 0.001 [c] Flooded: N/A	1	N/A	N/A
Wheat	Year 1: k=1.99 [a] Year 2: k=0.745 [a]	3	Year 1: k=0.811 [a] Year 2: k=0.658 [a]	3	$C_{0,1}$=75.90% [b] k_{C_1}=1.22 [b] $C_{0,2}$=24.10% [b] k_{C_2}= 0.09 [b]	2

a: (Ghidey & Alberts, 1993)

b: (Beyaert & Paul Voroney, 2011). Initial carbon fractions are average of those reported in all equations. Decay constants are average of those reported in reduced tillage equations.

c: (Yadvinder-Singh et al., 2010). Values converted to units of per year using Table 1 of the source.

5.2.3 Decay Equations for Agricultural Woody Residues

Woody agricultural residues are assumed to decay following a simple exponential (Equation 1 of Table 15), with decay rates based on the individual crop type as shown in Table 17. Literature values for grape vines were found, but none were found for almond and walnut. As a substitute, decay rates for walnut and almond were taken from similar taxonomic species – Hickory for walnut (sharing the family Juglandaceae), and other members of the Prunus genus for almond. Because the resultant decay rates for walnut and almond applied to coarse woody debris, the corresponding decay rate for chipped material assumed a "fine woody debris" size class and used the method outlined in Table 13 to convert the decay rates. Sources for decay rates of Hickory and Prunus genus species are shown in APPENDIX B.

Table 17: Woody Agricultural Residue Decay Constants

Crop	Scattered – Chipped – No Till	Piled	Source
Almond	0.034	Not considered	Calculated
Grape Vines	0.00179	Not considered	(Nikolaidou et al., 2010)
Walnut	0.1005	Not considered	Calculated

5.3 Decay Emissions Factors

We assume CO_2 and CH_4 as the only gas species emitted during the decay process. We assume that all carbon emitted into the atmosphere originates from fungal- and microbial-based respiration (Figure 5). The emissions factor for CH_4 (Ef_{CH_4}) is a static value discussed in the following sections. The emissions factor for CO_2 (Ef_{CO_2}) is calculated from the remaining carbon using the following equations:

$$Ef_{CO_2}(t) = \frac{44.01}{12.01}\left[C_{frac} - \left(E_{CH_4} \cdot \frac{12.01}{16.04}\right)\right]$$

where, C_{frac} is the carbon fraction of the species comprising the residue base, 12.01 is the molecular weight of carbon, 16.04 is the molecular weight of CH_4, and 44.01 is the molecular weight of CO_2 . The emissions factor is independent of size class and disposition, but does vary spatially based on biomass species composition.

The following sections detail the values for C_{frac} and Ef_{CH_4} used for forest and agricultural residues.

5.3.1 Forest Residues

The CH_4 emissions factor used for forest residues are shown in Table 18. The value used is that from (He et al., 2014), as elaborated on in Section 5.3.1.2. The same emissions factor is used for a variety of residue conditions. Use of different CH_4 emissions factors for various decay settings is left to future work.

Table 18: Decay Emissions Factors for Forest Residues

	Disposition	Carbon Fraction [C%]	CH4 Emissions Factor [kg $C_{as\ CH4}$ / kg residue lost]
In-field live forest residues	Piled	Spatial Raster	$C_{CH_4} = 1x10^{-5}$
In-field live forest residues	Scattered (not chipped)	Spatial Raster	$C_{CH_4} = 1x10^{-5}$
In-field snags	Piled	48.7	$C_{CH_4} = 1x10^{-5}$
In-field snags	Scattered (not chipped)	48.7	$C_{CH_4} = 1x10^{-5}$
Power plant storage piles	Piled	Mass weighted between live forest residues and snags	$C_{CH_4} = 1x10^{-5}$

5.3.1.1 Carbon Fraction of Forest Residues

For all fresh material, we use spatially explicit carbon content values that are mass weighted by spatially variable tree species composition.

For standing dead material we assume all snags are represented by decay class 1. The carbon fraction of bone dry residue mass from the harvest of standing dead trees uses 48.7 [C%] for decay class 1 downed material from Table 2 of (Mark E. Harmon et al., 2013). This value is for whole-stem, including bark. We apply this value to both CWD and FWD. We use the value for downed material since we only decay snag residue generated post silvicultural treatment (decay of standing dead wood, and movement of standing dead wood onto the forest floor, is outside the LCA boundary because it should be attributed to the silvicultural treatment activity).

We assume that carbon fraction is static through time. The fraction of fixed carbon in coarse woody debris (CWD), on a bone dry basis, has been shown to vary only slightly throughout the decomposition process (Battles et al., 2014; Laiho & Prescott, 1999). A similar assumption was also made in (Wihersaari, 2005). Therefore, we assume the same static value across the full 100-year decay period.

5.3.1.2 Decay Mechanisms & Emission Species for Forest Residues

For in-field woody material, literature indicates that decomposition is a primarily a biologically-driven process, and more precisely the result of microbial enzymatic digestion (Janusz et al., 2017). Aerobic fungi have been identified as the primary group of microbes responsible for such digestion, however, the presence of aerobic bacteria has also been noted for *in situ* forest wood decay (Swift, 1977).

Most of the gaseous emissions that are released from the surfaces of decomposing wood are understood to be the products of this biodigestion, and methane (CH_4), carbon dioxide (CO_2), and nitrous oxide (N_2O) have been identified as the primary species. While they are not considered here, non-methanous volatile organic compounds (NMVOCs) are also released as biomass degrades (Alakoski et al., 2016). However, these emissions are not products of biologically driven decomposition but are rather an intrinsic property of wood. Monoterpenes (a class of NMVOCs) are released by all living plants (Laothawornkitkul et al., 2009) and account for the aroma of wood. Biological, chemical, and physical degradation over the course of decay serve to further stimulate this release, and other classes of NMVOCs that were formerly bound in the biomass are released to the atmosphere as well. While there is extensive research on the emissions of NMVOCs from decomposing wood (He et al., 2014; Insam & Seewald, 2010), we leave this to future work. As NMVOCs are not accounted for, carbon losses are assumed to be the result of CH_4 and CO_2 generation, exclusively.

Nitrous oxide (N_2O) from the decay of CWD is also not accounted for here, as research has shown that nitrogen (N) content fluctuates significantly over the course of decay. This is thought to be the result of fungal translocation of limiting nutrients from the surrounding environment to the substrate (Laiho & Prescott, 1999). The release of N_2O during decomposition can thus not be assumed to be solely resultant from solid to gaseous conversion of N originally present in the wood.

For a long time, research indicated that the aerobic conditions characterizing in-field decay only allowed for colonization by CO_2-producing fungi and bacteria. This was in alignment with the assumption that CH_4 generation can only occur in anoxic settings, as these conditions have been known to foster colonization by comparably less efficient methanogenic (or CH_4-producing) archaea (Conrad et al., 2009). However, there is an increasing body of evidence indicating that aerobic CH_4 production does in fact occur. CO_2 and CH_4 generation has been observed during aerobic incubation of decomposing wood (Lenhart et al., 2012; Mukhin et al., 2006). Researchers have even been able to deduce that the observed CH_4 generation was directly due to the activity of saprophytic fungi, a novel finding as it was previously thought that fungi only provided a substrate on which methanogenic archaea could colonize (Lenhart et al., 2012). It has also been shown that CH_4 generation from dead dry foliage in an aerobic lab environment (Vigano, 2010). Additionally, it is plausible that in the later stages of decay in piled wood (when pile structure has deteriorated and the substrate resembles a homogenous pile of material rather than distinct pieces of wood) conditions in particular regions of the substrate are deprived of oxygen and thus could be sites of anaerobic CH_4 generation.

While these recent findings indicate that release of CH_4 during decay of forest residues is likely, there is a lack of published CH_4 emission measurements for in situ decay of CWD and FWD. Emission of CH_4 has, however, been quantified for compost, landfill, and in stored comminuted biomass settings and a summary of literature values is shown in Table 19. Only one of these studies provided sufficient data for calculation of an emission factor in units of kg CH_4 / kg residue lost (dry basis). This value is 1x10-5 kg CH_4 / kg residue lost (dry basis), and is applied to annual estimates of forest residue mass loss to decomposition (which is calculated using equations described in Section 5.1.1). Remaining C losses are assumed to go to CO_2 emission.

Table 19: Literature Values of CH_4 Emission from Decay

	kg CH4 / kg residue	kg C_{CH4} / kg $C_{residue\ lost}$	Notes	Source
Landfill / Mulch	$6.5x10^{-2}$		Anaerobic landfill	(M. K. Mann & Spath, 2002)
	$6.7x10^{-2}$		Anaerobic mulch	(M. Mann & Spath, 2001) Figure 1
	$1.1x10^{-1}$		Anaerobic landfill without landfill gas collection	(M. Mann & Spath, 2001) Figure 1
	$5x10^{-2}$		Cites (Placer County Air Pollution Control District & TSS Consultants, 2013) which cites (M. K. Mann & Spath, 2002)	(California Air Resources Board, 2020)
Processed Piles	$1.75x10^{-4}$		Sawdust piles, hardwood. Surface measurements. Time period is 1 month.	(Pier & Kelly, 1997) [a]
	$1.36x10^{-1}$		Sawdust piles, hardwood. Interior measurements. Mass on dry basis.	(Pier & Kelly, 1997)
	$< 9x10^{-8}$	$4x10^{-6}$ to $2x10^{-5}$	Chipped Douglas fir, controlled non-aerated conditions. Mass on a dry basis.	(He et al., 2014)
	$2x10^{-7}$		Stored pine pellets, controlled, 20ºC Mass on a wet basis, 4% moisture	(Kuang et al., 2008)
	$2.6x10^{-8}$		Coppice willow chip piles, exposed Mass corrected to dry basis assuming STP	(Whittaker et al., 2016)
	$2.0x10^{-5}$ $4.0x10^{-5}$		Stored pine pellets, controlled, 23ºC, low moisture. Stored pine pellets, controlled, 23ºC, high moisture. Mass on a wet basis, 5.1% moisture	(Kuang et al., 2008)
	$9.0x10^{-7}$		White pellets. Mass on a wet basis, 7.3% - 7.7%	(Yazdanpanah et al., 2014)
Un-processed: No literature sources found				

a: Calculated from mean CH_4 surface measurements in Table 3 of source. Converts to per-kg residue using 6.42cm3/g density and surface-to-volume ratio of 1/3 and 1/9 as recommended in paper. Average of results using range of CH_4 rates and both surface-to-volume ratios. Assumes a time period of one month. Small value is explained as CH_4 largely oxidized by the time it reaches the surface.

It should be noted that the CH_4 and dry matter loss (DML) measurements published in (He et al., 2014) were from lab-based wood chip incubation experiments, and that there are some caveats to applying the stated emission factor to decaying forest residues left in the field. First, lab-based incubation studies involve isolating material in a controlled chamber environment so that it is not exposed to the elements or additional input of decay-driving microorganisms. As these conditions are not reflective of *in situ* forest decomposition, it is likely that CH_4 generation is underestimated in laboratory-based research in general, and primarily because the degree of microbial colonization is limited. Second, it should be noted that the material incubated in (He et al., 2014) was chipped, and thus had a greater surface area to volume ratio when compared to the same mass of CWD or FWD. Surface area undoubtedly influences the rate of decomposition (and thus the rate of emission) as the pace of microbial colonization is a function of available surface area. It is thus likely that wood chips off-gas emissions at a quicker rate when compared to CWD.

One pathway of CO_2 and CH_4 production that is not specifically characterized in this framework is fragmentation due to invertebrate digestion. It has been noted that insects (e.g. beetles and termites) re-appropriate the organic compounds contained in forest residues (Cornwell et al., 2009) and excrete residual material as dust. Such forms of organic C can be prone to more rapid rates of decay depending on the physical location of that material, due to again, an increase in surface area to volume ratio (M. E. Harmon et al., 1986). Furthermore, fragmentation due to termite inhabitation of downed wood is of particular interest, as these organisms have an anaerobic digestive process that is facilitated by symbiotic protozoan or bacteria (Zimmerman et al., 1982). Invertebrate-driven fragmentation can thus not only result in more rapid release of CO_2, but also represents a potential pathway for CH_4 formation and emission. However, termite distribution is spatially variable, and most studies that have investigated the extent to which these organisms contribute to fragmentation and the magnitude of subsequent CH_4 production were located in tropical regions (Cornwell et al., 2009). Due to these reasons, this pathway is not specifically characterized, as shown in Figure 5. Note, however, that the fraction of carbon movement into soil organic C from invertebrate fragmentation is indirectly captured through the mass decay rates we derive from literature (see Sections 5.1 and 5.2). This is included in the mechanical degradation pathway in Figure 5.

5.3.2 Agricultural Residues

Description and sources for these values are described below.

5.3.2.1 Carbon Fraction of Agricultural Residues

Crop-specific initial carbon contents (or the carbon content of fresh material) found in (Jenkins et al., 1996) were employed for this work. Like forest residues, we assume that carbon fraction is static through time. See Section 5.3.1.1 for more information on this assumption .

Table 20: CH_4 Decay Emission Factors for Agricultural Residues

Crop	Disposition	Crop Type	CH_4 Emission Factor [kg / kg residue]
Almond Prunings	Piled	Woody	1.0e-5 [a]
Corn Stover	Scattered	Straw	6.5e-3 [b]
Cotton	Scattered	Straw	6.5e-3 [b]
Grape Prunings	Piled	Woody	1.0e-5 [a]
Rice Straw	Scattered	Straw	Flooded = 1.97e-2 [b] Non-flooded = 6.5e-3 [b]
Walnut Prunings	Piled	Woody	1.0e-5 [a]
Wheat Straw	Scattered	Straw	6.5e-3 [b]

[a] Source = (He et al., 2014)

[b] Source = (Fitzgerald et al., 2000)

5.3.2.2 Decay Emissions Species for Agricultural Residues

Similar to forest residues, CO_2 and CH_4 are assumed to be the only gaseous species released during decay of residues. CH_4 emissions from the decay of woody agricultural residues are assumed to parallel those of forest residues exactly, and so the CH_4 emission factor described in Section 5.3.1.2 is applied and remaining carbon mass losses are assumed to go towards generation of CO_2.

Currently, there is limited research on the species and magnitude of emissions produced during decay of straw residues and no reliable CH_4 emission factors for straw crops were found, save rice. Decay of rice straw residues is of particular interest from a carbon cycling perspective as management practices for this crop often create conditions that allow for CH_4 generation: during fallow months, fields are frequently flooded and in-field residues are left to decay in an oxygen-deprived setting, allowing for colonization by CH_4 producing microorganisms. Flooded and non-flooded decay rates for rice straw were derived from (Fitzgerald et al., 2000); this work measured carbon emissions from a variety of rice straw residue management schemes (incorporation, rolling, and burning) in both flooded and non-flooded conditions, and over two seasons. By dividing the cumulative CH_4 emissions by the straw mass inputs, CH_4 emissions factors were calculated for each season and treatment. To arrive at the values listed in Table 20, the annual emissions factor for incorporated and rolled residues for each season were averaged into a single value for flooded and non-flooded management schemes.

In the absence of CH_4 decay emission factors for all other straw residues, the non-flooded rice CH_4 value is assumed. The method for calculating the total mass of CO_2 emitted by decaying straw residues follows that described in 5.3.1.2 and in the first paragraph of this section.

CHAPTER 6
Combustion of In-Field Residues

In-field combustion of forest residues entails both wildfire and prescribed burn events, while in-field combustion of agricultural products only entails permitted burn events. The following sections describe the methods used to estimate the emissions associated with wildfire and prescribed burns for forest residues, and prescribed burns for agricultural residues.

Emissions from prescribed burn depend on whether residues are from forest or agriculture sources. C-BREC does not model both sources at the same time, so we do not sum the two emissions sources. Emissions from the prescribed burn of forest residues are calculated as follows:

$$E_{RX,g}^{forest}\delta(0) = \delta(0)\sum_{x,y,i,j}\sum_{cp}\left(M_0 - M_{recovered}^{piles} - M_{recovered}^{scattered}\right)_{x,y,i,j}F_{x,y,i.j,cp}Ef_{g,cp}^{forest},$$

where M_0 is the gross mass of residues, $M_{recovered}^{piles}$ is the mass of piled residues that are recovered (a fraction of M_{tech}^{piles} that is specified), $M_{recovered}^{scattered}$ is the mass of scattered residues that are recovered (a fraction of $M_{tech}^{scattered}$ that is specified), $F_{x,y,i.j,cp}$ is the fraction of residues that are consumed for a particular combustion phase cp, $Ef_{g,cp}^{forest}$ is the emissions factor for each gas species g and combustion phase cp, x is size class, y is disposition, i is spatial location, and j is decay class of sound or rotten. Emissions from the prescribed burn of agricultural residues are calculated as follows:

$$E_{RX,g}^{agriculture}\delta(0) = \delta(0)\cdot\left(M_0 - M_{recovered}^{piles} - M_{recovered}^{scattered}\right)\cdot Ef_g^{agriculture},$$

where $Ef_g^{agriculture}$ is a static emissions factor for each crop.

The emissions from combustion of forest residues in a wildfire are calculated with the same structure as prescribed burns, with two key differences:

- Fire weather conditions are different which results in different combustion phase fractions (described in detail in the following sections), and
- The mass exposed to wildfire varies over time due to decay and the quantity of residue that was "previously exposed" to probabilistic wildfire (described in detail in the following sections).

The wildfire emissions function results in the following:

$$E_{wf,g}(t)\cdot\Pi_f = \sum_{x,y,i,j}\Pi_{f_i}\sum_{cp}\left(M_0 - M_{recovered}^{piles} - M_{recovered}^{scattered} - \sum_{1}^{t-1}M_{exposed}\right)_{x,y,i,j}e^{-k_{x,y,i}t}F_{x,y,i.j,cp}Ef_{g,cp}^{forest},$$

The scaled rectangle function Π_{f_i} represents the spatially explicit probability of wildfire return interval at 25, 50, 75, and 100 years from present, and is defined as

$$\Pi_{f\,i} = \begin{cases} P_{f_1} \text{ for } 1 \leq t \leq 25 \\ P_{f_2} \text{ for } 26 \leq t \leq 50 \\ P_{f_3} \text{ for } 51 \leq t \leq 75 \\ P_{f_4} \text{ for } 76 \leq t \leq 100 \end{cases}.$$

The probability values are spatially explicit, and discussed further in Section 6.1.2. The value $\sum_1^{t-1} M_{exposed}$ represents the total quantity of residue mass that was previously exposed to wildfire from year 1 through year t-1. For a given size class *x*, disposition *y*, location *i*, and decay class *j*, this is defined for a given year as

$$M_{exposed_{x,y,i,j}}(t) = \left(MR_{x,i}\right)_{y,j}(t) \cdot \Pi_{f,i}(t),$$

where $MR_{x,i}$ is defined in APPENDIX B. Essentially the mass exposed is the sum total of all past years of remaining mass after decay multiplied by the probability of wildfire. The purpose of this is to ensure that mass is only exposed once to a wildfire event, regardless of whether the return interval allows for multiple wildfires within a 100-year period.

For forest residues, prescribed burn and wildfire are applied to residues in the following temporal order in association with other activities that influence the fate of the residues:

- Year 1: Collection -> Prescribed Burn -> Decay -> Wildfire
- All Other Years: Decay -> Wildfire

Wildfire emissions are modeled (using the methods described below) at 25-year increments for years 1, 25, 50, 75, and 100. For each of these years, the forest fuel bed is restored to year-1 conditions and fire weather is assumed the same as year 1. However, the quantity of residues is reduced by year-1 silvicultural and prescribed burn activities, annual decay, and annual probabilistic exposure to wildfire. To determine the emissions from wildfire for those years between those five that are modeled, the ratio of mass emissions / mass exposed by wildfire is linearly interpolated. This is then applied to remaining mass post decay for each interpolated year. Additional details are provided in APPENDIX C.

6.1 Wildfire and Prescribed Burn Modeling Methodology for Forest Residues

California has experienced an increase in the frequency and size of large wildfires over the past few decades (Anthony LeRoy Westerling, 2016), with some regions experiencing increases in fire severity (J. D. 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 (Abatzoglou & Williams, 2016; Anthony LeRoy Westerling, 2016) throughout much of the American west. Combined with over a century of fire suppression, these conditions have prompted the need for effective treatments that can reduce carbon emissions and reduce 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 (Agee & Skinner, 2005; Fulé et al., 2012). Additionally, wildfire modeling scenarios have shown that fuel treatments can effectively increase the carbon stability of forests (M. Hurteau & North, 2009; Krofcheck et al., 2017; Mitchell et al., 2009; North et al., 2009). While treatments can typically result in short-term reductions in carbon stock (Campbell et al., 2012; Krofcheck et al., 2018), subsequent work has demonstrated that increases in carbon stability from fuel treatments are persistent when considered under projected climate and wildfire scenarios (M. D. Hurteau, 2017), or if treatments are implemented at a large enough scale (Liang et al., 2017) when compared to untreated areas.

Many forests contain unmerchantable small diameter trees that often preclude treatment due to financial considerations. Areas that are financially conducive to thinning and harvesting treatments can generate substantial residues that can exacerbate wildfire. These conditions have prompted interest in utilizing this waste woody biomass for energy production (Evans & Finkral, 2009) to offset fossil fuel use and reduce emissions of greenhouse gases and health-impacting pollutants from wildfire (Reinhardt et al., 2008). However, much of the existing research has not explicitly considered the effectiveness of biomass residue utilization to reduce emissions compared to other more common forest residue treatments (e.g., pile burning, broadcast burning) or the retention of material left on-site to decay. Previous work that has considered biomass utilization has mostly included it as part of a suite of treatments that are applied to a particular area of interest (Chiono et al., 2015; Ganz et al., 2007). While this approach is informative for a given region and provides input into the effectiveness of these forest residue treatments across a broader scale, these studies do not provide direct comparisons among alternative residue treatment scenarios.

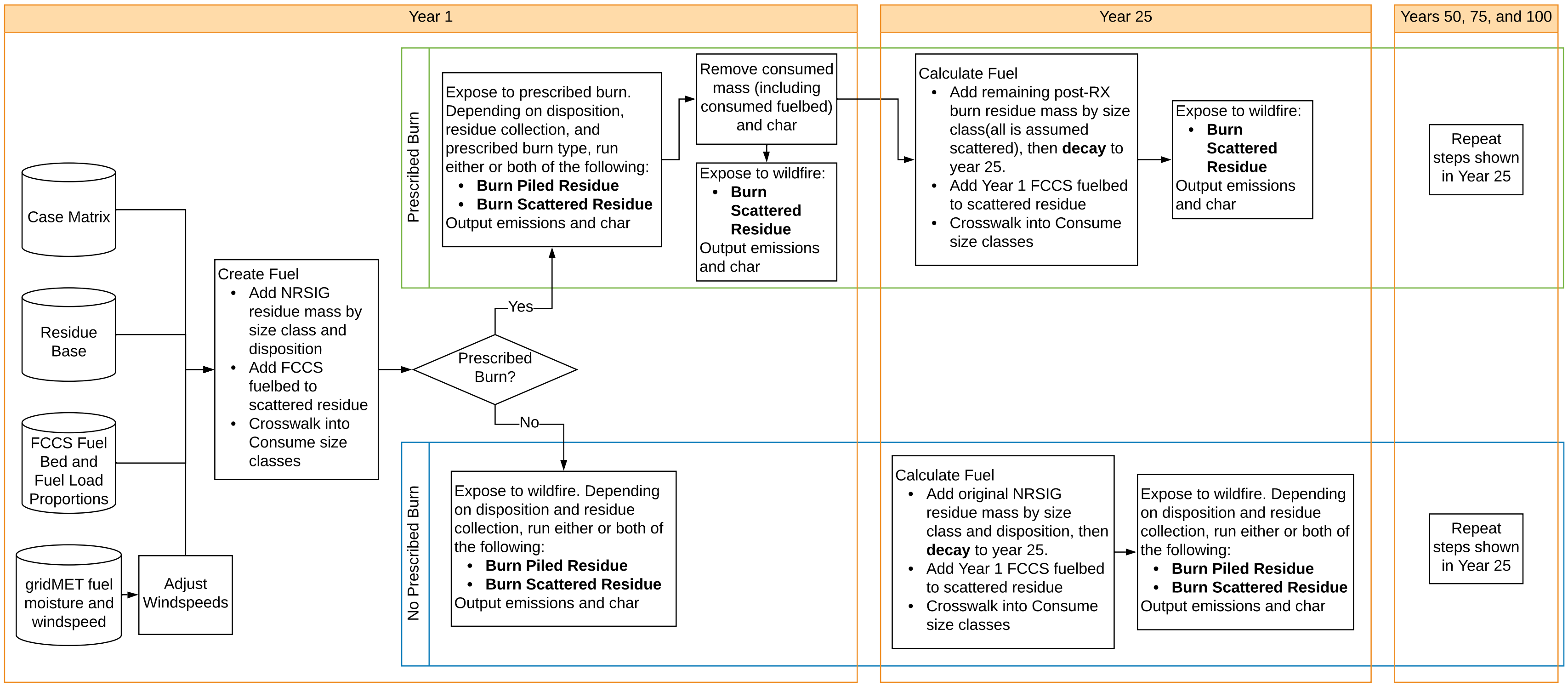
The general workflow for the fire emissions and effects modeling is illustrated in Figure 7. We used spatially-explicit raster data as inputs to well-established models in order to estimate the effects of biomass utilization on wildfire emissions across the state of California.

Prescribed burn options for the reference and use cases of forest residues include the following:

- Broadcast burn: all remaining in-field residues are scattered
- Pile burn: all remaining piles are burned

Spatially explicit data is used to derive per-tonne emissions, and modeled using the same methodology used for wildfire as described in Section 6.1.1.

Figure 7: Flow Diagram for Fire Modeling of Forest Residues



Burn Piled Residue

- 90% exposed mass is consumed. Assumed combustion phase fractions are:
  - flaming: 70%
  - smoldering: 15%
  - residual: 15%
- 1% of exposed mass is char
- 9% of exposed mass is unburnt, assigned to 1,000 hour size class, and treated as scattered.

Burn Scattered Residue

- Run woody fuels activity equations from Consume 4.2 to determine mass consumed by combustion phase and size class
  - 1-hr and 10-hr size classes are always completely consumed
  - Foliage and duff are burned using forest floor reduction equations
- Calculate char
  - Linear equation used to calculate char based on remaining mass
  - There is never char from duff, foliage, 1-hr, or 10-hr size classes.

Decay

- See Chapter 5 in the framework for details on the decay process

6.1.1 Modeling Emissions from In-Field Combustion

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 7). 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.

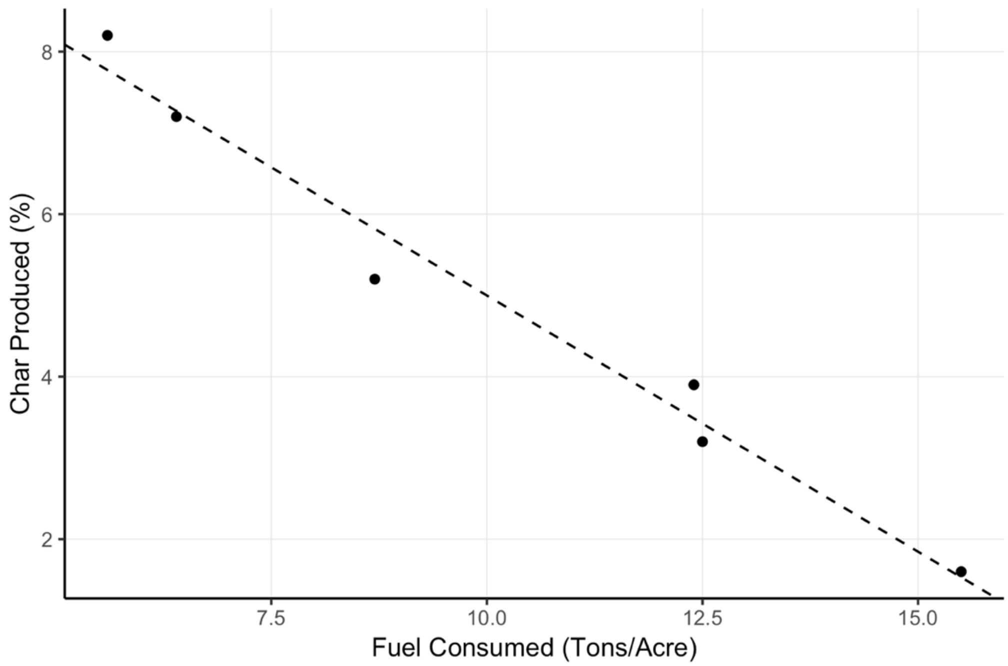
The activity fuels equations were developed for fuels "resulting from or altered by forestry practices such as timber harvesting or thinning" (p.141, (Prichard et al., 2006)), and are thus directly applicable to the silvicultural scenarios considered here. The activity fuels equations calculate consumption 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).

We also estimated charcoal production during combustion using data from (Pingree et al., 2012) (see Figure 8). For scattered material 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

$$charcoal = \sum_{i=1} BC_i \times ((11.30534 - 0.63064 \times BC_i) \div 100)$$

where BC_i is biomass consumed for size class *i*, and *charcoal* is the total amount of charcoal produced during combustion. For piled material, we assumed a static 1.0% of exposed pre-combustion material is converted to char.

Figure 8. Charcoal Production from the Combustion of Scattered Forest Residues



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).

Conceptual depictions of the consumption algorithms adapted from (Prichard et al., 2006) are given in Figure 9 through Figure 11. Smaller (1 & 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.

Figure 9: Flow Diagram for 1-, 10-, and 100-hour Fuel Algorithms

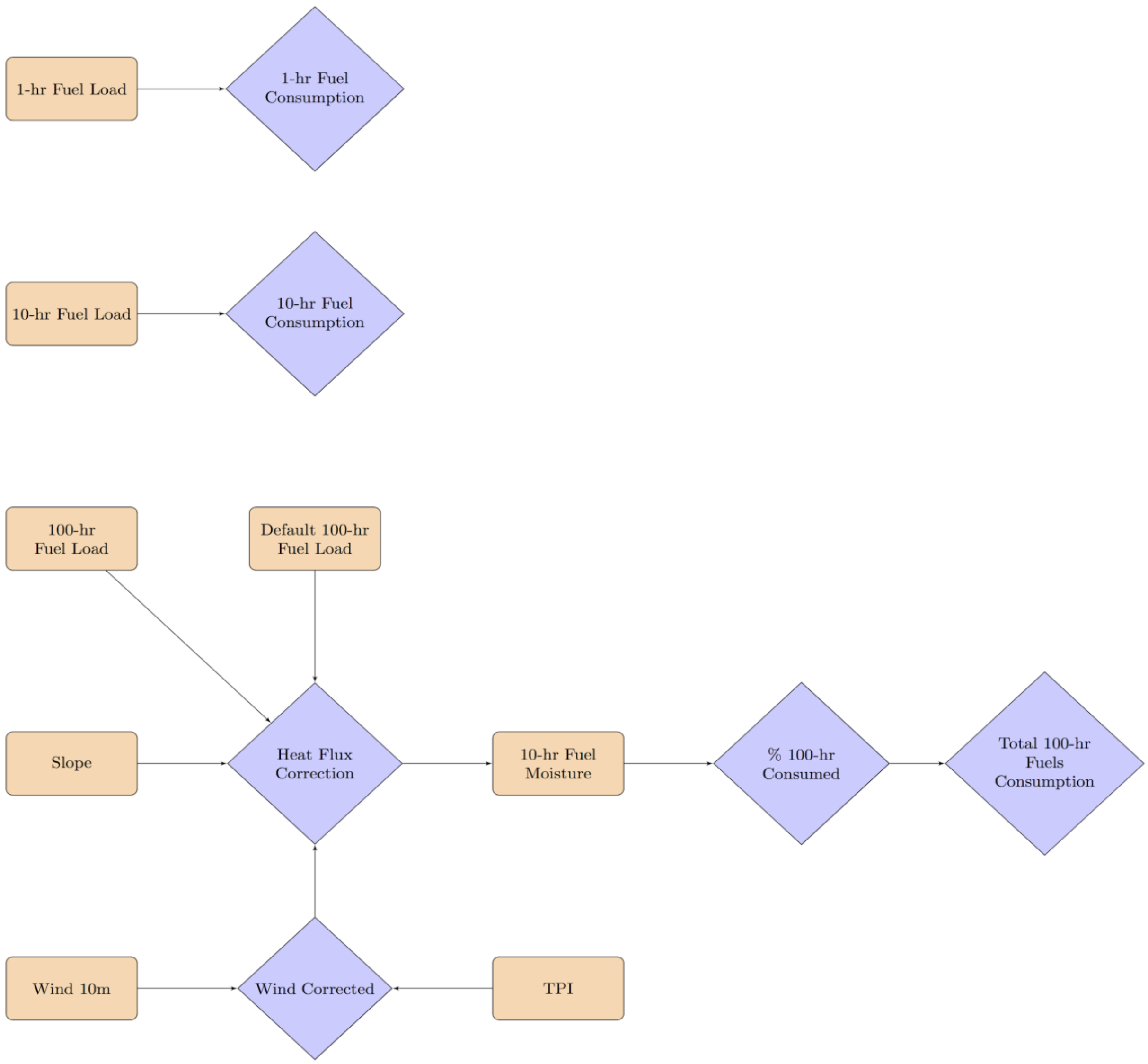


Figure 10: Flow Diagram Fuel Algorithm for 1,000-hour and Larger Fuels

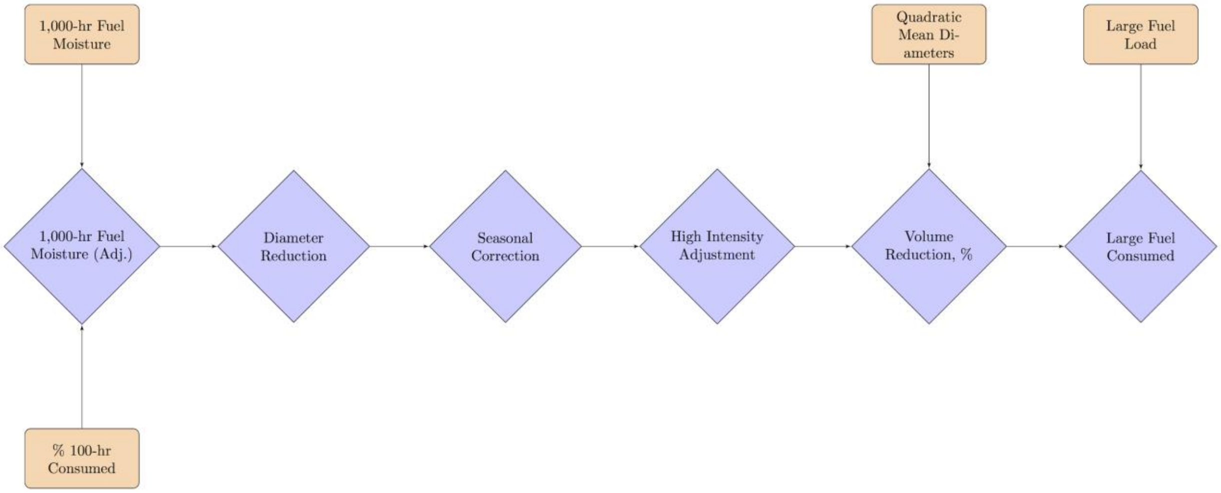
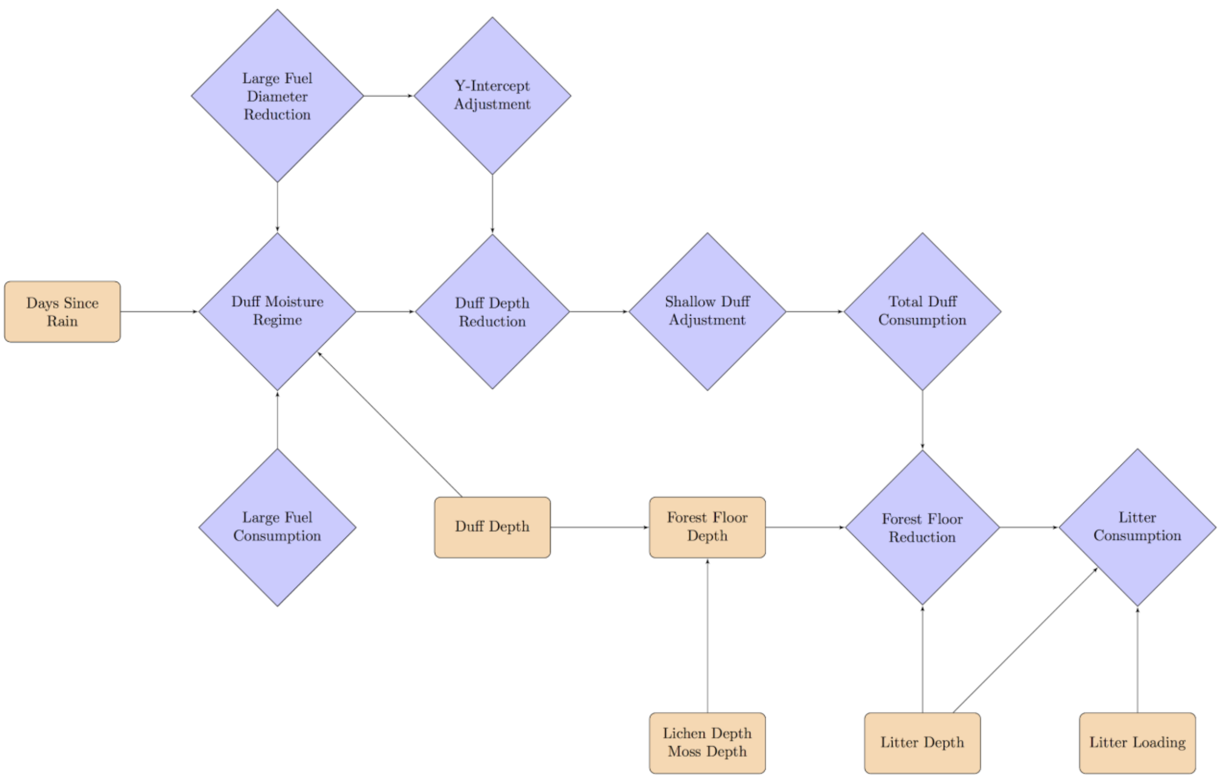


Figure 11: Flow Diagram for Litter Fuel Algorithm



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 disposition-specific (Table 21) emissions factors for 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., 2010), which can be found at the AirFire Github[3].

Table 21: Emissions Factors for Combustion of Scattered Forest Residues in R_X Fire and Wildfire

Emission Type	Scattered (kg/MT)	Piled (kg/MT)
PM_{10} flaming	8.4	see Table 22
$PM_{2.5}$ flaming	7.34	see Table 22
CO flaming	52.35	26.33
CH_4 flaming	2.1	1.64
NO_X flaming	0.00121	0.00121
SO_X flaming	0.00049	0.00049
NMHC flaming	3.25	1.78
PM_{10} smoldering & Residual	13.95	see Table 22
$PM_{2.5}$ smoldering & Residual	12.8	see Table 22
CO smoldering & Residual	146.15	65.19
CH_4 smoldering & Residual	7.8	5.52
NMHC smoldering & Residual	7.55	3.39
Black Carbon (BC)	Wildfire: $0.2 \cdot \left(PM_{2.5}^{flaming} + PM_{2.5}^{smoldering\ \&\ Residual}\right)$ R_X Burn: $0.202594 \cdot \left(PM_{2.5}^{flaming} + PM_{2.5}^{smoldering\ \&\ Residual}\right)$	
Ash (% dry weight)	See Table 35	
Carbon (% dry weight)		

All data from (Prichard et al., 2006) and (Larkin et al., 2010), except black carbon (BC) fractions from (California Air Resources Board, 2016b) (wildfire value is the recommended value, R_X Burn uses ID 463).

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 Core Team, 2018). While translating the equations, we made some limited modifications to better fit the algorithm to our use case, including the charcoal production model described above. The original Consume activity equations included 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 size classes (≥3 inches) is lower in more intense fires because fine fuels are more rapidly consumed and burn durations are shorter (Prichard et al., 2006). In order to eliminate the need to specify either fire size or ignition time, we modified the algorithm 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 follow suit. 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.

We estimated combustion emissions from piled fuels by multiplying the total mass consumed by the specific pile emissions factor (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

[3] See the fepsef.py script at https://github.com/pnwairfire/eflookup

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). We calculated pile emissions for both "clean" and "very dirty" scenarios.

Table 22: Pile Cleanliness Categories and Associated Particulate Emissions Factors

Pile Cleanliness	Soil Contaminants, % of Pile Mass	$PM_{2.5}$ (kg/MT)	PM_{10} (kg/MT)
Clean	0%	6.75	7.75
Dirty	>0-10%	8.5	10
Really Dirty	>10%	11.8	14

Data from (Prichard et al., 2006)

The activity fuels equations require inputs for fuel loading, fire weather, and topography. Data sources for each input are summarized in Table 23.

Table 23: Inputs to the Consume Model

Variable	Data Source	Citation
Fuel moisture	GRIDMET	(Abatzoglou & Brown, 2012; Cohen & Deeming, 1985)
Mid-flame windspeed	GRIDMET	(Abatzoglou & Brown, 2012; Andrews, 2012)
Fuel loading	GNN/FVS/FCCS	(Dixon, 2002; Ohmann & Gregory, 2002; Riccardi et al., 2007)
Slope	NED	(Gesch et al., 2018)
Days since rain	Broadcast Burn: 10 Pile Burn: 50 Wildfire: 50	See Section 6.1.1.3

6.1.1.1 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 (Riccardi et al., 2007; Sandberg et al., 2001). 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. Time lag 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 & Gregory, 2002)) as inputs to Forest Vegetation Simulator (Dixon, 2002) to estimate 2018 conditions. See CHAPTER 4 for additional details.

Our biomass resource base projections binned 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. Table 4 in CHAPTER 4 depicts the method we used to reclassify the residue. All foliage was classified as litter, and litter depth was estimated using fuelbed-specific depth-to-loading ratios. See Table 2 for a detained breakdown of residues by size class. 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 harvest type and logging system used (see Section 4.1.1.5 for specific proportions). 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.

6.1.1.2 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 Figure 25 in APPENDIX C for details).

6.1.1.3 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, 2013; Abatzoglou & Brown, 2012). 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 (Anthony LeRoy Westerling, 2016). We assumed that the number of days since rain under wildfire conditions was 50 for input into the consume model. For prescribed broadcast 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 10 days since rain prior to a prescribed broadcast fire. We assumed 50 days since rain for prescribed pile burns.

6.1.1.4 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 & Deeming, 1985).

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

6.1.1.5 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 C.

6.1.1.6 Drip Torch

In addition to the emissions from prescribed burns, the fuel used in drip torches to start the prescribed burns are quantified. The total fuel used was calculated from values for piled and open forest landscape prescriptions, representing the pile and scattered scenarios. These values come from personal communication with Jeremey Bailey of the Nature Conservancy and represent gallons of fuel per acre treated (J. Bailey, personal communication). This represents the total additional fossil fuels used when performing prescribed burns in the field.

The fuel mix is assumed to be a 3:1 ratio of diesel to gasoline. Emissions factors for the diesel and gasoline come from the EPA and are represented as Distillate Fuel Oil No.2 and Motor Gasoline respectively (United States Environmental Protection Agency, 2021). Emissions are calculated for CO_2, CH_4, and N_2O based on the total area treated and total gallons of fuel used. For each greenhouse gas g emissions are calculated as:

$$diesel\ emissions_g = acres \cdot \frac{gallons\ of\ fuel}{acre\ treated} \cdot \frac{0.75\ gallons\ diesel}{gallon\ fuel} \cdot \frac{emissions\ factor_g}{diesel\ gallon}$$

$$gasoline\ emissions_g = acres \cdot \frac{gallons\ of\ fuel}{acre\ treated} \cdot \frac{0.25\ gallons\ gasoline}{gallon\ fuel} \cdot \frac{emissions\ factor_g}{gasoline\ gallon}.$$

Emissions of N_2O are explicitly reported while other emissions from prescribed burn are inferred from a NO_X emissions factor.

Emissions factors and gallons of fuel used per acre are shown in Table 24.

Table 24: Drip Torch Fuel Consumption and Emissions Factors.

		Pile Burn	Broadcast Burn	Source
Gallons of fuel per acre		0.064	0.15	Personal Communication
Diesel / Gasoline Ratio		3:1		
CO2 (kg/gallon)	Gas	8.780		(United States Environmental Protection Agency, 2021)
	Diesel	10.21		
CH4 (g/gallon)	Gas	0.38		
	Diesel	0.41		
N2O (g/gallon)	Gas	0.08		
	Diesel	0.08		

6.1.2 Fire Probability

To assign emissions from wildfire to the reference case in a given location, we need to apply the probability of fire occurring at that site in a given year. The wildfire modeling described above generated output rasters of wildfire emissions based on the input fuel, fire weather, and topographical inputs. We then estimated the fire probability to allocate these emissions across time on a probabilistic basis. For example, if there is a 100-year mean fire return interval on a given site, 1% of the emissions from wildfire at that site would be allocated to a particular year. Climate change is leading to an increased risk of wildfire in California. To account for this, we alter the probabilistic annual allocation of emissions from later wildfires based on projected wildfire return intervals at 25, 50, 75, and 100 years from present.

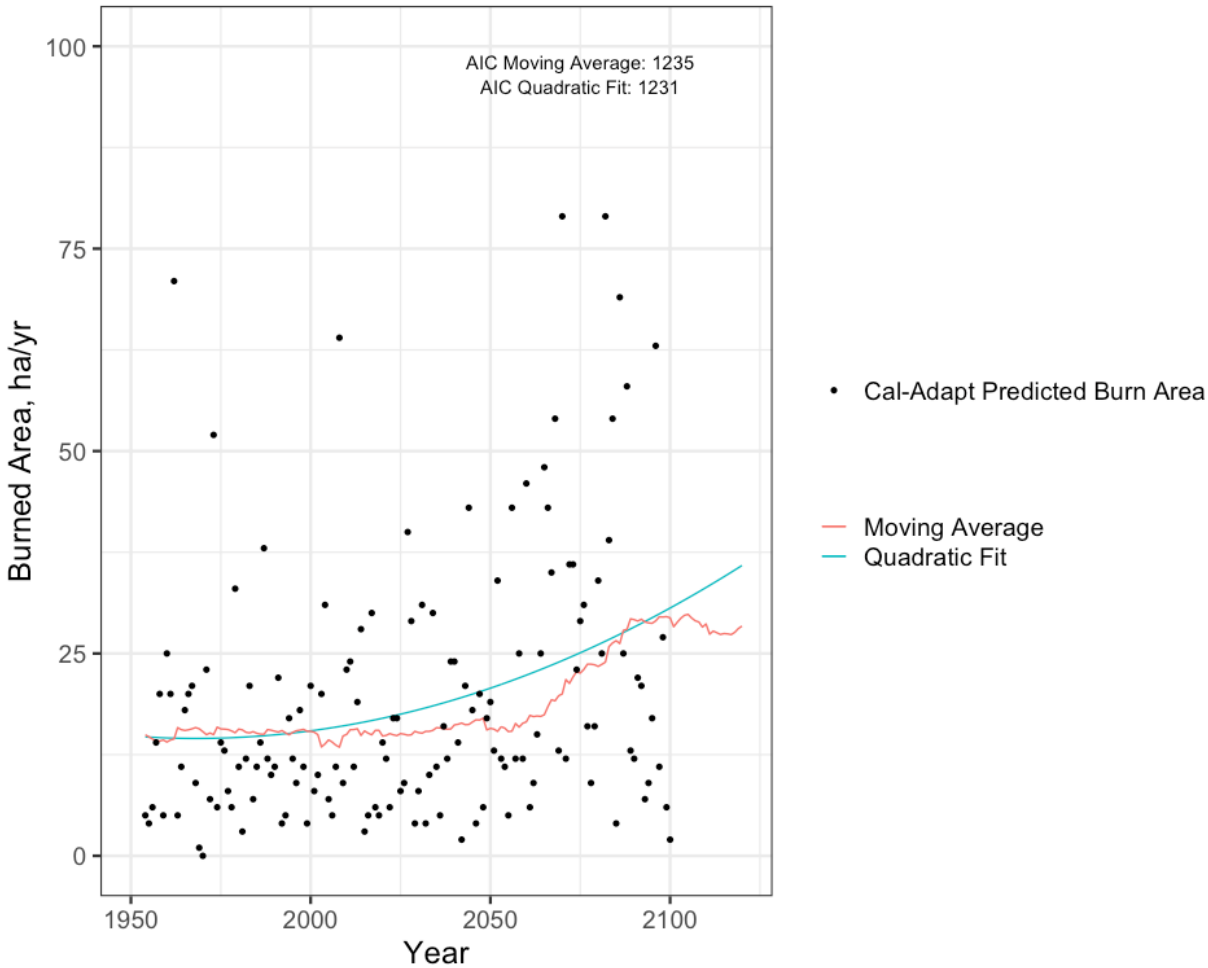
As wildfire on any given site is a probabilistic phenomenon, we needed to evaluate the effect of fires across the 100-year time horizon of our study. To this end, we modeled wildfires five times at a given site - 0, 25, 50, 75, and 100 years. The net effect of residue presence on wildfire emissions changes over time as decay removes some of the fuels and changes others from sound to rotten, which increases their smoldering time. For the purposes of this analysis, we are assuming that additional input and output rates of non-residue generated fuels are equivalent for all size classes, so the baseline FCCS fuel loading values remain static over time, while study residues decay according to the methods outlined in the decay section (see chapter 5). When the biomass in the larger fuel size classes (1,000-hour and higher) is > 64% of its original weight, we consider it sound fuel, otherwise we consider it rotten (Rebain, 2015).

Present and future wildfire probability in California is determined using data published on Cal-Adapt (Anthony Leroy Westerling, 2018). Data available from Cal-Adapt predicts the number of hectares burned each year in every 6 km by 6 km grid cell in California. 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. Future wildfire probability data were used for climate model HadGEM2-ES (Warm/Drier), emissions scenario with representative concentration pathway (RCP) 4.5, and business as usual population growth. The projections are fit to a moving average (red line) and a quadratic trend line (blue line) and evaluated to determine the line of best fit (Figure 12). The two projections are compared with the Akaike information criterion (AIC) and the projection with the lower AIC value is selected as the best fit for each grid cell.

The best fit trend line predicts the area burned in each grid cell. To determine the wildfire probability, the area burned per year is divided by the total area per grid cell, which is 6 km by 6 km or 3,600 ha. This is then up-sampled to the same 30m spatial resolution as the forest resource base (see CHAPTER 4).

Data from Cal Adapt was used instead of CALFIRE's Fire Resource and Assessment Program (FRAP) because Cal-Adapt has future projections for a longer interval out to 2100 rather than FRAP's static estimate to 2050. For a comparison of these two data sources see APPENDIX C.

Figure 12: Example Derivation of Wildfire Probability Value



Area burned due to wildfire for an example 6 km by 6 km cell in California (using climate model HadGEM2-ES, emission scenario RCP 4.5, and business as usual population growth). The modeled data from Cal-Adapt are shown next to two projected trend lines. For this grid cell, the quadratic line was a better fit (AIC = 1,231) compared to the moving average (AIC = 1,235). Data from Cal-Adapt (Anthony Leroy Westerling, 2018).

6.2 Prescribed Burn Emissions of Agricultural Residues

Currently, prescribed burning is limited by the approval of local air quality control boards, and state legislation has placed additional restrictions to strongly discourage rice residue burning in particular (Summers Consulting LLC, 2012). While these restrictions minimize the number of burn events, burning is currently still allowed in those cases where pest or fungal management is needed. Therefore, field burning is provided as a reference case.

We use literature reported emissions factors for specific crops. These are shown in Table 25. We lean heavily on (Jenkins et al., 1996) with modifications via guidance provided by CARB (Shimp, 2000).

All prescribed burn emissions are assumed to occur in the same year as the primary treatment. All straw residues are assumed to be scattered, and all woody residues are assumed to be piled (not chipped).

Table 25: Open Field Combustion Emission Factors for Agricultural Residues

Crop	Open Field Combustion Products [% residue dry weight]										Carbon Content [% dry weight]	
	CO	NOx	N2O	NMHC	CH4	SOx	SO2	PM10	PM2.5	Ash	Feedstock	Char
Almond Prunings (piled)	4.702 [1]	0.515 [1]	0.030 [1]	0.134 [1]	0.095 [1]	0.009 [1]	0.011 [1]	0.541 [1]	0.511 [1]	1.31 [1]	49.14 [1]	7.48 [1]
Corn Stover (scattered)	3.879 [1]	1.27e-1 [3]	5.40e-3 [3]	0.144 [1]	0.175 [1]	0.024 [1]	0.020 [1]	0.621 [1]	0.598 [1]	6.12 [1]	44.78 [1]	8.86 [1]
Cotton	73.1 [2]	2.55e-1 [3]	1.08e-2 [3]	2.00e-4 [4]	3.30 [2]	3.30e-3 [4]	1.57 [2]	8.87 [2]	6.19 [2]	5.31 [7-9**]	45.79 [7-9**]	8.86 [1**]
Grape Prunings	4.903 [1*]	0.500 [1*]	0.030 [1*]	0.1 [1*]	0.131 [1*]	0.018 [1*]	0.019 [1*]	0.490 [1*]	0.461 [1*]	3.29 [5-6**]	46.13 [5-6**]	8.86 [1**]
Rice Straw (scattered)	3.240 [1]	1.49e-1 [3]	6.30e-3 [3]	0.056 [1]	0.074 [1]	0.076 [1]	0.060 [1]	0.359 [1]	0.336 [1]	18.87 [1]	37.79 [1]	10.48 [1]
Walnut Prunings (piled)	5.104 [1]	0.029 [3]	0.484 [3]	0.066 [1]	0.167 [1]	0.026 [1]	0.026 [1]	0.438 [1]	0.411 [1]	3.82 [1]	48.02 [1]	8.34 [1]
Wheat Straw (scattered)	6.669 [1]	1.27e-1 [3]	5.40e-3 [3]	0.294 [1]	0.182 [1]	0.056 [1]	0.047 [1]	0.574 [1]	0.544 [1]	9.38 [1]	44.28 [1]	17.96 [1]

[1] Source = (Jenkins et al., 1996)

[2] Source = (McCarty, 2011). Note that values were taken from Table 1 of this paper, and were informed by multiple published literatures values. See APPENDIX C for the range of literature values used to arrive at the listed cotton emission factor values.

[3] Calculated using methodology outlined in (United States Environmental Protection Agency, Office of Atmospheric Programs, 2011). See APPENDIX C for more details.

[4] Source = (Scarborough et al., 2002). Note values are very low compared with other straw residues. Our confidence in these values is low.

[5] Source = (Nasser et al., 2014)

[6] Source = (Mendívil et al., 2013)

[7] Source = (Mailto et al., 2018)

[8] Source = (Afif et al., 2019)

[9] Source = (Çetin & Durusoy, 2017)

* No emission factor values for combustion of grape prunings were found in literature. Instead, we relied on averages for other woody agricultural residues (e.g. almond and walnut prunings).

** No values for carbon content of chars produced from combustion of grape prunings and cotton char were found in literature. Instead, we relied on the char carbon content of the crop whose initial, pre-combustion carbon content (shown under the “Feedstock” column) mostly closely matched the crop under consideration. For both the case of cotton and grape prunings, this happened to be corn stover.

CHAPTER 7
Soil CO_2 Efflux from A, E and B Horizons

Carbon emissions from soil can be disaggregated based on the different soil layers, or horizons as shown in Figure 13. Emissions from decomposition processes in the O Horizon are included through the decay modeling discussed in CHAPTER 5. However, there are additional carbon emissions at time scales relevant to this framework via different processes that occur within deeper soil layers.

The carbon balance at any particular site is governed by a tight interrelation and long term balance among inputs from photosynthesis (carbon and energy capture and sources to soil from root exudates and decomposition of biomass), annual efflux (from both autotrophic (plant respiration) and heterotrophic (decomposition by soil micro- through macro-organisms), and the storage of carbon in soil organic matter (conditioned by complex physiochemical factors like mineralogy, physical protection in aggregates, etc.). Soil CO_2 efflux is one important indicator that integrates multiple factors associated with site soil function and overall soil health that is directly affected by different levels of treatment-disturbance.

Soil carbon and carbon efflux is well documented as an important part of the full ecosystem carbon cycle of natural and working lands. A preliminary analysis of changes in CO_2 efflux on forest land disaggregated by primary treatment activity and autotrophic/heterotrophic source was conducted for this project and is discussed in APPENDIX D. This analysis provides preliminary arguments that removal of residues generated by primary treatment activities can likely occur with minimal impact to soil carbon efflux and long term site carbon. Therefore, while an important component of ecosystem scale LCA modeling, we do not have evidence to suggest that the presence or absence of forest residues will significantly impact soil carbon efflux originating from the A, E and B Horizons.

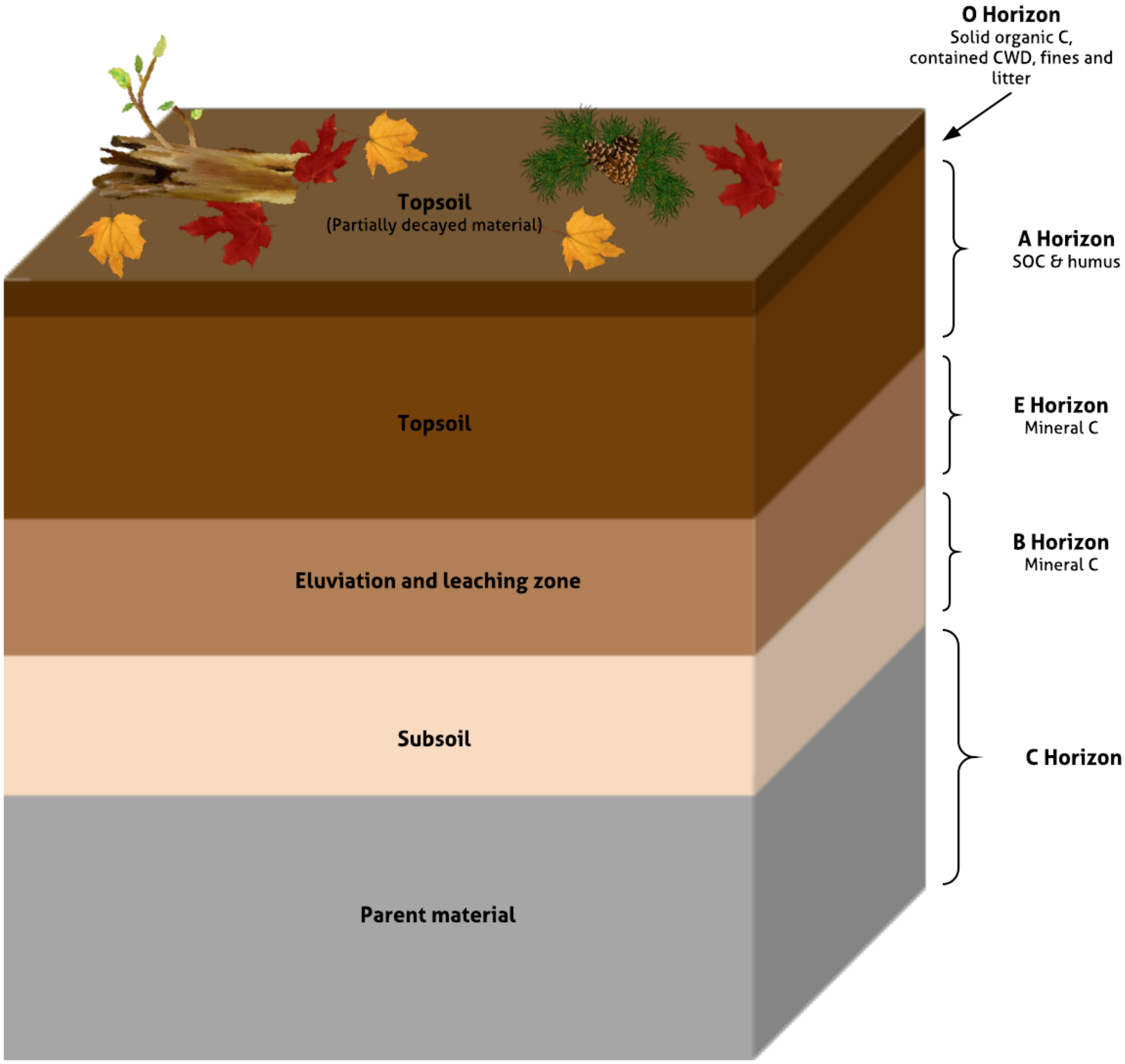
It is worth noting that there are four key challenges that currently limit the ability to rigorously quantify changes to soil carbon efflux originating in the A, E and B Horizons within the LCA boundary of this framework:

- Changes in autotrophic CO_2 efflux should be attributed to the primary activity that is generating residues, while changes in heterotrophic CO_2 efflux can be at least partially attributed to residue management activities. Disaggregating autotrophic and heterotrophic contributions to CO_2 efflux measurements is challenging and depends on many complex factors, some of which are not well correlated (note that a preliminary analysis of this disaggregation is included in APPENDIX D).
- The degree to which changes in heterotrophic CO_2 efflux are correlated with the presence or absence of residues is not well understood. While residue retention is an important driver of post-disturbance soil carbon dynamics related to site productivity and nutrient capital, current data does not provide the resolution needed to confidently quantify the effects of different residue retention volumes on soil CO_2 efflux.

- There are additional post-disturbance management activities outside the boundary of this LCA that also correlate with significant variability in changes to heterotrophic CO_2 efflux, such as irrigation, fertilization, and replanting practices.
- As the soil returns to a post-disturbance equilibrium state it's expected that any changes in soil carbon efflux below the O horizon that are attributable to the presence or absence of residues would largely disappear. The time scale is anticipated to be on the order of 1-to-5 years. Unfortunately there are insufficient data with which to develop a reasonable time series of this return to equilibrium.

Further discussion of the above points is provided in APPENDIX D. More research and active monitoring is needed to identify the key drivers of spatial and temporal heterogeneity in soil CO_2 efflux.

Figure 13: Cross Section of Soil Layers



CHAPTER 8
Mobilization Emissions

This section describes the process of accounting for emissions from collection, processing, transportation, and storage of forest and agricultural residues. For each gas species g these emissions are calculated as

$$E_{supply,g} = E_{C\&P,g} + E_{trans,g} + E_{storage,g}$$

where $E_{C\&P}$ represents the diesel emissions from equipment used to collect and process (C&P) residues, E_{trans} represents the diesel emissions from the transport of material from where residues are generated to the power plant gate, and $E_{storage}$ represents decay emissions associated with dry matter loss during storage. Each of these terms are discussed in more detail in the following sections.

Upstream emissions associated with equipment manufacturing used for residue collection, processing, or transportation are excluded from the lifecycle inventory. This follows the choice to exclude operations upstream of the residue. Furthermore, there is no clear information on how much of the equipment time would be allocable to biomass recovery vs. the primary activity. Upstream emissions associated with fuel and lubricants are included.

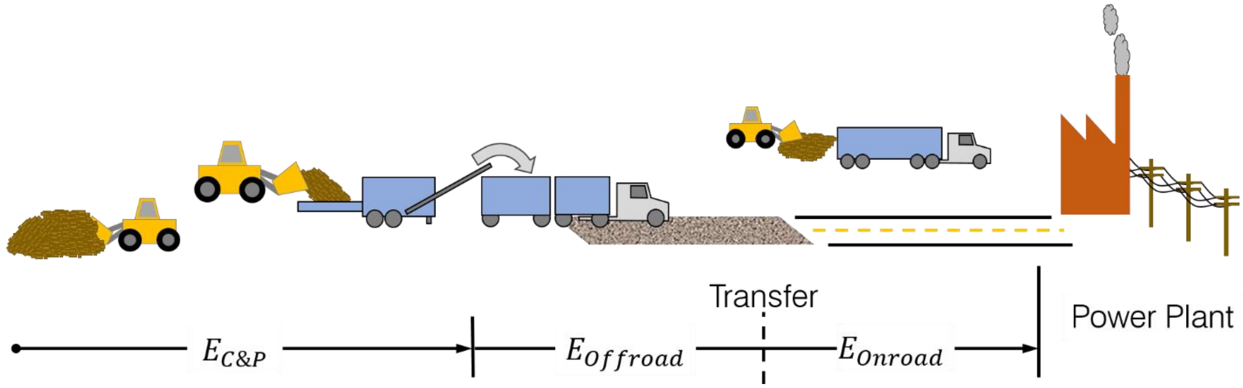
8.1 Collection, Processing and Transportation

Collection represents gathering, handling, and loading the residues from their initial state into the processing stage. Processing represents chipping and grinding only. Other processing steps such as drying or densifying are not captured given limited data availability and is left to future work.

8.1.1 Forest Residues

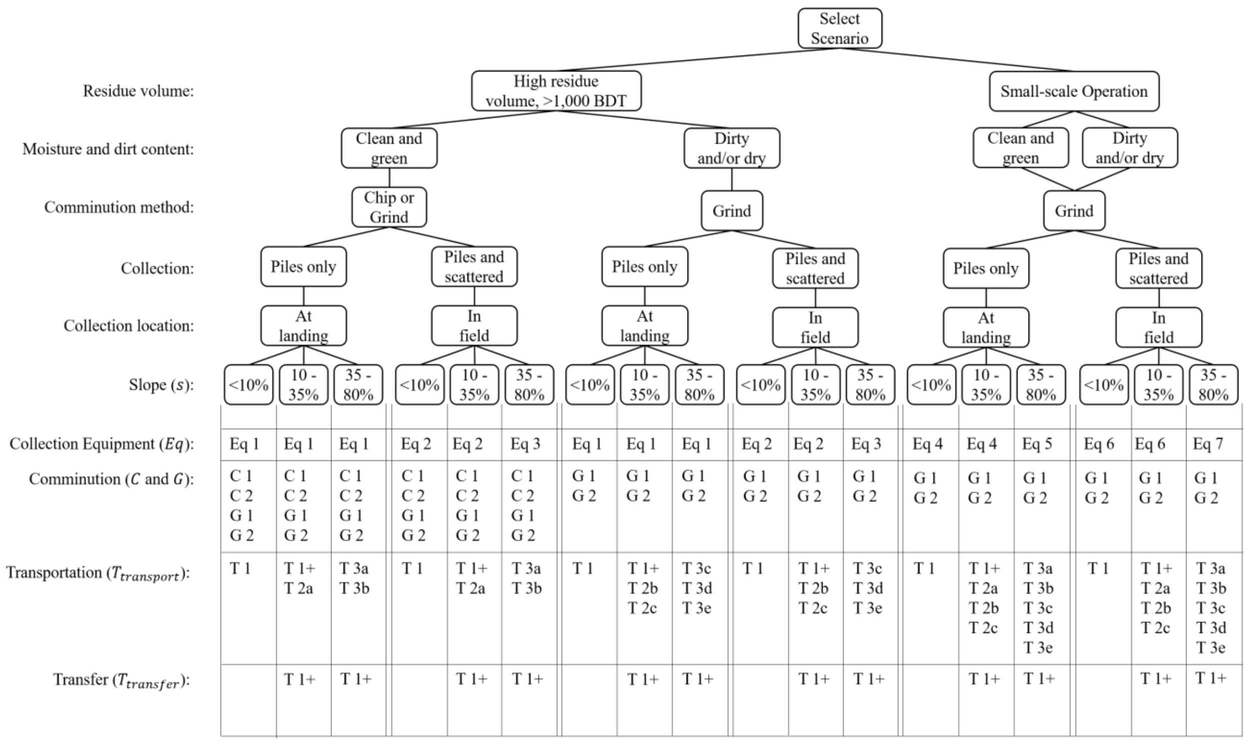
Biomass residue mobilization is classified as the mechanical activities that take residues from their disposition in the forest to the gate at the power plant. The mobilization pathway is split into three main steps: in field collection and comminution, off-road transportation, and on-road transportation (Figure 14).

Figure 14: Illustration of Forest Residue Mobilization Pathway



For equipment, comminution, and transportation systems, different options are available depending on the characteristics of the forest and biomass residues. Figure 15 shows a decision tree for available equipment systems depending on the characteristics of the biomass and slope of the forest. A more detailed version is also include in APPENDIX E. The different equipment system option codes are described in detail in the following sections.

Figure 15: Mobilization Equipment Selection Decision Tree



For each gas species g collection and processing emissions are calculated as

$$E_{C\&P,g} = \sum_{s} \left(M_{tech}^{piles} + M_{tech}^{scattered}\right)_s \cdot \left(Eq_g + C_g + G_g\right)_s + E_{fixed,g},$$

where M_{tech}^{piles} and $M_{tech}^{scattered}$ represent technically recoverable material as defined in Section 4.2, s represents slope, $(Eq + C + G)$ represents variable emissions factors from collection equipment

(Eq), chippers (C), and grinders (G) respectively that depend on the mass of biomass that is collected and processed, and E_{fixed} represents fixed emissions from movement of equipment and crew to a project site that are independent of the quantity of biomass collected. The variables Eq, C, and G are described in detail in Sections 8.1.1.1 and 8.1.1.2, and variable E_{fixed} is described in Section 8.1.1.5.

For each gas species g transportation emissions are calculated as

$$E_{trans,g} = \left(1 + (1 - F)\right) \cdot \sum_{s} \left(M_{tech}^{piles} + M_{tech}^{scattered}\right)_s \cdot \left(E_{offroad,g} + E_{onroad,g}\right)_s$$
$$E_{offroad,g} = (d_a + d_b) \times T_{transport,g} ,$$
$$E_{onroad,g} = d_c \times T_{transfer,g}$$

where $T_{transfer}$ represents emissions rates for trucks and loaders moving residue from the project site to a transfer point, $T_{transport}$ represents emissions rates for trucks moving residue from the transfer point to the power plant, variables d_a, d_b, and d_c represent one-way hauling distances as shown in Figure 16, and $\left(1 + (1 - F)\right)$ captures round trip miles where the unloaded return trip results in F% fewer emissions, and F is set to a value of 15%. The variables $T_{transfer}$ and $T_{transport}$ are described in detail in Sections 8.1.1.3 and 8.1.1.4.

Collection and processing emissions include a fixed emission and a variable emission portion. Variable emissions depend on the mass of biomass that is collected or processed. These variable emissions are reported as mass of emissions per bone-dry tonne of biomass. Variable emissions include the operation of equipment, such as a chipper whose emissions are based on the number of tonnes of biomass it processes. Fixed emissions, on the other hand, are independent of the mass of biomass that is collected. Fixed emissions include hauling equipment to and from the site for biomass operations.

Equipment systems are delineated by “large” and “small” projects. “Large” is defined as a project that yields greater than 1,000 BDT of residue with an average residue density of 13 BDT/acre[4]. “Small” is defined as all other projects that do not meet the definition of “large”.

Fuel and lubricant use on a per BDT biomass basis are calculated and emissions associated with their manufacturing and use are included in the LCI emissions data. Upstream emissions of consumables (fuel, lubricants) are based on national averages for what it takes to produce diesel as far back as its recovery at the well through refining, what it takes to transport that diesel to its point of eventual use (US average data) and emissions associated with combustion.

Equipment used for residue collection depends on the initial disposition of residues in the forest at the landing or in the field. For example, residues collected from the landing following a whole tree harvest will use a different set of equipment than residues collected from the field after cut-to-length harvesting. Furthermore, the characteristics of the forest stand (i.e. trees per acre and basal area per acre) drive the choice and efficiency of equipment used for biomass

[4] The decision on 13 BDT per acre comes from an analysis of National Forest residue production in Northern and Central California by Steve Brink, VP of Public Relations with the California Forestry Association.

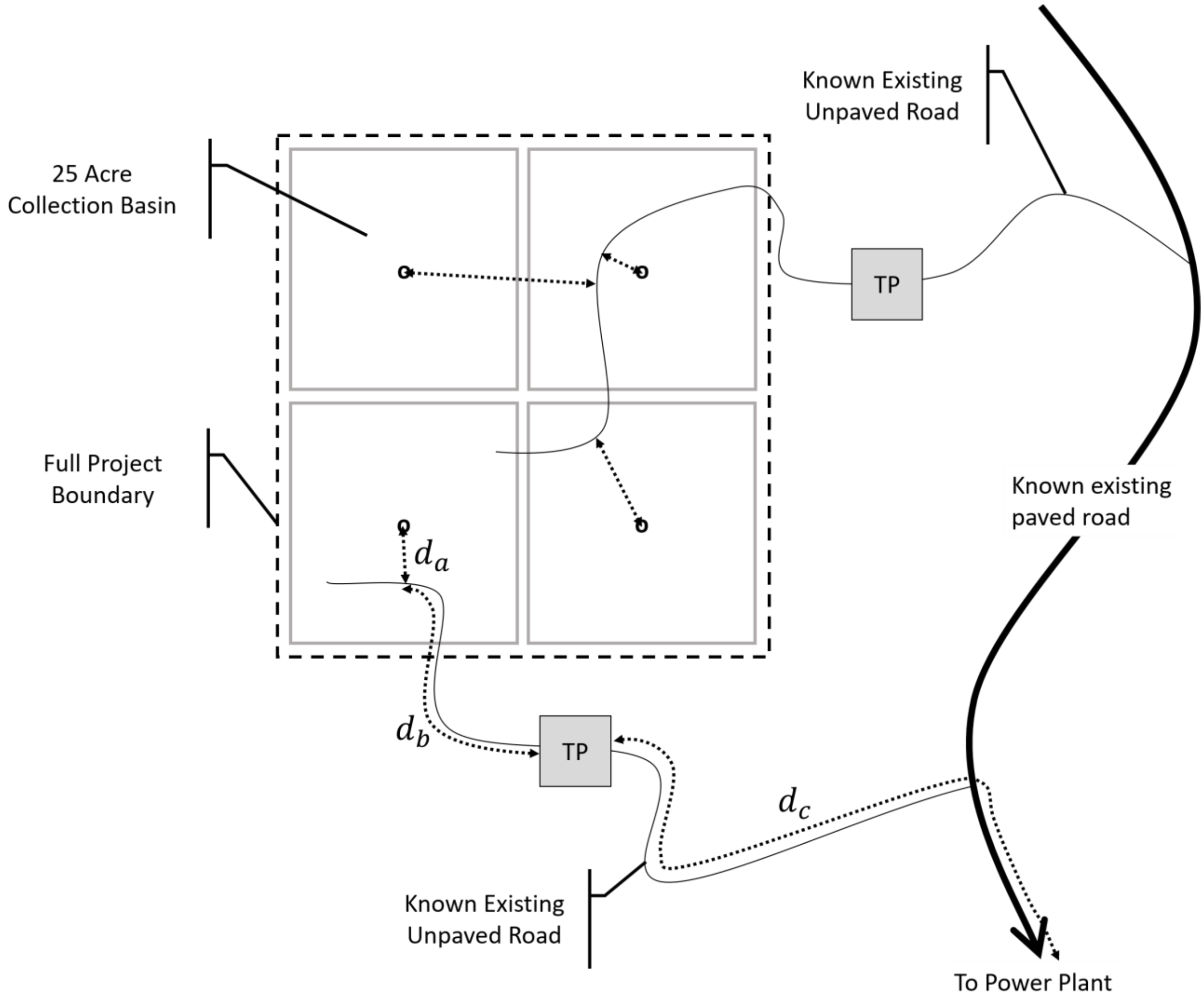
collection. Emission profiles were generated for biomass recovery equipment based on efficiency and utilization data for commercial operations.

Operations at the roadside or landing include processing, grinding or chipping, and loading. Different biomass types can have different pathways for densification based on piece size and quality. Alternatives were provided for integration into C-BREC. Regardless of harvest system or level of silvicultural treatment, roadside operations will have a similar carbon footprint per BDT under the assumption that equipment will not come on site unless it can be fully utilized.

As shown in Figure 16, each project area is divided into 25 acre catch basins. The smallest distance between the centroid of a catch basin and the nearest known road (paved or unpaved) is used to calculate d_a. The remaining distance to a transfer point is represented by d_b. The distance to a transfer point $(d_a + d_b)$ is set to a static value of 5 miles; therefore, $d_b = 5 - d_a$. If $(d_a + d_b + d_c)$ happens to be less than 5 miles, then there is no transfer point, additional loading equipment emissions are not included, and the selected vehicles for $T_{transport}$ are assumed to haul the residues the full distance to the power plant. Whether the nearest known road to the centroid is paved or unpaved does not impact whether or not there is a transfer point. The presence of a transfer point can be set to true or false, and is assumed true by default.

The Consortium for Research on Renewable Industrial Materials (CORRIM) developed equipment systems and associated emissions factors for the collection, processing, and transportation of biomass residue. The details of their work are provided in APPENDIX E.

Figure 16: Graphic Representation of Forest Residue Hauling Distances



8.1.1.1 Collection Equipment

Equipment is used to collect biomass residues from piles or scattered dispositions and load them into a grinder or chipper[5]. The equipment system that is deployed depends on the total volume of residue for the project, the slope of the terrain, and the cleanliness of the residues (moisture and dirt). Helicopter yarding is not considered as it's assumed that residues would not be collected from terrain where the slope is such that helicopter yarding of saw logs is required.

A description of the seven different equipment systems listed in Figure 15 are given below. In parenthesis are the equipment labels that are used in the report by CORRIM for cross-reference in CORRIM's report and in the emissions factors tables in Section 8.1.1.5.

[5] Note that hauling of whole logs or baled residue is not currently included in the C-BREC model. The CORRIM report includes equipment options for hauling of whole logs which are not used.

- Eq 1 - high volume collection of piles at landing only
    - 250 horsepower loader to pick up piles and load into the grinder or chipper (L.1)
    - Grinder or chipper loads directly into hauling truck
- Eq 2 - high volume collection of piled and scattered residues
    - Modified, all-wheel drive dump truck to transport from unit to landing (T.1)
    - Loader to sort logs and pulp at the landing (clearcut, thinning) (L.3)
    - 250 horsepower loader to pick up piles and load into the grinder or chipper (L.1)
    - Grinder or chipper loads directly into hauling truck
- Eq 3 - high volume collection on slopes >35%
    - Skyline cable yarder - exact yarding system selected based on treatment type (clearcut, thinning) (CY.1)
    - Modified, all-wheel drive dump truck to transport from field to landing (T.1)
    - Loader to sort logs and pulp at the landing (clearcut, thinning) (L.3)
    - 250 horsepower loader to pick up piles and load into the grinder or chipper (L.1)
    - Grinder or chipper loads directly into hauling truck
- Eq 4 - low volume collection of piles only
    - 250 horsepower loader to pick up piles and load into the grinder or chipper (L.1)
    - Grinder or chipper creates piles on the ground
    - 250 horsepower loader to pick up piles and load into hauling truck (L.1)
- Eq 5 - low volume collection of piles only on slopes >35%
    - Loader to sort logs and pulp at the landing (clearcut, thinning) (L.3)
    - 250 horsepower loader to pick up piles and load into the grinder or chipper (L.1)
    - Grinder or chipper creates piles on the ground
    - 250 horsepower loader to pick up piles and load into hauling truck (L.1)
- Eq 6 - low volume collection of piled and scattered residues
    - Skid steer, 120 horsepower turbo diesel, for fuel reduction and mastication (clearcut, thinning) (SS.2.WT)
    - Loader to sort logs and pulp at the landing (clearcut, thinning) (L.3)
    - Chainsaw for hand pile and sorting (CS.1)
    - 250 horsepower loader to pick up piles and load into the grinder or chipper (L.1)
    - Grinder or chipper creates piles on the ground
    - 250 horsepower loader to pick up piles and load into hauling truck (L.1)
- Eq 7 - low volume collection of piled and scattered residues on slopes >35%
    - Skyline cable yarder - exact yarding system selected based on treatment type (clearcut, thinning) (CY.1)
    - 250 horsepower loader pick up yarded material and load into dump truck (L.1)
    - Modified, all-wheel drive dump truck to transport from field to landing (T.1)
    - Loader to sort logs and pulp at the landing (clearcut, thinning) (L.3)
    - Chainsaw for hand pile and sorting (CS.1)
    - 250 horsepower loader to pick up piles and load into the grinder or chipper (L.1)
    - Grinder or chipper creates piles on the ground
    - 250 horsepower loader to pick up piles and load into hauling truck (L.1)

8.1.1.2 Comminution

Biomass residues are comminuted into smaller pieces with a chipper or grinder before transportation to the power plant. Chippers can only be used with clean and green residues. Grinders can be used with any quality of biomass

- C 1 - Chipper, Mobark, 875 horsepower
- C 2 - Micro-chipper, Peterson model 4300, 765 horsepower. Produces small chips.
- G 1 - Small Grinder, Peterson Pacific horizontal grinder, 475 horsepower
- G 2 - Large Grinder, Peterson Pacific horizontal grinder, 1050 horsepower

8.1.1.3 Transportation

Emissions from transportation of biomass from the field to the power plant are based on truck emissions factors and the travel time. The emissions factors are calculated in mass of emissions per bone dry tonne of biomass hauled per tonne per kilometer. Emissions factors for several different type of trucks were developed to allow flexibility in the type of transportation between the forest and the power plant gate (Table 26). All trucks use diesel fuel achieving 5.1 miles per gallon fuel economy (Mason et al., 2008).

Table 26: Description of Truck Transportation Options for Forest Residues

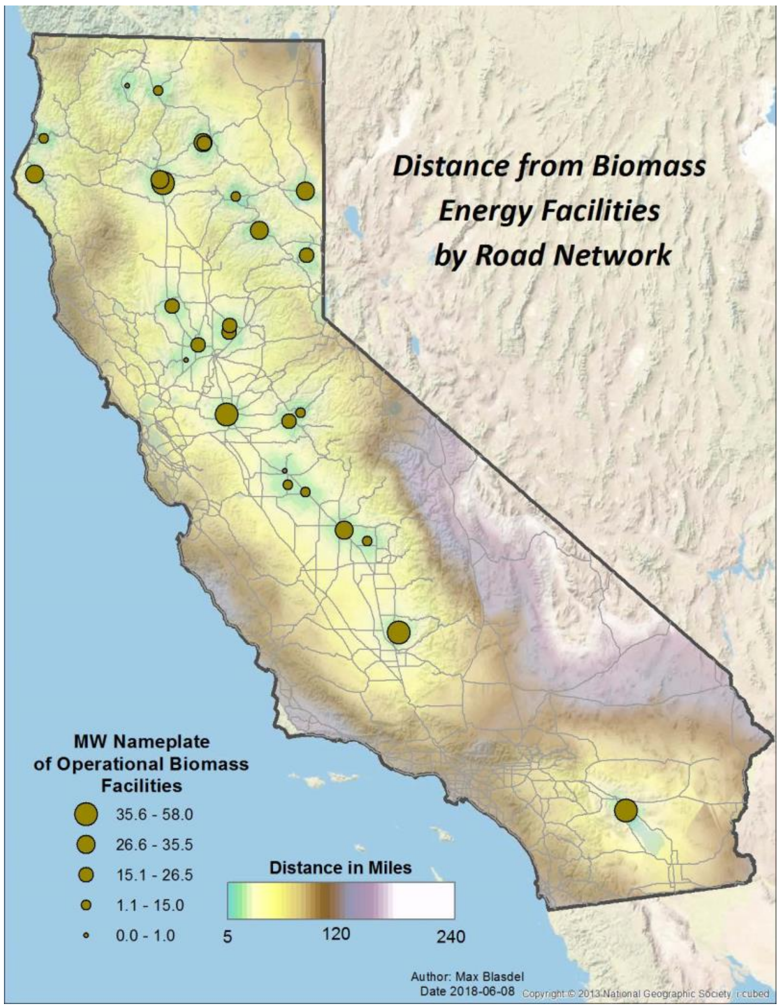
Limit	Biomass	Access	Truck Type	Payload	MC
Weight limited	Pulp logs, hauled whole	Flat and easy access	Mule train	12.99 BDT	50%
Weight limited	Pulp logs, hauled whole	Flat and easy access	Mule train	9.62 BDT	63%
Weight limited	Chipped	Flat and easy access	Chip van	9.62 BDT	63%
Weight limited	Chipped	Flat	Truck plus trailer	14.08 BDT	50%
Weight limited	Chipped	Flat	Truck plus trailer	10.43 BDT	63%
Weight limited	Chipped	Steep	Truck only	6.81 BDT	50%
Weight limited	Chipped	Steep	Truck only	5.05 BDT	63%
Volume limited	Chipped	Flat	Truck plus trailer + sides to 25 CY	12.16 BDT	50%
Volume limited	Chipped	Steep	Truck only + sides to 17 CY	4.13 BDT	63%
Volume limited	Chipped	Steep	Truck only + sides to 20 CY	4.86 BDT	50%
Volume limited	Chipped	Steep	Truck plus trailer + sides to 25 CY	6.08 BDT	63%

Moisture content (MC) is % mass on a wet basis

Biomass transportation is constrained by highway weight limits or truck volume capacity. Mass-limited transportation occurs when the gross weight of a vehicle reaches the maximum allowable highway gross vehicle weight before the volume of the truck/trailer is filled. In California, the maximum allowable gross vehicle weight for large truck/trailers is 80,000 lbs (California Department of Transportation, 2019). The payload of each truck/trailer (provided in Table 26) depends on the weight of the vehicle before loading. Volume limitations occur when a truck reaches its volume capacity before reaching the maximum allowable vehicle weight. Due to the low bulk density of biomass fuel, transportation is commonly volume limited. Mass limitations can occur when wet fuel is loaded into a large and light trailer (e.g. a chip van).

Emissions from transportation depends on the distance to the power plant. Transportation distance is determined by evaluating the required distance by road between the resource and the power plant. Hauling distance can either be manually specified or calculated for each existing and potential biomass power plant location in California using actual road networks (Figure 17). Travel distance are summarized into a spatial raster dataset as described in APPENDIX A for each power plant location. The spatial data contains the travel distance along existing roads to all power plants within 240 mile round trip range. Locations within a distance greater than 240 miles from an existing power plant are fixed at a haul distance of 240 miles.

Figure 17: One-Way Hauling Distance to Biomass Facilities in California



Transportation emissions are also included for round-trip hauling of biomass collection and processing equipment to the site. Hauling distances for equipment mobilization is assumed to be 50 miles one-way. Two round-trip journeys must be made to mobilize equipment: one round-trip to bring equipment to the site and another round-trip to pick up and return the equipment to the holding yard after completing the residue collection. Total equipment hauling distance is thus 200 miles per piece of equipment.

Transportation options include the hauling of comminuted material from the road to either the power plant facility or to a transfer point. If transported directly to the power plant, a single hauling vehicle is used for the entire distance. If a transfer point is used, the first vehicle (selected from these transportation options) hauls the material to a transfer point assumed to be at a flat, open access location. Then the material is loaded onto a chip van for the remaining distance (see Transfer Options in the next section).

A description of the transportation options listed in Figure 15 are given below. In parenthesis are the equipment labels that are used in the report by CORRIM for cross-reference. Payload BDT for each option can be determined by cross referencing with Table 26.

- T 1 - Chip van (H.5)
  - Slope < 10% with adequate turnaround
  - 63% moisture content, weight-limited hauling
- T 1+ - Chip van + extra loader (H.5+L.1)
  - Slope < 10% with adequate turnaround
  - 63% moisture content, weight-limited hauling
  - Add a 250 horsepower loader to pick up piles and transfer into chip van or between vehicles
- T 2a - Truck and trailer combination (H.6)
  - Slopes between 10% and 35% with adequate turnaround
  - 63% moisture content, weight-limited hauling
- T 2b - Truck and trailer combination (H.1)
  - Slopes between 10% and 35% with adequate turnaround
  - 50% moisture content, weight-limited hauling
- T 2c - Truck and trailer (H.4)
  - Slopes between 10% and 35% with adequate turnaround
  - < 50% moisture content, volume-limited hauling, 25 cubic yard capacity
- T 3a - Dump truck (H.3)
  - All slopes
  - 50% moisture content, weight-limited hauling
- T 3b - Dump truck (H.9)
  - All slopes
  - 63% moisture content, weight-limited hauling
- T 3c - Dump truck (H.8)
  - All slopes
  - < 50% moisture content, volume-limited hauling, 25 cubic yard capacity
- T 3d - Dump truck (H.10)
  - All slopes
  - < 50% moisture content, volume-limited hauling, 20 cubic yard capacity
- T 3e - Dump truck (H.11)
  - All slopes
  - < 50% moisture content, volume-limited hauling, 17 cubic yard capacity

8.1.1.4 Transfer

The transfer option is used when residues are hauled from a steep, roadside location in the forest to a central transfer station. The assumed distance between location of residue and transfer point is 5.0 miles. The transfer point allows the material to be loaded into a chip van for transport along the remaining distance to the power plant. There is only one option for transportation after the transfer point: a chip van plus a loader.

- T 1+ - Chip van + extra loader (H.5+L.1)
    - Transfer comminuted resides to a chip van from the original hauling vehicle.
    - Includes use of a 250 horsepower loader to move material.
    - A chip van hauls the remaining distance to the power plant.

8.1.1.5 Emissions Factors

All emissions equipment factors were modeled using SimaPro v8.5.2.0 employing the impact assessment method TRACI 2.1 v1.01. Emissions factors include upstream emissions associated with fuels, lubricants, and transport, but do not include emissions associated with manufacturing of the equipment. Two types of emissions factors are used: fixed and variable. Fixed emissions factors are independent of the quantity of residues created while variable emissions factors are dependent on the quantity of residues. These are discussed in the following subsections.

Fixed Emissions Factors

Fixed emissions factors are associated with hauling of equipment to a forest operations site, and daily movement of crews. These are provided on a per-hour and per-person-km basis. The emissions factors used are shown in Table 27.

For equipment hauling, each project is assumed to have a one-way hauling time of 2 hours. The total emissions are multiplied by two, once for delivery and once for retrieval of field equipment. For crew hauling, each project is assumed to have a 50-mile (80.5 km) driving distance. Total trips of crew hauling is determined by the total collected residue mass and literature suggested logging crew productivity. A survey study in Virginia found, on average, 2.8 workers are on a logging crew and each crew produces 224.62 merchantable tonnes per week in the mountain region (Barrett et al., 2017). Assuming a five day work week, 16.04 tonnes of merchantable timber can be produced per worker-day. Each worker-day is the equivalent of two crew hauling trips (i.e., round trip).

Table 27: Fixed Emissions for Equipment Hauling and Crew Mobilization

	Equipment Hauling (kg / hour)	Crew Hauling (kg / person-km)
CO2	55.45	8.741E-01
CO	4.850E-01	7.645E-03
N2O	4.410E-05	6.952E-07
CH4	7.786E-02	1.227E-03
NOX	1.010	1.592E-02
PM10	2.410E-06	3.799E-08
PM2.5	1.758E-04	2.771E-06
SOX	8.521E-02	1.343E-03
VOC	2.650E-02	4.177E-04

Data from CORRIM as described in APPENDIX E.

Variable Emissions Factors

Variable emissions depend on three key project variables: total BDT of residues, hauling distance from field to transfer point (if applicable), and hauling distance to the power plant. These project variables are used along with the emissions factors shown in Table 29, Table 30, and Table 31. For chainsaw emissions, which are given in units of kg / hr, the following are used to convert to units of kg / MT:

- Value of 16.3 m^3/h was used by averaging the uneven-aged and even-aged estimates from (Han et al., 2015).
- 16.3 m^3/h was converted to metric tons per hour using a conversion factor of 0.4501 MT/m3 calculated using the bone dry density of Douglas-fir from (Hardy, 1996).

For black carbon emissions, the fractions of $PM_{2.5}$ shown in Table 28 are used from (California Air Resources Board, 2016b).

Table 28: Black Carbon Speciation Values for Diesel Sources

	Value $\left(\frac{m_{BC}}{m_{PM_{2.5}}}\right)$	Notes
Off-road Diesel Equipment	0.610165	ID 6208, model year 2020.
On-road Diesel Equipment	0.181326	ID 6202, model year 2020, HDDT-Cruising

All values are from (California Air Resources Board, 2016b)

Table 29: Forest Residue Recovery Equipment Emissions Factors

	%BA*	CO2	CO	N2O	CH4	NOX	PM10	PM2.5	SOX	VOC
CS.1***	All	5.669E-01	3.464E-02	1.492E-05	1.082E-03	8.494E-03	2.763E-08	2.015E-06	9.707E-04	6.929E-04
CS.2***	All	2.312E+00	2.011E-02	1.813E-06	3.202E-03	4.216E-02	9.908E-08	7.227E-06	3.510E-03	1.106E-03
L.1**	All	1.820E+00	1.600E-02	1.450E-06	2.560E-03	3.320E-02	7.930E-08	5.780E-06	2.800E-03	8.720E-04
L.3**	20%	1.691E+00	1.479E-02	1.340E-06	2.374E-03	3.080E-02	7.350E-08	5.360E-06	2.598E-03	8.080E-04
L.3**	40%	1.566E+00	1.369E-02	1.250E-06	2.198E-03	2.852E-02	6.800E-08	4.960E-06	2.406E-03	7.481E-04
L.3**	60%	1.458E+00	1.275E-02	1.160E-06	2.047E-03	2.655E-02	6.340E-08	4.620E-06	2.240E-03	6.965E-04
L.3**	80%	1.273E+00	1.114E-02	1.010E-06	1.788E-03	2.319E-02	5.530E-08	4.040E-06	1.957E-03	6.084E-04
L.3**	100%	1.057E+00	9.243E-03	8.400E-07	1.484E-03	1.925E-02	4.590E-08	3.350E-06	1.624E-03	5.050E-04
SS.2.WT**	20%	1.645E+02	1.439E+00	1.308E-04	2.309E-01	2.996E+00	7.150E-06	5.214E-04	2.528E-01	7.859E-02
SS.2.WT**	40%	1.523E+02	1.332E+00	1.211E-04	2.138E-01	2.774E+00	6.620E-06	4.828E-04	2.340E-01	7.277E-02
SS.2.WT**	60%	1.418E+02	1.240E+00	1.128E-04	1.991E-01	2.583E+00	6.160E-06	4.495E-04	2.179E-01	6.775E-02
SS.2.WT**	80%	1.238E+02	1.083E+00	9.850E-05	1.739E-01	2.256E+00	5.380E-06	3.926E-04	1.903E-01	5.918E-02
SS.2.WT**	100%	1.028E+02	8.991E-01	8.180E-05	1.443E-01	1.872E+00	4.470E-06	3.259E-04	1.580E-01	4.912E-02
CY.1**	20%	3.426E+01	2.997E-01	2.730E-05	4.811E-02	6.241E-01	1.490E-06	1.086E-04	5.266E-02	1.637E-02
CY.1**	40%	3.224E+01	2.820E-01	2.560E-05	4.526E-02	5.872E-01	1.400E-06	1.022E-04	4.954E-02	1.540E-02
CY.1**	60%	3.044E+01	2.662E-01	2.420E-05	4.274E-02	5.544E-01	1.320E-06	9.650E-05	4.677E-02	1.454E-02
CY.1**	80%	2.724E+01	2.383E-01	2.170E-05	3.825E-02	4.962E-01	1.180E-06	8.640E-05	4.186E-02	1.302E-02
CY.1**	100%	1.571E+01	1.374E-01	1.250E-05	2.206E-02	2.862E-01	6.830E-07	4.980E-05	2.414E-02	7.507E-03

Data from CORRIM as described in APPENDIX E.

* Represents primary treatment percent basal area (BA) removed.

** Units are kg / BDT

*** Units are kg / hr

Table 30: Forest Residue Comminution Equipment Emissions Factors (kg / BDT)

	%BA*	CO2	CO	N2O	CH4	NOX	PM10	PM2.5	SOX	VOC
C.1	All	1.670E+00	1.460E-02	1.330E-06	2.340E-03	3.040E-02	7.250E-08	5.290E-06	2.560E-03	7.980E-04
C.2	All	7.800E+00	6.820E-02	6.200E-06	1.100E-02	1.420E-01	3.390E-07	2.470E-05	1.200E-02	3.730E-03
G.1	All	9.190E+00	8.040E-02	7.310E-06	1.290E-02	1.670E-01	3.990E-07	2.910E-05	1.410E-02	4.390E-03
G.2	All	9.120E+00	7.980E-02	7.260E-06	1.280E-02	1.660E-01	3.970E-07	2.890E-05	1.400E-02	4.360E-03

Data from CORRIM, 2018. See APPENDIX E.

* Represents primary treatment percent basal area (BA) removed.

Table 31: Forest Residue Hauling Equipment Emissions Factors (kg / BDT-km)

	%BA*	CO2	CO	N2O	CH4	NOX	PM10	PM2.5	SOX	VOC
H.1	All	1.080E-01	5.610E-04	2.590E-06	2.200E-04	7.260E-04	3.200E-09	2.330E-07	1.180E-04	3.430E-05
H.3	All	2.230E-01	1.160E-03	5.350E-06	4.550E-04	1.500E-03	6.610E-09	4.820E-07	2.430E-04	7.090E-05
H.4	All	2.500E-01	1.300E-03	1.040E-05	5.070E-04	1.680E-03	7.420E-09	5.410E-07	2.740E-04	7.630E-05
H.5	All	2.580E-01	1.350E-03	1.050E-05	5.240E-04	1.740E-03	7.650E-09	5.580E-07	2.810E-04	8.660E-05
H.6	All	2.910E-01	1.510E-03	1.050E-05	5.910E-04	1.960E-03	8.640E-09	6.300E-07	3.210E-04	9.740E-05
H.8	All	5.000E-01	2.600E-03	1.090E-05	1.030E-03	3.370E-03	1.480E-08	1.080E-06	5.480E-04	1.630E-04
H.9	All	6.020E-01	3.130E-03	1.110E-05	1.230E-03	4.050E-03	1.790E-08	1.300E-06	6.590E-04	1.950E-04
H.10	All	6.250E-01	3.260E-03	1.110E-05	1.280E-03	4.210E-03	1.850E-08	1.350E-06	6.800E-04	1.960E-04
H.11	All	7.350E-01	3.820E-03	2.130E-05	1.500E-03	4.960E-03	2.180E-08	1.590E-06	7.990E-04	2.390E-04

Data from CORRIM, 2018. See APPENDIX E.

* Represents primary treatment percent basal area (BA) removed.

8.1.2 Agricultural Residues

As with forestry residues, mobilization and conversion requires collection, processing, and transportation. However, the ease of field access and different equipment capabilities mean that agricultural residues are converted to electricity in three steps:

- Collection and processing - emissions from gathering residues from the field and processing for transport, such as baling straw residues or chipping woody residues.
- Transportation - emissions from round-trip hauling between the farm and the power plant
- Energy conversion – combustion of bales or chips in a power plant

8.1.2.1 Straw Residues

Currently, no combine harvester can simultaneously harvest grain and collect straw residues, so straw is left on the field post-harvest. Residue removal and processing typically occurs simultaneously, as straw is baled before it can be moved. Additional processing may occur before transport to a power plant.

The three equipment pieces of assumed for straw residue collection and processing are a 100 HP tractor, a 100 HP baler, a 100 HP bale wagon, and a 100 HP loader. The efficiency of the straw residue collection and processing is assumed at 3.5 acres per hour. On-road hauling uses the same emissions factor as a chip van (H.5) from forest residue work. Emissions factors are shown in 8.1.2.3.

8.1.2.2 Woody Residues

Woody debris is chipped upon removal, so removal and processing occur simultaneously. Additional processing of woody residues may occur before transport to a power plant. The equipment assumed to be used in the woody residue collection and processing are a 100 HP tractor, a 300 HP chipper/shredder, and a 100 HP loader. The efficiency of the woody residue collection and processing is assumed at 1.75 acres per hour, half that of the straw residue. The reason for this is because the woody residue collection and processing equipment set, the tractor and the shredder with hopper, is responsible for both shredding the woody biomass and transporting the collected biomass to the in-farm collection site whereas the straw residue collection and processing equipment has the bale wagon which is dedicated to only collecting and transporting the in-farm collection site in additional to the baler. This estimate is reasonably consistent with one published average of 1.48 acres per hour for olive prunings (Suardi et al., 2020), although may be an overestimate of efficiency, particularly for grape prunings which can be located on relatively steep terrain. On-road hauling uses the same emissions factor as a chip van (H.5) from forest residue work. Emissions factors are shown in 8.1.2.3.

8.1.2.3 Emissions Factors

The emissions factors used for agricultural collection and processing equipment are shown in Table 32.

Table 32: Agricultural Residues Collection and Processing Equipment Emissions Factors

	Applied Residue Type	Equipment	Model Year	HP	CH4	CO	CO2	NOx	PM10	PM2.5	SO2	VOC	BC	N2O	Fuel Consumption
B.1	Straw and Wood	Tractor	2020	100	2.2	269	76,885	291	35.3	34.2	0.44	36.9	26.4	2.02	0.243
B.2	Straw	Baler	2020	100	2.03	343	76,815	414.1	48.5	47.1	0.5	60.1	36.3	2.02	0.243
B.3	Straw	Bale Wagon *	2020	100	2.2	319	76,853	653	47.2	45.8	0.5	55.9	35.3	2.02	0.313
B.4	Wood	Chipper *	2020	300	2.1	128	76,880	353	25.3	24.6	0.4	38.0	18.9	2.02	0.219
B.5	Straw and Wood	Loader *	2020	100	2.2	319	76,853	653	47.2	45.8	0.5	55.9	35.3	2.02	0.313

All data from (Li et al., 2016). Units are g/mmBtu diesel, except Fuel Consumption which is units of lb/hr/hp

* Assumes Agriculture Other Equipment emissions factors from (Li et al., 2016)

Table 33: On-Road Truck Hauling Emissions Factors for Agricultural Residues

	Applied Residue Type	Equipment	CO2	CO	N2O	CH4	NOX	PM10	PM2.5	SOX	VOC
H.5	Straw and Wood	Hauling Truck	2.580E-01	1.350E-03	1.050E-05	5.240E-04	1.740E-03	7.650E-09	5.580E-07	2.810E-04	8.660E-05

Data from CORRIM, 2018. See APPENDIX E.

8.2 Storage

Mass losses associated with storage phases within the power plant operation segment of the supply chain must also be considered. In practice, comminuted biomass is delivered to power plants and piled on landings that are often uncovered and thus left open to the elements. Depending on the duration of storage, such conditions can potentially give-way to biologically-driven decomposition as well as other, chemically-driven degradation processes.

A 2013 meta-analysis found that emissions from fuel storage piles are typically not included, are uncertain, or are based on rough estimates (EPRI, 2013). The generation of CH_4 during storage of biomass chips may contribute to a greater global warming potential then typically reported from biomass supply chain lifecycle assessments (Giuntoli et al., 2015). Some regulatory agencies that are studying biomass power systems do consider emissions from storage (US EPA, 2014).

Emissions from storage are calculated as

$$E_{storage,CH_4} = DML \cdot \sum_{s} \left(M_{tech}^{piles} + M_{tech}^{scattered}\right)_s \cdot Ef_{CH_4}$$

$$E_{storage,CO_2} = \frac{44.01}{12.01}\left[DML \cdot \sum_{s} \left(M_{tech}^{piles} + M_{tech}^{scattered}\right)_s \cdot C_{frac} - \left(E_{storage,CH_4} \cdot \frac{12.01}{16.04}\right)\right],$$

where DML represents the percent dry matter loss (DML) of material collected and delivered to the power plant gate, M_{tech}^{piles} and $M_{tech}^{scattered}$ represent technically recoverable material as defined in Section 4.2 that is delivered to the power plant gate, s represents slope, Ef_{CH_4}represents the methane emissions factor, C_{frac} represents the carbon fraction of the material which is discussed in Section 5.3, and the values 12.01, 16.04, and 44.01 represent the molecular weight of carbon, methane, and carbon dioxide respectively. The calculation of CO_2 emissions uses a carbon balance approach consistent with decay methods described in CHAPTER 5. Furthermore, emitted species from decay during storage are limited to CO_2 and CH_4, also consistent with in-field decay methods.

8.2.1 Forest Residues

Resultant degradation of wood polymers (i.e. cellulose, hemicellulose, and lignin) is reported as dry matter loss (DML) and expressed as a percentage of the original dry matter present; note that DML does *not* account for fluctuations in moisture content that occur over the course of storage. The extent of DML during storage of piled comminuted forest residues is of concern from an industry perspective because it can influence energy content, and so it is reasonably well documented. A dry matter loss of 9.7% is assumed for on-site storage phases of piled comminuted forest residues. This value was calculated assuming a storage duration of 6 months[6] and with the following:

[6] Informed by Schatz Energy Research Center field research.

$$DML(t) = 2.1469\ln(t) - 1.504$$

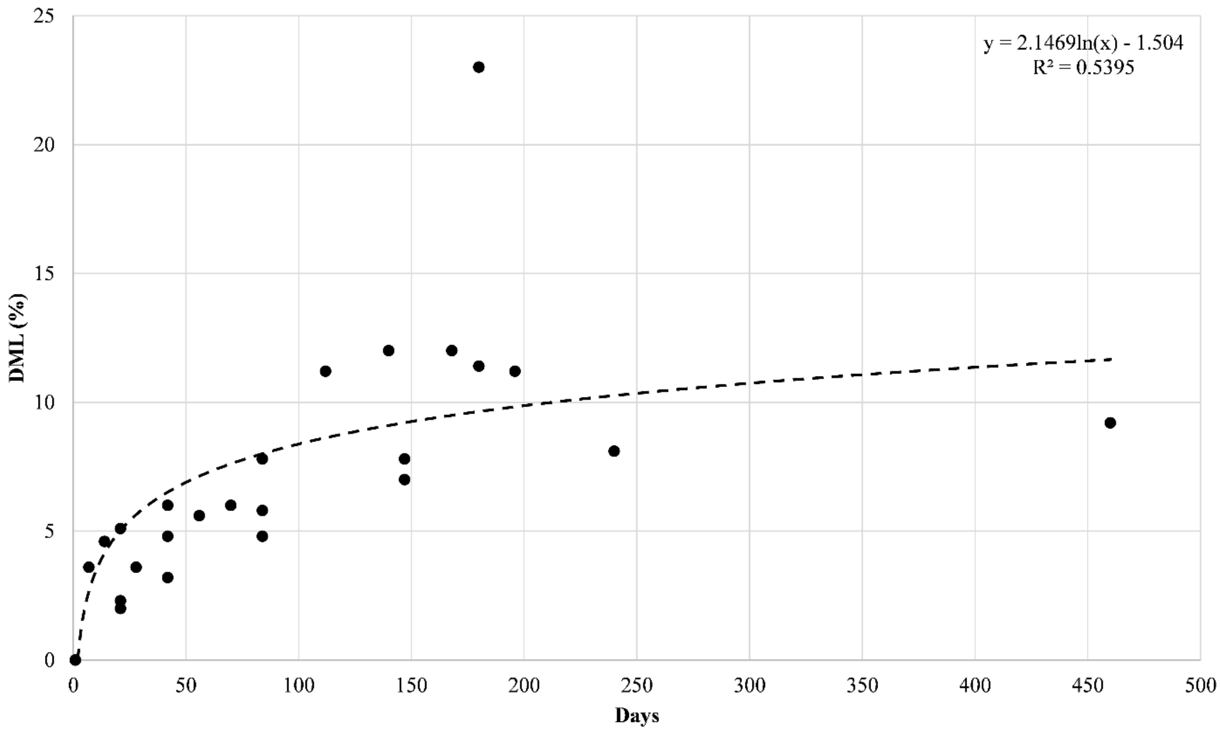
where time t is in days. This time-based equation represents a logarithmic fit for softwood, woodchip DML data points taken from a number of different studies (and as reported in the Supplemental Material of (Sahoo et al., 2018)). Values were only used if they represented DML for piles stored in outdoor and open-air conditions. Table 34 shows the utilized DML values while Figure 18 displays this data plotted with respect to time. It should be noted that a logarithmic fit proved to have a higher R-squared value when compared to linear regression, and that this is in alignment with what other biomass storage studies have observed: the first few weeks of storage are characterized by rapid DML rates which then plateau for the remaining duration of storage (Hofmann et al., 2018; Lenz et al., 2015; Sahoo & Mani, 2017).

Table 34: Literature Values of Dry Matter Loss (DML) during Power Plant Storage Phases

Storage duration (d)	Final dry matter loss (%)	Wood type	Source
147	7.8	Spruce	(Hofmann et al., 2018)
147	7.0	Spruce	(Hofmann et al., 2018)
180	11.4	Conifers	(Gislerud, 1990)
196	11.2	Logging residues	(Thörnqvist & Jirjis, 1990)
240	8.1	Logging residues	(Thörnqvist, 1986)
460	9.2	Forest residues	(Garstang et al., 2002)

Dry matter loss results in the emission of gases such as CH_4, CO_2, CO, non-methanous volatile organic compounds (NMVOCs), and N_2O from the surface of piles (Alakoski et al., 2016; Wihersaari, 2005); this process is referred to as “off-gassing”. CH_4 off-gassing is of particular concern as the nature of power plant storage practices is thought to foster conditions in which methanogens (or CH_4-producing archaea) can thrive (Pier & Kelly, 1997; Wihersaari, 2005). In theory warm, oxygen-depleted “hot spots” can form near the center of the storage pile as a result of relatively rapid aerobic microbial activity (Wihersaari, 2005). It is at this point that anaerobic methanogenesis ensues, however, as another biomass storage phase analysis pointed out, the extent of CH_4 production and oxidation has yet to be elucidated (Biomass Technology Group BV, 2002). This is in part the reason CH_4 is rarely considered in studies of the life cycle greenhouse gas intensity of bioelectricity.

Figure 18: Dry matter loss (DML) for Comminuted Softwood Storage Piles



As part of a separate project, we are quantifying emissions from the decay of biomass chips that are stored in large piles. At the time of this report these data are not available. They will be included in a future iteration. We thus rely on the same CH_4 emission factor (E_{CH_4}) described in Section 5.3.1.2, which was derived from CH_4 concentration and dry matter loss (DML) values reported in a wood chip incubation study (He et al., 2014), as shown in Table 19.

Carbon monoxide (CO), non-methanous volatile organic compounds (NMVOCs), and nitrous oxide (N_2O) off-gassing is not accounted for in this work. Instead, it assumed that remaining C losses after accounting for CH_4 go towards CO_2 emission.

8.2.2 Agricultural Residues

Emissions from storage are currently not included for agricultural residues.

8.3 Power Plant On-site Equipment

Equipment is operated on-site a power plant using fossil fuels. Loaders, haulers, forklifts and other equipment is used to move material around the site. This on-site equipment is currently not included. Emissions factors recommended for future inclusion of this equipment can be found in APPENDIX E.

CHAPTER 9
Conversion to Electricity and Process Heat

At the power plant, biomass is converted into energy using thermal processes. The emissions accounting from the power plant are described in the following section.

Emissions resulting from energy conversion of biomass into heat and electricity are calculated based on the biomass fuel properties, power plant specifications, and pollutant emissions factors. The emissions are calculated using the carbon content and heating value of the species delivered to the power plant; the conversion rate of fuel to heat and electricity is obtained from performance data of existing power plants; and the emissions rates are calculated using the carbon content of the fuel to find the CO_2 emissions and reported emissions factor for other stack gas constituents.

In addition to capturing performance characteristics of all existing biomass power plants in California, we characterize five different generic power plants:

- Current generation biomass combustion
- Current generation integrated gasification / combustion
- Next generation thermochemical conversion gasifier
- 5MW gasifier
- <1 MW gasifier

Emissions from energy conversion are calculated as:

$$E_{energy,g} = E_{pp,g} - E_{chp,g}$$

$$E_{pp,g} = \sum_{s} \left(M_{tech}^{piles} + M_{tech}^{scattered}\right)_s \cdot (1 - DML) \cdot HHV \cdot \eta_{pp} \cdot Ef_{pp,g}$$

$$E_{chp,g} = \sum_{s} \left(M_{tech}^{piles} + M_{tech}^{scattered}\right)_s \cdot (1 - DML) \cdot HHV \cdot \left(1 - \eta_{pp}\right) \cdot \eta_{cogen} \cdot Ef_{ng,g}$$

where E_{pp} are emissions from the power plant, and E_{chp} are the emissions from offset natural gas associated with combined heat and power. The variables M_{tech}^{piles} and $M_{tech}^{scattered}$ represent technically recoverable material as defined in Section 4.2 that is delivered to the power plant gate and vary by slope s, DML represents dry matter loss from storage as described in Section 8.2, HHV represents the higher heating value of the residue which is discussed in Section 9.1, η_{pp} is the power plant electrical effiency and η_{cogen} is the cogeneration efficiency which are both discussed in Section 9.2, $Ef_{pp,g}$ is the emissions factor for the power plant stack for each emitted gas species g except CO_2 which is calculated via carbon balance, and $Ef_{ng,g}$ is the emissions factor for a standard natural gas boiler with controls. Emissions factors are discussed in Section 9.4.

In addition, carbon sequestered in the flyash output of the power plant is also captured. This is calculated as:

$$E_{char} = \sum_{s} \left(M_{tech}^{piles} + M_{tech}^{scattered}\right)_s \cdot (1 - DML) \cdot (U - A),$$

where U is the fraction of input material that is uncombusted on average, and A is the fraction of the input material that is ash (via proximate analysis). This is discussed in more detail in Section 9.3. Because values for U and A are pulled from multiple different literature sources, it is possible for $U < A$. In this case we set $E_{char} = 0$.

Black carbon emissions are calculated as a fraction of PM2.5 which is discussed in more detail in Section 9.4. Finally, CO_2 is calculated via carbon balance as:

$$E_{CO_2} = \frac{44.01}{12.01} \cdot \left[\left(\sum_{s} \left(M_{tech}^{piles} + M_{tech}^{scattered}\right)_s \cdot (1 - DML) \cdot C_{frac}\right) - \left(\sum_{g} E_{pp,g} \cdot C_g\right) - \left(E_{char} \cdot C_{char}\right)\right],$$

where C_{frac} represents the carbon fraction of the material which is discussed in Section 5.3, $E_{pp,g}$ is the emissions of those gases g that contain carbon, C_g is the carbon fraction of those gases shown in Table 41, and C_{char} is the carbon fraction of the char component of flyash.

9.1 Biomass Properties

Biomass properties are spatially explicit and weighted by species composition of the biomass. Properties for forest residues were obtained from (Fantini, 2017; Gaur & Reed, 1995; International Commission of Agricultural Engineering, 1999) for the species in California, and processed into average values by species groups as shown in Table 35. Values for agriculture residues are shown in Table 36. Mean values are used.

Although carbon content analysis of flyash from power plants is not well researched, it is known that carbon content of flyash from the power plant can vary widely depending on the power plant technology, operational efficiency, and feedstock (James et al., 2012). This framework assumes a carbon fraction of the char content of flyash of 0.83 [g C / g char] (from Table 2 of (Jindo et al., 2014), using the value for oak at 800 ºC)[7] as representative of the carbon content of flyash absent the proximate ash content of the input biomass.

[7] In conversation with Grant Scheve of Oregon Biochar Solutions, the estimated carbon content of flyash is 30% - 35% [g carbon / g flyash]. The method used in this framework results in a flyash carbon content of 60% - 65% depending on the biomass species and power plant technology. Reconciling this is left to future work.

Table 35: Higher Heating Values, Ash, and Carbon Content of Tree Species Groups

Biomass Group	HHV (MJ/kg)	Ash (A) (%)	Carbon (C_{frac}) (%)	C_{char} (%)
Aspen/alder/cottonwood/willow	19.3	0.400	49.6	83
Cedar/larch	21.4	0.353	52.8	
Douglas-fir	20.4	0.100	50.6	
Hard maple/oak/hickory/beech	19.1	0.930	49.0	
Juniper/oak/mesquite	19.7	0.800	50.7	
Mixed hardwood	19.7	0.788	49.0	
Pine	20.1	0.395	49.3	
Soft maple/birch	19.7	0.467	49.5	
Spruce *	20.1	0.395	49.3	
True fir/hemlock	20.0	1.23	49.7	

All HHV, ash %, and carbon % values adapted from (Fantini, 2017; Gaur & Reed, 1995; International Commission of Agricultural Engineering, 1999). Value for C_{char} is from (Jindo et al., 2014), Table 2, value for oak at 800C.
* Values for the Spruce group are set equal to those for Pine

Table 36: Higher Heating Value of Agricultural Residues

Crops	HHV (MJ/kg)	Ash (A) (%)	Carbon (C_{frac}) (%)	C_{char} (%)
Corn stover	18.77	See Table 25		
Cotton stalks	15.83			
Rice straw	15.42			
Wheat straw	17.51			
Almond prunings	20.01			
Walnut	19.73			
Grape vineyard prunings	19.13			

HHV adapted from (Jenkins & Ebeling, 1985)

Dry matter loss through decay during storage is accounted for (see Section 8.2), yet this was determined to not significantly impact the higher heating value of the material entering the power plant. Changes in extractable energy content during storage phases of comminuted biomass do occur due to changes in moisture content and subsequent magnitude of dry matter loss (DML), as well as changes in chemical composition and carbon content (Buratti et al., 2019). Fluctuations in moisture content heavily influence the lower heating value (LHV) of the fuel under consideration, however, the higher heating value (HHV) is primarily a function of chemical composition (Sahoo et al., 2018). Chemical composition can be altered over the course of biodegradation as a result of inconsistent decay rates between cellulose, hemicellulose, and lignin (L. Pari et al., 2015; Skyba et al., 2013). Both increases (Lenz et al., 2015; L. Pari et al., 2015; Luigi Pari et al., 2017) as well as decreases (Hofmann et al., 2018) in gross calorific value (or HHV) due to changes in chemical composition have been noted, but were determined to be negligible in all cases.

9.2 Power Plant and Cogeneration Efficiency

Specifications and historical performance of existing power plants are obtained from the (California Energy Commission, 2018) for years 2008 to 2016. This dataset provides annual gross electricity output, net electricity output, fuel energy input, nameplate capacity, and a technology description for all of the power plants in California.

The efficiency of each power plant (η_{pp}) is calculated as

$$\eta_{pp} = \frac{Net\ energy\ generation\ (MWh)}{Primary\ Fuel\ Use\ (MMBTU)} * \frac{3.412\ MMBTU}{1\ MWh}$$

The net electricity output is used instead of the gross output so that the calculated efficiency does not include the output of onsite power plant electrical loads.

The inventory of the power plant and power plant technology type was pulled from the biomass power plant facilities databases from the California Biomass Collaborative[8] and Woody Biomass Utilization Group[9]. The facilities with unspecified power plant technology type (i.e., Big Valley Biomass Power, DTE Mt. Poso Cogen, DTE Stockton Biomass Power, Mt. Lassen Power, and Roseburg Forest Products Biomass Power) were assumed to be biomass stokers (see Table 37).

Table 37: Power Plant Characteristics Substitutions

Power Plant	Data Replacement Power Plant	Data Replacement Variables
Big Valley Biomass Power Plant	ARP Loyalton Biomass Power Plant	All Emissions Data
Covanta Delano Power Plant	Greenleaf Desert View Power Plant	All Emissions Data
Roseburg Forest Products Biomass Power Plant	SPI Burney Biomass Power Plant	SOx

The default generation efficiency and emissions for 1) current generation biomass combustion power plant, 2) current generation integrated gasification/ combustion power plant, and 3) next generation thermochemical conversion power plant were adapted from (Cooper, 2008). The efficiencies of the default 5 MW and less than 1 MW gasification power plants used the average efficiency documented in various literature (Table 39). Efficiencies used are summarized in Table 38.

Table 38: Power Plant Technology Types and Efficiency Values Used

Power Plant	Technology Type	Efficiency (η_{pp})	Source
Existing	Stoker or Fluidized Bed	varies	(California Energy Commission, 2018)
Current Generation	Stoker	0.20	(Cooper, 2008)
Current Generation	Integrated Gasification / Combustion	0.22	(Cooper, 2008)
Next Generation	Gasifier	0.28	(Cooper, 2008)
5MW	Gasifier	0.28	Average of values in Table 39
<1 MW	Gasifier	0.19	Average of values in Table 39

[8] California Biomass Facilities Reporting System, California Biomass Collaborative. https://biomass.ucdavis.edu/tools/california-biomass-facilities-reporting-system/.
[9] California Forest Products and Biomass Power Plant Map, Woody Biomass Utilization Group. https://ucanr.edu/sites/WoodyBiomass/California_Biomass_Power_Plants/.

Table 39: Literature Review of Efficiencies of Small Nameplate Power Plants

Category	Capacity in Literature	Efficiency	Source
< 1 MW	0.02 MW	5-12%	(Ahmed et al., 2019)
< 1 MW	0.5 MW	25%	(Haslinger, 2016)
< 1 MW	1 MW	16-18%	(Xiuli Yin et al., 2009)
< 1 MW	1 MW	25%	(Haslinger, 2016)
5 MW	2 MW	25%	(Simader, 2004)
5 MW	2.8 MW	33%	(Haslinger, 2016)
5 MW	3.7 MW	25%	(Haslinger, 2016)
5 MW	5.5 MW	26-28%	(Xiuli Yin et al., 2009)

To allow for characterizing emissions on a per kWh generated basis, we also estimate electrical energy output. The electrical output is calculated as

$$e = \sum_{s} \left(M_{tech}^{piles} + M_{tech}^{scattered}\right)_s \cdot (1 - DML) \cdot HHV \cdot \eta_{pp} \cdot \frac{1\ MWh}{3{,}600\ MJ}.$$

Cogeneration of process heat from biomass power plants offsets combustion of other fuels for heating. Heat from a CHP plant is assumed to offset natural gas heating in California. Emissions from the CHP power plant are calculated the same as for an electric only power plant, then the emissions associated with burning the offset amount of natural gas is subtracted from the overall emissions. Cogeneration efficiency is set to a static value of

$$\eta_{cogen} = 0.8\ .$$

This value is taken from the CPUC QF/CHP Settlement[10] minimum efficiency requirement. Note this is likely a high estimate of the actual quantity of heat being used on-site such that the calculated quantity of natural gas is likely high.

For existing power plants, the addition of heat recovery does not change the biomass conversion process and emissions, but it may change the parasitic load of the power plants with the addition of pumps or blowers. The increase in on-site energy consumption is included in the dataset of existing plants within their net energy output calculation (California Energy Commission, 2018) and, thus, no additional factors are added to the biomass power emissions equations for CHP. For generic power plants, this impact to parasitic load is not accounted for.

Note that displaced grid electricity is specifically not included in this framework. There are many different defensible power generation sources that could be applied to displaced grid electricity (grid average, marginal natural gas, marginal solar, etc.). It is up to the user to decide whether to account for displaced electricity. The desired emissions factors for displaced electricity can be multiplied by the output electrical energy and subtracted from the gross mass of each emissions species for the mobilization (use) case. Net emissions would then be calculated, then converted to CO_2e via the method described in CHAPTER 10.

[10] Commission decision (D) 10-12-035. https://www.cpuc.ca.gov/General.aspx?id=5432

9.3 Byproducts and Wastes

The unburned fuel losses (U) of the different biomass power plant technologies were referenced from the biomass inputs for the System Advisor Model specified in the technical manual (Jorgenson et al., 2011). In the technical manual, the unburned fuel losses were specified for three technologies—biomass stoker, fluidized bed combustor, cyclone combustor. For this study, the gasification technologies not specified in the technical manual (i.e., gasifier, integrated gasification and combustion) were assumed to have the same unburned fuel losses as the fluidized bed combustor technology which has the lowest unburned fuel losses. Results are shown in Table 40. Additionally, the existing Wadham Biomass Power has a suspension fired boiler and is assumed to have the same characteristics (i.e., unburned fuel percent) as a biomass stoker.

Table 40: Power Plant Unburned Fuel Fractions

Technology Type	Unburned fuel (U) (%)
Stoker	3.0
Fluidized Bed Combustor	0.25
Cyclone Combustor	3.0
Gasifier	0.25
Integrated Gasification and Combustion	0.25

Values from (Jorgenson et al., 2011).

The lifecycle emissions of solid byproducts from the power plant are not considered in the assessment. Waste products include wastewater and used oils or lubrication (see APPENDIX E for details on proposed emissions factors left to future work). Furthermore, the amounts of solid combustion byproduct of ash and char are quantified, but the lifecycle emissions of the fate of these waste products are not quantified. These waste products can be disposed of at a landfill, through incineration, or by application to soils. These additional emissions sources can be added to gross mobilization (use) case emissions results if desired.

9.4 Emissions Factors

Emissions factors for existing power plants and generic power plants of different technologies and nameplates are used. These are described in the following sections. Table of emissions factors can be found in APPENDIX E.

For all power plants, the carbon fraction values (C_g) for organic gases used are those shown in Table 41.

Table 41: Carbon Fractions of Emitted Atmospheric Species

Gas Species Containing Carbon	${}^{m_C}/_{m_g}$ (C_g)	Source
Carbon Dioxide	$\frac{12.01}{44.01}$	Ratio of molecular weights
Methane	$\frac{12.01}{16.04}$	Ratio of molecular weights
Carbon Monoxide	$\frac{12.01}{28.01}$	Ratio of molecular weights
PM10 (woody residues)	0.74	(Turn et al., 1997), Table 4
PM10 (straw residues)	0.47	
Volatile Organic Compounds (VOC) *	0.68	Calculated with data from (Gilman et al., 2015). See APPENDIX F for details.

* Applied to NMHC as well

9.4.1 Existing Power Plants

Emission rates are calculated using each power plant's historical emission rate. Total stack gas emissions are obtained from California Air Resources Board (CARB) in mass per year for between 2008 - 2016 (California Air Resources Board, 2016a), and are listed in APPENDIX E. Carbon monoxide (CO) emissions were provided by CARB via special request (see APPENDIX E for these data) as they are not reported by these sources.

The power plant emissions for existing power plants were calculated as the energy generation weighted mean in kg per MWh.

$$Energy\ Generation\ Weighted\ Mean\ Emissions = \frac{\sum Emissions\ Weight}{\sum Net\ Electricity\ Generation}.$$

The values were calculated as the total emissions of the specific emissions species divided by the total energy generation from the available CARB power plant emissions data and the available CEC power plant generator output data from 2008 to 2016. Years without either energy generation or the emissions weight data were excluded from the calculation. Big Valley Biomass Power Plant, Covanta Delano Power Plant, and Roseburg Forest Products Biomass Power Plant emissions data were processed differently due to the lack of data availability. Emissions data were filled in or replaced with the data from another power plant with similar net output efficiency (Table 37).

9.4.2 Generic and New Technology Power Plants

Emissions factors for the five different generic and new technology power plants are pulled from those sources shown in Table 42. The PM emissions are reported as an aggregated single value in (Cooper, 2008), and therefore was separated into $PM_{2.5}$ and PM_{10} using the ratio between $PM_{2.5}$ and PM_{10} from the emission data of the existing power plants used. Emissions values can be found in APPENDIX E.

Table 42: Emissions Factor Sources for Generic Power Plant Technologies

Generic Power Plant Technology	Technology Type	Emissions Factor Source
Current Gen Combustion Plant Default	Stoker	(Cooper, 2008)
Current Gen IG/Combustion Plant Default	Integrated Gasification and Combustion	(Cooper, 2008)
Next Gen Thermochemical Gasifier	Gasifier	(Cooper, 2008)
5 MW Gasifier	Gasifier	Set equal to Next Gen Thermochemical Gasifier
<1 MW Gasifier	Gasifier	Set equal to Next Gen Thermochemical Gasifier

CHAPTER 10
Life Cycle Impact Assessment

The C-BREC framework focuses specifically on air emissions with a focus on GHGs. The impact of GHGs is assessed using climate indicators as described in the following sections. All other air emissions are simply reported as mass emitted per functional unit.

Resulting climate change impacts are presented in the well-known unit of CO2 equivalent (CO2e), but the use of published GWP and GTP factors is avoided. C-BREC finds an equivalent pulse of CO2 that results in the same $\left[\frac{W}{m^2} \cdot yr\right]$ (AGWP) or $[K]$ (AGTP) as the actual emission profile. The following approach for AGWP is used:

$$CO_2e_{TH} = \frac{1}{AGWP_{CO_2,TH}^{Pulse}} \cdot \sum_{i=GHG} AGWP_{i,TH}^{Scenario}$$

where TH is the chosen time horizon, i represents each well mixed greenhouse gas (WMGHG) emitted, $AGWP_{i,TH}^{Scenario}$ is the net climate impact between the Reference and Use cases $\left[\frac{W/_{m^2} \cdot yr}{MT_{residue}}\right]$, $AGWP_{CO_2,TH}^{Pulse}$ is the climate impact at time horizon TH of a pulse of one kg of CO2 in year 1 $\left[\frac{W/_{m^2} \cdot yr}{kg_{CO_2,pulse}}\right]$, and CO_2e_{TH} is the equivalent mass of CO_2 $\left[\frac{kg_{CO_2}}{MT_{residue}}\right]$ emitted as a pulse in year 1 that would equal the climate forcing by the biomass scenario at time horizon TH. The same approach is used with the AGTP climate metric.

As recommended by (Levasseur et al., 2016), short-term climate impacts are conveyed using AGWP with a 100-year time horizon, and long-term climate impacts are conveyed using AGTP with a 100-year time horizon.[11] Different biomass mobilization scenarios can be compared in a table similar to the following:

Scenario	CO_2e (short)	CO_2e (long)
	AGWP, TH=100	AGTP, TH=100
1		
2		
⋮		
n		

[11] In addition, (Levasseur et al., 2016) recommend the use of AGWP of near-term climate forcers (NTCFs) evaluated at a time horizon of 20 years for a sensitivity analysis on the short-term impacts by WMGHGs. Given the challenge with acquiring appropriate factors for the impulse response functions of NTCFs, evaluation of their impacts is left to future work.

10.1 Climate Indicator Methodology

Two climate metrics are being considered: the Absolute Global Warming Potential (AGWP) and the Absolute Global Temperature Potential (AGTP). The common formulation of these metrics is derived from a single pulse of emissions at a single point in time. Alternatively, this project develops an "emissions scenario" approach as discussed by (Myhre et al., 2013), elaborated on by (Aamaas et al., 2012), and recently implemented in a few publications (Giuntoli et al., 2015). The result is a time-explicit AGWP and AGTP that approximates the global radiative forcing and temperature response, respectively, to a time-explicit emissions profile $E_i(t)$ generated by the C-BREC model.

The two climate metrics AGWP and AGTP are chosen to reflect short term and long term impacts respectively. As recommended by (Levasseur et al., 2016), the AGWP of well-mixed greenhouse gases (WMGHGs) evaluated at a time horizon of 100 years is useful for communicating short-term impacts, and the AGTP of WMGHGs evaluated at a time horizon of 100 years is useful for communicating long-term impacts.

10.1.1 The Emissions Profile $\boldsymbol{E_g(t)}$

The emissions profile $E_g(t)$ from C-BREC has the units of ${}^{kg_i}/_{yr \cdot MT_{residue}}$. The subscript g refers to individual GHG species. $E_g(t)$ is not linear.

10.1.2 Emissions Scenario AGWP and AGTP

Following the approach described in Section 3.3 of (Aamaas et al., 2012), the "emissions scenario" climate metrics are obtained with a convolution of $E_g(t)$ and the associated metric for a pulse emission:

$$AGWP_g^{Scenario}(t) = \left(E_g * AGWP_g^{Pulse}\right)(t) = \int_0^t E_g(t')AGWP_g^{Pulse}(t-t')dt'$$

$$AGTP_g^{Scenario}(t) = \left(E_g * AGTP_g^{Pulse}\right)(t) = \int_0^t E_g(t')AGTP_g^{Pulse}(t-t')dt'$$

where the definitions for $AGWP_g^{Pulse}$ and $AGTP_g^{Pulse}$ are found in APPENDIX G. This follows the approach by (Giuntoli et al., 2015) which names $AGTP_g^{Scenario}(t)$ as Instantaneous Surface Temperature Response SRT(i). (Cherubini et al., 2013) also define $AGTP_g^{Scenario}(t)$ and named this metric the Sustained Absolute Global Temperature Potential SAGTP.

The resulting units for the emissions scenario metrics are as follows:

$$AGWP_g^{Scenario}(t) \rightarrow \left[\frac{kg_g}{yr \cdot MT_{residue}} \cdot \frac{\frac{W}{m^2} \cdot yr}{kg_i} \cdot yr\right] = \left[\frac{\frac{W}{m^2} \cdot yr}{MT_{residue}}\right]$$

$$AGTP_g^{Scenario}(t) \rightarrow \left[\frac{kg_g}{yr \cdot MT_{residue}} \cdot \frac{K \cdot yr}{kg_i}\right] = \left[\frac{K}{MT_{residue}}\right]$$

10.1.3 Calculation of the Scenario Climate Metrics

To implement the convolution integral, $E_g(t)$ is first represented as a piecewise constant function at time intervals of one year over the time period $1 \le t \le 100$. This allows treatment of $E_g(t)$ as a constant at each one year time step such that it can be pulled out of the integral:

$$AGWP^{Scenario}(t) = \sum_{s=0}^{t-1} E_s \int_s^{s+1} AGWP^{Pulse}(t - t')dt'$$

for each gas g. The integral of $AGWP^{Pulse}(t - t')$ is solved as an indefinite integral, then pre-calculated over all values of t and s to develop a 2-D lower triangular matrix of static values independent of the emissions profile (see APPENDIX G for details). Standard matrix multiplication is then used to complete the convolution:

$$AGWP^{Scenario}(t) = \sum_{s=0}^{t-1} AGWP_{ts}^{Pulse} E_s$$

where

$$AGWP_{ts}^{Pulse} = \begin{cases} \int_s^{s+1} AGWP^{Pulse}(t - t')dt' & 0 \le s \le t - 1 \\ 0 & s \ge t \end{cases}$$

The same approach is used for the $AGTP$ metrics.

CHAPTER 11
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APPENDIX A
Forest Biomass Resource Methodology Details

A.1 Clustering Analysis Description

The spatial variability in residue base was simplified down to 177 representative stands by Natural Resources Spatial Informatics Group (NRSIG) at the University of Washington in order to facilitate the LCI emissions analysis conducted by CORRIM (see APPENDIX E, and associated separate report by CORRIM). This section discusses the methodology used to create these representative stands.

First, all GNN stands were classified into species groups by basal area. Stands with greater than 80% basal area in a single species were classified by that species (i.e. “DF” for Douglas fir). Stands with less than 80% were classified as mixed (prepended with an “M”), followed by the species with the majority or plurality of basal area, followed by other species with at least 20% basal area in descending order (i.e. “MDF” for mixed Douglas fir with minor species, “MDFBO” for mixed Douglas fir with a significant black oak component (> 20% by basal area)). All species groups that made up at least 1% of forest area in California were identified. The remaining species groups were generalized by first keeping the majority/plurality species but lumping minor species into hardwoods or softwoods (i.e. “MDFOS” for mixed Douglas fir with other softwoods or “MDFOH” for mixed Douglas fir with other hardwoods). Finally, species groups that still didn’t make up at least 1% of forest area were further generalized into “MOSOH” (mixed other softwoods with other hardwoods) or “MOHOS” (mixed other hardwoods with other softwoods).

Next, for each species group, k-means clustering was used to group stands with similar structural attributes. Centering and scaling was used to normalize TPA, QMD, stand height, snag tons per acre, and downed woody debris tons per acre. “Elbow” plots of within groups sums-of-squares were produced using 1 to 15 clusters, and the “optimal” number of clusters was identified for each species group.

Finally, for each species-structure group, a representative stand was identified. This was the stand with the minimum Euclidean distance from the mean values in normalized space. A total of 177 groups/ representative stands were identified.

Table 43: Summary and Count of Representative Stand Dominant Tree Species

FREQUENCY	DomSpp	# sub-groups
29563	PP	4
19011	DF	4
13154	MOS	5
11887	MWFOS	5
11806	OS	5
10748	MOSOH	5
10570	MPPOS	4
10096	MDFOS	5
9636	JP	5
8950	MICOS	5
8642	None	
6776	WF	5
6412	BO	6
5310	MDF	5
5238	MJPOS	4
4571	MOH	4
4363	MBOOS	4
3941	MRFOS	5
3889	MOHOS	4
3849	OH	6
3446	CY	4
3137	MDFOH	5
3135	BL	3
2894	WJ	4
2865	RF	5
2770	MWF	5
2552	MCYOS	4
2294	LP	4
2150	MPP	5
2123	MBOOH	4
2088	MDFBO	5
1827	MLPOS	5
1419	PM	4
1282	MDFTO	5
1279	MTOOS	5
785	LO	4
737	MBLOH	3
646	MGPOH	4
331	MBLGP	3
31	MBLOS	5

Calculated using data generated by NRSIG.

Graphics demonstrating the derivation of the 177 representative stands are included as a separate document named “Appendix A.1 Cluster Analysis Plots.pdf”.

A.2 Summary of 20 Years of Timber Harvest Plans and Non-Industrial Timber Management Plans

Timber harvest plans (THPs) and non-industrial timber management plans (NTMPs) were analyzed in order to understand how the C-BREC silvicultural treatment definitions correlated with typical activity in the state. In addition, a results analysis of the C-BREC model was conducted for all THPs and NTMPs that occurred in the state over the last five years. Data in this appendix is intended to provide insight on typical forestry activity in the state.

Data for timber harvest plans (THPs) and non-industrial timber management plans (NTMPs) were obtained from the CalFire Forest Practice Open Data Hub[12]. Data were downloaded for a 20 year period ranging from 1997 through 2017. A summary by region and treatment type are shown in Table 44.

Table 44: Summary of THPs and NTMPs in California

Region	Silvicultural Type	THP			NTMP		
		Total Count	Total Acres	Acres / Project	Total Count	Total Acres	Acres / Project
Coast	Clear Cut	19,783	194,888	9.9	46	1,419	30.9
	Forest Health	2,297	33,384	14.5	664	10,183	15.3
	Heavy Thin	26,786	421,346	15.7	3,316	254,552	76.8
	Light Thin	5,214	139,441	26.7			
	Unknown	11,314	44,457	3.9	370	5,304	14.3
Coast South	Clear Cut	8	297	37.1			
	Forest Health	20	444	22.2			
	Heavy Thin	7	291	41.5			
Northern	Clear Cut	24,919	533,704	21.4	24	773	32.2
	Forest Health	1,792	54,240	30.3	28	695	24.8
	Heavy Thin	13,166	986,506	74.9	440	59,669	135.6
	Light Thin	8,945	470,276	52.6			
	Unknown	3,400	50,616	14.9	119	4,555	38.3
Southern	Clear Cut	4,829	78,975	16.4	27	1,820	67.4
	Forest Health	322	5,944	18.5	45	918	20.4
	Heavy Thin	3,354	126,168	37.6	205	24,190	118.0
	Light Thin	1,619	50,748	31.3			
	Unknown	1,764	16,184	9.2	114	1,968	17.3

The silvicultural type was defined using a cross-walk with the silvicultural activity specified in the logged THPs and NTMPs. This cross-walk is detailed in Table 45.

[12] https://forest-practice-calfire-forestry.hub.arcgis.com/, retrieved March, 2018.

Table 45: Silvicultural Type Cross-Walk with THPs and NTMPs

Silviculture Type	Logged Silvicultural Activity
Clear Cut	Clear Cut Fuel Break Road Right of Way Sanitation Salvage Seed Tree Seed Cut
Forest Health	Conversion Rehabilitation – Overstocked Special Treatment Area Substantially Damaged Timberland
Heavy Thin	Commercial Thin Group Selection Selection Transition Unevenaged Management Variable Retention
Light Thin	Seed Tree Removal / Commercial Thin Seed Tree Removal Cut Shelterwood Prep Cut Shelterwood Removal / Commercial Thin Shelterwood Removal Cut
Unknown	All others

A.3 Cross-Walk Between Forest Practice Rules and C-BREC Treatments

An analysis of reported biomass generated from THPs was conducted and compared with the modeled biomass generated by the NRSIG resource base. THP shapefiles were used to extract biomass for the same region in the NRSIG data across 13 different modeled silvicultural treatments (as listed in Table 3), and compared with reported biomass. The resulting cross-walk is shown in Table 46. This table can be used to guide the selection of an appropriate C-BREC silvicultural treatment when modeling past or expected silvicultural activity.

Table 46: Cross-Walk between C-BREC Treatments and Forest Practice Rules Treatments

Silvicultural Treatment (TPH)	Residue Base (low)	Residue Base (high)
Clearcut	RM100	RM100
Commercial Thin	TFB20	TFB60
Selection	TP20	TP80
Group Selection	TP20	TP80
Alternative Prescription	TP20	TP80
Shelterwood Removal Cut	TFA20	TFA60
Transition	TP20	TP60
Variable Retention	TFB60	TFB80
Sanitation-Salvage	TP20	TP80
Seed Tree Removal Cut	TFA20	TFA60

A.4 Tree Species List

The list of species included in the biomass resource assessment is shown in Table 47. These species are used to calculate decay parameters, and higher heating value. These values are calculated using a mass-weighted approach at a 30x30 meter resolution (resolution of the NRSIG data set).

Table 47: Forest Tree Species List

Common Name	Scientific Name	Biomass Group
subalpine fir	Abies lasiocarpa	True fir/hemlock
apple species	Malus	Mixed hardwood
quaking aspen	Populus tremuloides	Aspen/alder/cottonwood/willow
bristlecone pine	Pinus aristata	Pine
bigcone Douglas-fir	Pseudotsuga macrocarpa	Douglas-fir
buckeye, horsechestnut	Aesculus	Mixed hardwood
blue oak	Quercus douglasii	Hard maple/oak/hickory/beech
bigleaf maple	Acer macrophyllum	Soft maple/birch
California black oak	Quercus kelloggii	Hard maple/oak/hickory/beech
Bishop pine	Pinus muricata	Pine
Brewer spruce	Picea breweriana	Spruce
Cascara buckthorn	Frangula purshiana	Mixed hardwood
California buckeye	Aesculus californica	Mixed hardwood
Northern California walnut	Juglans hindsii	Mixed hardwood
Modoc cypress	Cupressus bakeri	Cedar/larch
cherry	Prunus	Juniper/oak/mesquite
California juniper	Juniperus californica	Juniper/oak/mesquite
chinkapin oak	Quercus muehlenbergii	Hard maple/oak/hickory/beech
California laurel	Umbellularia californica	Mixed hardwood
California nutmeg	Torreya californica	True fir/hemlock
Coulter pine	Pinus coulteri	Pine
cypress species	Cupressus	Cedar/larch
black cottonwood	Populus balsamifera ssp. trichocarpa	Aspen/alder/cottonwood/willow
canyon live oak	Quercus chrysolepis	Hard maple/oak/hickory/beech
Douglas-fir	Pseudotsuga menziesii	Douglas-fir
Pacific dogwood	Cornus nuttallii	Mixed hardwood
desert ironwood	Olneya tesota	Juniper/oak/mesquite
Emory Oak	Quercus emoryi	Hard maple/oak/hickory/beech
Engelmann oak	Quercus engelmannii	Hard maple/oak/hickory/beech
Engelmann spruce	Picea engelmannii	Spruce
Fremont cottonwood	Populus fremontii	Aspen/alder/cottonwood/willow
Oregon ash	Fraxinus latifolia	Mixed hardwood
foxtail pine	Pinus balfouriana	Pine
Great Basin bristlecone pine	Pinus longaeva	Pine
giant chinquapin	Chrysolepis chrysophylla	Mixed hardwood
grand fir	Abies grandis	True fir/hemlock
California foothill pine	Pinus sabiniana	Pine
giant sequoia	Sequoiadendron giganteum	Cedar/larch
honey mesquite	Prosopis glandulosa var. torreyana	Juniper/oak/mesquite
hawthorn species	Crataegus	Mixed hardwood
incense cedar	Calocedrus decurrens	Cedar/larch

Common Name	Scientific Name	Biomass Group
interior live oak	Quercus wislizeni	Hard maple/oak/hickory/beech
Jeffrey pine	Pinus jeffreyi	Pine
knobcone pine	Pinus attenuata	Pine
subalpine larch	Larix lyallii	Cedar/larch
limber pine	Pinus flexilis	Pine
California live oak	Quercus agrifolia	Hard maple/oak/hickory/beech
lodgepole pine	Pinus contorta	Pine
Pacific madrone	Arbutus menziesii	Mixed hardwood
curl-leaf mountain mahogany	Cercocarpus ledifolius	Juniper/oak/mesquite
mountain hemlock	Tsuga mertensiana	True fir/hemlock
Rocky Mountain maple	Acer glabrum	Juniper/oak/mesquite
Monterey cypress	Cupressus macrocarpa	Cedar/larch
Monterey pine	Pinus radiata	Pine
Narrowleaf cottonwood	Populus angustifolia	Aspen/alder/cottonwood/willow
noble fir	Abies procera	True fir/hemlock
oak, deciduous species	Quercus	Hard maple/oak/hickory/beech
Other Live/Dead Hardwood		Mixed hardwood
Oregon crabapple	Malus fusca	Mixed hardwood
MacNab's cypress	Cupressus macnabiana	Cedar/larch
Other tree species		Mixed hardwood
ash species	Fraxinus	Mixed hardwood
paper birch	Betula papyrifera	Soft maple/birch
Port Orford cedar	Chamaecyparis lawsoniana	Cedar/larch
plum/cherry species	Prunus	Mixed hardwood
singleleaf pinyon	Pinus monophylla	Pine
ponderosa pine	Pinus ponderosa	Pine
Pacific yew	Taxus brevifolia	True fir/hemlock
red alder	Alnus rubra	Aspen/alder/cottonwood/willow
western red cedar	Thuja plicata	Cedar/larch
California red fir	Abies magnifica	True fir/hemlock
Rocky Mountain juniper	Juniperus scopulorum	Juniper/oak/mesquite
black locust	Robinia pseudoacacia	Juniper/oak/mesquite
redwood	Sequoia sempervirens	Cedar/larch
Sargent's cypress	Cupressus sargentii	Cedar/larch
Southern California walnut	Juglans californica	Mixed hardwood
Pacific silver fir	Abies amabilis	True fir/hemlock
bristlecone fir	Abies bracteata	True fir/hemlock
screwbean mesquite	Prosopis pubescens	Juniper/oak/mesquite
sugar pine	Pinus lambertiana	Pine
Sitka spruce	Picea sitchensis	Spruce
Scotch pine	Pinus sylvestris	Pine
Scouler's willow	Salix scouleriana	Aspen/alder/cottonwood/willow
California sycamore	Platanus racemosa	Mixed hardwood
tree of heaven	Ailanthus altissima	Mixed hardwood
tanoak	Lithocarpus densiflorus	Mixed hardwood
Utah juniper	Juniperus osteosperma	Juniper/oak/mesquite
velvet ash	Fraxinus velutina	Mixed hardwood
vine maple	Acer circinatum	Mixed hardwood
valley oak	Quercus lobata	Hard maple/oak/hickory/beech

Common Name	Scientific Name	Biomass Group
white alder	Alnus rhombifolia	Aspen/alder/cottonwood/willow
whitebark pine	Pinus albicaulis	Pine
Washoe pine	Pinus washoensis	Pine
White fir	Abies concolor	True fir/hemlock
western hemlock	Tsuga heterophylla	True fir/hemlock
willow species	Salix	Aspen/alder/cottonwood/willow
western juniper	Juniperus occidentalis	Juniper/oak/mesquite
western larch	Larix occidentalis	Cedar/larch
walnut species	Juglans	Mixed hardwood
Oregon white oak	Quercus garryana	Hard maple/oak/hickory/beech
western white pine	Pinus monticola	Pine
water birch	Betula occidentalis	Soft maple/birch
Alaska cedar	Chamaecyparis nootkatensis	Cedar/larch

A.5 Forest Resource Methodology Document

The Natural Resources Spatial Informatics Group (NRSIG) at the University of Washington developed the underlying forest biomass resource for the C-BREC model. The methodology report by NRSIG is included below.

METHODS TO DEVELOP THE FORESTLAND DATABASE FOR THE CALIFORNIA BIOPOWER IMPACTS PROJECT

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W NRSIG

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Precision Forestry Cooperative
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July 5, 2018

CONTENTS

1 INTRODUCTION

Two Tasks for the California Biopower Impacts Project are supported by the methodologies and datasets described in this document. First, an estimate of forest conditions and residual timber harvest biomass for a wide range of treatments was developed for Task 5: California Residual Biomass-To-Energy Carbon Accounting Tool (CARBCAT). All treatments were simulated at all locations and a transportation analysis was also developed to over 100 facilities. It is intended for the user of CARBCAT to select treatments and locations that result in a useful analysis.

The primary inputs for characterizing forest conditions across California included the 2012 Gradient Nearest Neighbor dataset and disturbance layers for timber harvest, fire, and mortality events. Forest conditions were updated to 2018 by simulating disturbances and growth in annual time steps in the Forest Vegetation Simulator. A set of silvicultural treatments was implemented on the updated forest conditions to bracket potential management intensities ranging from no action to thinning to clearcut. For each treatment, residual standing and harvested tree biomass was calculated for stem, branches, foliage, and bark categories. Rasters summarizing these results were provided for each treatment.

Inputs for the transportation analysis included potential facility locations and a road network layer. ArcGIS Network Analyst was used to calculate travel times and distances to each facility from locations in California. Results were converted into rasters that align with the treatment summary rasters.

Second, a harvested parcels dataset was developed for Task 4: Residual Biomass-To-Energy Life Cycle Emissions Accounting Framework. Parcels were harvested to match historical harvest levels. Treatments were selected by county and owner to reflect typical forest management as identified in timber harvest plans and activities datasets.

Inputs for the parcel analysis included parcel data for each county in California and streams, waterbodies, and wetlands layers. Buffers were calculated for each water feature to identify riparian and upland management zones. A large intersect analysis was then conducted on the parcel, updated forest condition, and management zone layers. The resulting layer identified owner, forest condition, and management zone for each location in California. Appropriate treatments were identified for each owner class, and treatments were restricted to upland zones with appropriate forest conditions. Residual standing and harvested tree biomass are provided for each harvested parcel.

This analysis builds on two related projects. The big data approach used in this analysis was first developed for the Washington Forest Biomass Supply Assessment project. Much of the parcel, ownership, water, and forest data used in this study was developed for the Waste to Wisdom project, which expanded the scope the Washington Forest Biomass Supply Assessment to include Oregon and California. These projects are described first.

2 RELATED PROJECTS

2.1 WASHINGTON FOREST BIOMASS SUPPLY ASSESSMENT

The Washington Forest Biomass Supply Assessment integrated tax parcel, water, and forest condition datasets to estimate residual timber harvest biomass in Washington state (Perez-Garcia et al., 2012).

The project was funded by the Washington State Department of Natural Resources. The project developed a high-resolution spatially explicit database to identify owner, forest class, and management zone. Owner surveys were conducted to inform modeling of harvest techniques and biomass recovery. Silvicultural treatments were modeled, and harvests were simulated on parcels to match historical harvest levels for counties and owner classes. Most of the methods developed for the Washington Forest Biomass Supply Assessment remain applicable for this project.

2.2 Waste to Wisdom

The Waste to Wisdom project investigated the conversion of forest residues into biofuels and other products through new collection techniques and localized processing facilities. It was funded by the U.S. Department of Energy Biomass Research and Development Initiative program. For this project, a new spatially explicit database was developed for Washington, Oregon, and California using the methods established previously (Oneill et al., 2017). The database supported supply chain optimization using mobile processing units, demand curve estimation of locally produced biomass products, local air quality assessments of biomass burning, and a life-cycle assessment of biomass recovery. The tax parcel, ownership, water, and forest condition datasets obtained for the Waste to Wisdom project form the starting point for this analysis.

2.3 COMPARISON TO RELATED PROJECTS

Methodologies between this project and related projects differ in a few ways. First, the Washington Forest Biomass Supply Assessment and Waste to Wisdom projects only provided summarized results at the parcel level. This project provides treatment summaries at the 30 meter raster cell resolution for the CARBCAT tool and parcel summaries for the Residual Biomass-To-Energy Life Cycle Emissions Accounting Framework. Second, previous projects used ownership, management zone, and forest conditions to restrict treatment results to a set that was representative of typical management activities. This project summarized the full range of treatments for all owners at all locations in California. Third, each project differed in how the Forest Vegetation Simulator (FVS) was incorporated. The Washington Forest Biomass Supply Assessment used FVS to updated forest conditions to a common year by simulating timber harvests to match tabular data by county and owner class, then simulated treatments 30 years into the future. The Waste to Wisdom project did not use FVS to update forest conditions or simulate future treatments. This project used FVS to update forest conditions using spatially explicit timber harvest, fire, and tree mortality disturbance layers, but did not simulate growth or treatments into the future. Treatments implemented on the updated forest conditions are reasonably representative for a 10 year time period, after which addition growth should be accounted for. Fourth, the previous projects used recovery and economic factors to determine the amount of residual harvest biomass left scattered in the woods, piled at the landing, and delivered to processing facilities. This project does not make use of these factors but does provide the ownership, slope, and transportation data necessary to allow them to be applied.

3 Forestland Database

The Forestland Database was developed by intersecting spatial layers for tax parcels, forest condition, and riparian management zone. This intersection divides California into approximately 112 million segments, with a maximum segment size of 900 square meters. To process the large dataset, custom scripts were written with the ArcPy package for Python (ESRI, 2016; Python Software Foundation). ArcGIS version 10.5 and Python version 2.7 were used for this analysis. A description of the input layers and processing steps are provided next. Prior to the intersection analysis, the forest condition dataset (GNN) was updated with recent timber harvests and disturbance events. This process is described in the following section.

3.1 Parcels and Ownership

A tax parcel layer was obtained for California as part of the Waste to Wisdom project. Tribal and publicly owned parcels were identified using the Protected Areas Database of the United States (PADUS) layer (US Geological Survey 2012). Private industrial parcels were identified using a layer provided by the California Department of Forestry and Fire Protection (2015). Other parcels were assumed to be private non-industrial. All parcels were classified as either private non-industrial, private industrial, California Department of Forestry and Fire Protection, state other, tribal, Forest Service, Bureau of Land Management, or federal other. Permanently unmanaged parcels were also identified using the PADUS layer.

3.2 Forest Condition (GNN)

The Gradient Nearest Neighbor (GNN) dataset is produced by the Landscape Ecology, Modeling, Mapping & Analysis research group, a partnership of the USDA Forest Service, Pacific Northwest Research Station and the Department of Forest Ecosystems and Society, Oregon State University. GNN is a spatially explicit forest inventory covering Washington, Oregon, and California. It is developed by imputing inventory plots from Landsat imagery, topographic attributes, climate and other environmental variables as predictor variables (Ohmann and Gregory, 2002). GNN data is distributed as a raster of forest class identification number (FCID) that corresponds to an inventory plot, and a database of tree, snag, and coarse woody debris records suitable for simulation and analysis with the Forest Vegetation Simulator. The GNN raster was converted into polygons during the intersection process for the Forestland Database.

3.3 Waterbodies, Watercourses, and Wetlands

Watercourses and waterbodies spatial layers were obtained from the California Department of Fish and Wildlife (2015). The National Wetlands Inventory was used to locate wetlands (US Fish and Wildlife Service, 2016). Water features were buffered by 150 feet to delineate riparian management zones.

3.4 Slope

During the intersection process, the average slope was calculated for each segment. A 1 arc second (approximately 30 meter) digital elevation model was obtained from the 3D Elevation Program (US Geological Survey, 3D Elevation Program, 2017). A slope raster was created using the ArcGIS Spatial Analyst Slope tool, and the Zonal Stats tool was used to calculate average slope for each polygon.

4 Updating GNN Forest Inventory

The most recent GNN imputation maps are based on Landsat imagery from 2012. Forest disturbance events and growth occurring after 2012 are not accounted for. To address this, timber harvests and natural disturbances were simulated in the Forest Vegetation Simulator (FVS) growth model from 2012 through 2017 (Dixon, 2002). Fires were simulated with the Fire and Fuels Extension for FVS (Rebain, 2010). FVS variants covering California are listed in Table 1.

Table 1. FVS variants covering California and used in this analysis.

Code	FVS Variant	Description
1	CA	Inland California and Southern Cascades
2	CR	Central Rockies
3	NC	Klamath Mountains
4	SO	South Central Oregon and Northeast California
5	WS	Western Sierra Nevada

Spatial datasets were identified for timber harvest, fire, and tree mortality. These layers were overlaid on the original GNN raster, along with the FVS variant layer, and the unique combination of growth and disturbances to be simulated with each forest class was determined. The types of each disturbance are described below. Simulating growth and disturbances in FVS is then described in the following section.

4.1 Timber Harvest

Timber harvest plans for private industrial and non-industrial owners are available from the California Department of Forestry and Fire Protection (California Department of Forestry and Fire Protection Timber Harvest Plans 2018). These plans include sale boundaries, year completed, and the silvicultural treatment applied. Silvicultural treatments were classified into reforestation, salvage, pre-commercial thin, commercial thin, shelterwood thin, seed tree thin, overstory removal, clearcut, and uneven-aged management. These treatments are described in the California Forest Practices Rules and Act (California Department of Forestry and Fire Protection 2018). Each treatment category has a range of allowable harvest amounts. The most common harvest parameters from past timber harvest plans were used as the quantitative definition for each category, shown in Table 2.

Forest Service silvicultural activities are provided in a number of spatial datasets covering reforestation, timber stand improvement, fuel treatment reduction, and timber harvests (2018). For this analysis, treatments were first classified into the nine classes listed in Table 2. Where multiple treatments occurred, the most intensive treatment was assigned.

No significant amount of timber harvest activity occurred in other ownerships during the analysis period. For reference, Table 3 lists the reported acres by owner, treatment type, and year. Caution is required when interpreting the table. First, the Forest Service commonly reports the same activity in multiple datasets (i.e. a thin appears in both the Hazardous Fuels Reduction and Timber Harvest datasets). This double counting is accounted for in the GNN updating process but not in Table 3. Second, the regeneration category for private industrial and non-industrial owners in Table 3 likely reports only those acres of regeneration not associated with another silvicultural treatment. Regardless, for this analysis, regeneration was simulated in FVS following all shelterwood, seed tree, and clearcut treatments.

Table 2. Silvicultural treatments used to update GNN.

Code	Treatment	Description
1	Regeneration	Plant 435 trees per acre
2	Salvage	Remove all dead trees and plant 435 trees per acre
3	Pre-commercial thin	Thin from below to 300 trees per acre and remove all dead trees and hardwoods
4	Commercial thin	Thin from below to 100 sq ft of basal area and remove all dead trees
5	Shelterwood thin	Thin proportionally to 30 sq ft of basal area above 18 inches and 45 sq ft of basal area below 18 inches and plant 435 trees per acre
6	Seed tree thin	Thin from below, minimum DBH of 4 inches, to 30 sq ft of basal area and plant 435 trees per acre
7	Overstory removal	Remove all trees greater than 18 inches and thin from below to 100 sq ft of basal area
8	Clearcut	Remove all trees (0 trees per acre) and plant 435 trees per acre
9	Uneven-aged management	Thin proportionally to 100 sq ft of basal area and plant 435 trees per acre

Table 3. Silviculture treatment acres by owner, type, and year.

Private Industry						
	2012	**2013**	**2014**	**2015**	**2016**	**2017**
Reforestation	1,279	1,688	563	863	272	94
Salvage	13,984	1,464	4,920	3,308	4,287	516
Pre-commercial thin	-	-	53	-	-	114
Commercial thin	10,115	7,972	4,375	4,737	2,013	291
Shelterwood thin	150	-	142	-	71	-
Seed tree thin	526	490	503	361	39	68
Overstory removal	25,059	21,672	10,551	13,160	4,497	1,779
Clearcut	90,302	96,257	52,789	77,737	56,853	14,084
Uneven-aged management	6,449	9,209	7,478	8,023	1,233	469
Private Non-Industrial						
	2012	**2013**	**2014**	**2015**	**2016**	**2017**
Reforestation	402	-	98	-	91	-
Salvage	60	-	-	-	-	344
Pre-commercial thin	-	-	-	-	-	-
Commercial thin	28	-	-	94	-	78
Shelterwood thin	-	-	-	-	-	-
Seed tree thin	-	-	-	-	-	-
Overstory removal	-	-	-	-	-	-
Clearcut	7,226	1,544	3,612	2,655	5,556	2,161
Uneven-aged management	-	-	229	-	794	-
Forest Service						
	2012	**2013**	**2014**	**2015**	**2016**	**2017**
Reforestation	7,288	6,739	5,711	13,652	12,039	13,739
Salvage	1,680	230	294	299	1,542	104
Pre-commercial thin	39,132	35,769	32,012	37,134	24,680	24,523
Commercial thin	50,300	49,125	60,329	46,833	62,437	54,943
Shelterwood thin	-	-	-	-	-	-
Seed tree thin	36	601	5,223	424	2,351	74
Overstory removal	131	-	13	-	-	-
Clearcut	784	430	2,342	5,808	8,172	2,802
Uneven-aged management	-	-	-	-	-	-

4.2 Fire

Fire datasets for years 2012 through 2015 were available from the Monitoring Trends in Burn Severity (MTBS) program (US Geological Survey and USDA Forest Service Geospatial Technology and Applications

Center, 2017). This interagency program maps fire perimeters and burn severity at 30 meter resolution using Landsat data (Eidenshink et al., 2007). Burns are classified into low, moderate, and high severity. Low severity burns may kill 50% of sapling-size trees and up to 25% of intermediate and overstory trees. High severity burns kill greater than 75% of overstory trees. The moderate class is described as transitional in magnitude between the other classes.

MTBS data was not available for 2016 and 2017. For Forest Service land in 2016, fire severity was determined using the Rapid Assessment of Vegetation Condition after Wildfire (RAVG) dataset (USDA Forest Service Geospatial Technology and Applications Center, 2017). The RAVG dataset estimates the percentage of basal area loss following wildfire. This data was classified into low, moderate, and high severity classes matching those from the MTBS data: less than 25% mortality, 25-75% mortality, and greater than 75% mortality for low, moderate, and high severity, respectively.

For non-Forest Service land in 2016 and all ownerships in 2017, only fire perimeter data was available. Datasets were downloaded from the USGS Geospatial Multi-Agency Coordination website (https://www.geomac.gov/). Within these fire perimeters, high severity fires were assumed. Table 4 reports the acres of low, moderate, high, and unknown fire severity by year.

Table 4. Wildfire acres by fire severity class and year.

Fire Severity Class	2012	2013	2014	2015	2016	2017
Low	361,638	195,370	170,808	293,163	50,569	0
Moderate	195,753	173,882	162,486	216,646	42,980	0
High	96,622	109,834	158,816	156,421	215,541	0
Unknown	0	0	0	0	129,692	1,090,673

Quantitative definitions for fire severity classes are provided in Table 5. Wind speed, moisture, and temperature are model variables used by FFE to adjust fire behavior. The values listed in Table 5 correspond to the default low, moderate, and high severity fire conditions as described in the FFE documentation. A limited examination of simulation results was conducted to determine that output mortality reflected input classification ranges.

Table 5. Parameters to simulate fire in FFE by fire severity class.

Code	Severity Class	Wind Speed	Moisture	Temperature
1	Low	6	3	60
2	Moderate	6	2	70
3	High	20	1	80

4.3 Tree Mortality

Tree mortality spatial datasets were obtained from the California Tree Mortality Task Force (http://www.fire.ca.gov/treetaskforce/). Annual mortality polygons with estimated severity have been developed from aerial surveys conducted by the USDA Pacific Southwest Region Forest Health

Protection staff. For this analysis, annual mortality was summed from 2012 to 2017 except where a silvicultural treatment, moderate severity fire, or high severity fire occurred. At those locations, mortality was summed only for years later than the disturbance. This assumes dead trees were removed or knocked over during a silvicultural treatment or consumed by the fire. Mortality was then classified into low, moderate, and high severity classes based on threshold values in Table 6. Because the mortality was estimated from an airplane, it is assumed the surveys were of overstory trees. Therefore dead TPA simulation targets are for trees greater than 4 inches DBH.

Table 6. Tree mortality class and dead tree simulation target definitions.

Code	Severity Class	Dead Trees Per Acre	FVS Target Dead TPA
1	Low	10 - 30	20
2	Moderate	30 - 80	50
3	High	>= 80	110

4.4 Treatment Order

It was possible for more than one disturbance to occur at a single location during the update years. For tree mortality, this was accounted for as described in the Tree Mortality section above and in the FVS modeling. After summing tree mortality over the years, it was assumed to represent 2018 conditions. Between silvicultural treatment and fire, order was determined from the datasets, with options including silviculture before fire, fire before silviculture, or both treatments occurring during the same year. In the last case, order was determined by FVS internal program execution, with silvicultural treatments simulated before fire.

Because FVS always simulates silvicultural treatments before fire within a growth cycle, two growth cycles were used to update GNN from 2012 to 2018. If both silviculture and fire occurred during a simulation, and not during the same year, the first disturbance was simulated in 2012, then the inventory was grown to 2015. The second disturbance was then simulated in 2015, and the inventory was grown to 2018. If both occurred in the same year or only one occurred, the disturbances were simulated in 2015. Tree mortality was always simulated in 2018. Table 7 lists the treatment order possibilities.

Table 7. Treatment order definitions.

Code	Description
1	Silviculture and fire occur in the same year
2	Silviculture occurs before fire
3	Fire occurs before silviculture

4.5 Example GNN Update Table

Table 8 provides an example intermediate result from the update process described above. Tables 1, 2, 5, 6, and 7 can be referenced to translate the codes. The FCID column provides the initial GNN forest class identification number in 2012. For FCID 69907 (row 1), the Inland California and Southern Cascades variant was used to simulate a moderate severity fire in 2012, followed by a pre-commercial thin in 2015. After growing the inventory to 2018, additional mortality was simulated if necessary to equal 50 dead trees per acre greater than 4 inches DBH. Finally, a new FCID was created for the unique combination of FCID, growth, and disturbance. The update process resulted in 226,203 unique forest classes in 2018.

Table 8. Example intermediate result from the GNN update process.

FCID	FVS Variant	Silviculture	Fire	Tree Mortality	Treatment Order	New FCID
69907	1	3	2	2	3	351732796
102192	1	7	1	1	3	484613032
106385	1	3	3	1	2	520992807
139505	1	7	1	1	3	579903032
77884	1	7	2	1	3	376523048

4.6 Forest Vegetation Simulator

Simulations were performed with FVS for each set of values in the update table (part of which is presented in Table 8). Default growth model values (location, habitat code, slope, aspect, elevation, site index, maximum stand density index) were used for each variant. Standing and cut tree list tables were parsed from the main FVS output files providing tree species, DBH, height, board foot and cubic foot volumes, and trees per acre expansion factor. The Detailed Snag Report, Down Woody Debris Cover Report, Down Woody Debris Volume Report, and All Fuels Report were obtained from FFE. Field descriptions and units are available for each report in the FFE documentation or the User Guide to the Database Extension (Crookston et al., 2003).

4.7 Updated GNN Raster

A new raster was created that provides the updated GNN forest class (FCID) at each location in California in 2018. The FCID provides the relationship to the simulated tree, snag, and course woody debris data from FVS. The GNN update process resulted in an identical data structure to the original GNN dataset.

5 Simulating Treatments

5.1 Treatment Descriptions

Fourteen treatments were simulated on each 2018 GNN FCID. Treatments were simulated on all FCID's, including those which would not be feasible for economic or operational reasons. For each treatment, a harvested (or cut) and residual standing tree list was created. The harvested tree list represents those trees that would be removed during the treatment. The residual tree list represents those trees that would be left standing following the treatment.

First, no action and clearcut treatments were simulated for each FCID. No action removed no trees and clearcut removed 100% of the trees. Next, three sets of treatments were simulated, each removing 20, 40, 60, and 80% of the basal area. To achieve these targets, trees were removed solely on the basis of DBH without preference for species. The first set removed trees from below by DBH. This removed the smallest trees (by DBH) first until the basal area removal target was achieved. The second set of treatments removed trees proportionally by DBH. This removed an equal proportion of each tree in the tree list across the range of DBH's in the stand until the basal area removal target was achieved, again with no preference for species. The last set of treatments removed trees from above by DBH. This removed the largest trees (by DBH) first until the basal area target was achieved.

5.2 Snags and Downed Woody Debris

Snags and downed woody debris were summarized separately from live trees. A table was created reporting snag density (snags per acre), basal area, quadratic mean diameter, and biomass, and downed woody debris biomass. Biomass is reported in pounds per acre. Snag size, number, cubic foot volume, and decay class (hard or soft) was calculated by FVS FFE. Snag biomass was then calculated by multiplying volume by wood specific gravity (Forest Products Laboratory, 2010). Snags in the soft decay had biomass reduced by a factor of .5 to account for decay. FFE reports downed woody debris biomass directly. For each of the 14 treatments described, snags could be included or excluded in the silvicultural prescription using this table.

5.3 Treatment Summaries

Summary tables were produced for each treatment. An identical set of fields were reported for both residual standing and cut trees. It is possible to calculate pre-treatment conditions by summing residual standing and cut fields. All values are reported on a per acre basis. For each FCID, standard stand structure variables including trees per acre, basal area (square feet per acre), and quadratic mean diameter (inches) were reported. Volume fields included cubic foot and board foot volumes to a six-inch top in trees less than nine inches DBH and in trees greater than nine-inch DBH; and cubic foot volume between a six- and four-inch stem diameter.

Biomass was reported in pounds per acre for stem, bark, branch, foliage, stump, and root components. Stem biomass fields include biomass to a six-inch top in trees less than nine-inches DBH and in trees greater than nine-inches DBH, and biomass between a six- and four-inch stem diameter. Stump biomass was reported separately assuming a one-foot tall stump. Bark biomass was reported for categories that correspond to the stem and stump categories. Branch biomass includes stem biomass from the top of a tree above a four-inch stem diameter. Discussions on the volume and biomass fields are provided in the next section. All summary table fields are described in Table 9.

Table 9. Treatment raster field descriptions.

Field	Description
Value	GNN FCID 2018 version.
Age	Pre treatment stand age.
TPA	Post treatment residual trees per acre.
BA	Post treatment residual basal area (square feet per acre).
QMD	Post treatment residual quadratic mean diameter (inches).
CV6LT9	Post treatment residual cubic foot volume per acre to a 6 inch top in trees with DBH less than 9 inches.
CV6GE9	Post treatment residual cubic foot volume per acre to a 6 inch top in trees with DBH greater than or equal to 9 inches.
CV4To6	Post treatment residual cubic foot volume per acre between 4 to 6 inches stem diameter.
BF6LT9	Post treatment residual board foot volume to a 6 inch top in trees with DBH less than 9 inches.
BF6GE9	Post treatment residual board foot volume to a 6 inch top in trees with DBH greater than or equal to 9 inches.
Stem6BLT9	Post treatment residual stem biomass (pounds per acre) to a 6 inch top in trees with a DBH less than 9 inches.
Stem6BGE9	Post treatment residual stem biomass (pounds per acre) to a 6 inch top in trees with a DBH greater than or equal to 9 inches.
Stem4To6B	Post treatment residual stem biomass (pounds per acre) between 4 to 6 inches stem diameter.
BarkStem6BLT9	Post treatment residual bark biomass (pounds per acre) to a 6 inch top in trees with a DBH less than 9 inches.
BarkStem6BGE9	Post treatment residual bark biomass (pounds per acre) to a 6 inch top in trees with a DBH greater than or equal to 9 inches.
BarkStem4To6B	Post treatment residual bark biomass (pounds per acre) between 4 to 6 inches stem diameter.
BranchB	Post treatment residual branch biomass (pounds per acre).
FoliageB	Post treatment residual foliage biomass (pounds per acre).
StumpB	Post treatment residual stump biomass (pounds per acre).
BarkStumpB	Post treatment residual stump bark biomass (pounds per acre).
RootB	Post treatment residual root biomass (pounds per acre).
CutTPA	Harvested trees per acre.
CutBA	Harvested basal area (square feet per acre).
CutQMD	Harvested quadratic mean diameter (inches).
CutCV6LT9	Harvested cubic foot volume per acre to a 6 inch top in trees with DBH less than 9 inches.
CutCV6GE9	Harvested cubic foot volume per acre to a 6 inch top in trees with DBH greater than or equal to 9 inches.
CutCV4To6	Harvested cubic foot volume per acre between 4 to 6 inches stem diameter.
CutBF6LT9	Harvested board foot volume to a 6 inch top in trees with DBH less than 9 inches.
CutBF6GE9	Harvested board foot volume to a 6 inch top in trees with DBH greater than or equal to 9 inches.

CutStem6BLT9	Harvested stem biomass (pounds per acre) to a 6 inch top in trees with a DBH less than 9 inches.
CutStem6BGE9	Harvested stem biomass (pounds per acre) to a 6 inch top in trees with a DBH greater than or equal to 9 inches.
CutStem4To6B	Harvested stem biomass (pounds per acre) between 4 to 6 inches stem diameter.
CutBarkStem6BLT9	Harvested bark biomass (pounds per acre) to a 6 inch top in trees with a DBH less than 9 inches.
CutBarkStem6BGE9	Harvested bark biomass (pounds per acre) to a 6 inch top in trees with a DBH greater than or equal to 9 inches.
CutBarkStem4To6B	Harvested bark biomass (pounds per acre) between 4 to 6 inches stem diameter.
CutBranchB	Harvested branch biomass (pounds per acre).
CutFoliageB	Harvested foliage biomass (pounds per acre).
CutStumpB	Harvested stump biomass (pounds per acre).
CutBarkStumpB	Harvested stump bark biomass (pounds per acre).
CutRootB	Harvested root biomass (pounds per acre).

5.4 Treatment Rasters

Summary tables for treatments and snags were joined to the updated GNN raster to create 14 rasters that represent the post-harvest biomass for each treatment described above. Fields are described in Table 9. These provide biomass and harvest volume data for each treatment at all locations in California.

6 Calculating Tree Biomass

6.1 Tree Component Biomass

Tree component biomass was calculated using the component ratio method (Heath et al., 2009). First, biomass in the merchantable stem was calculated from tree volume estimates and wood specific gravity (Forest Products Laboratory, 2010). Merchantable volume from FVS was used for this analysis.

Next, merchantable stem biomass was calculated again using national biomass estimators (Jenkins et al., 2003). This approach uses allometric equations to predict tree component biomass from DBH and species. The ratio of merchantable stem biomass using the two approaches was calculated. Finally, tree component biomass for bark, live branches, dead branches, foliage, and roots was calculated using the national biomass estimators and scaled using the calculated ratio.

Jenkins defined the merchantable stem by a one-foot stump and minimum top diameter of four inches. Biomass in the stem top was included with the live branches and stump biomass was disregarded. In FVS, merchantability was defined as a one-foot tall stump and six-inch minimum top diameter. To be consistent between to two merchantable stem biomass estimates described above, biomass representing the stem between four- and six-inches was added to the FVS estimate. First, cubic foot volume including top and stump (CVTS) was obtained from FVS. CVTS is a standard tree metric measuring woody stem volume from the ground (root collar) to the tip of the bole. Subtracting the merchantable volume from the total volume leaves the volume in the stump and the top (above a six-inch diameter) of the tree. Stump volume was calculated as the frustum of a cone, with the top of the stump five percent larger than the DBH and the bottom of the stump 10% larger than the DBH. The stump volume was subtracted away leaving only the top volume. The top of the stem above a six-inch diameter was assumed to be a cone. The volume between a six- and four-inch top was therefore assumed to be 56% of the remaining top volume. Stem biomass calculated using CVTS and wood specific gravity was allocated proportionally by volume among the stem sections. Bark biomass calculated using the component ratio method was also divided among the stem sections in the same way.

6.2 Residual Harvest Biomass

Residual harvested biomass is the biomass from harvested trees that is not part of a merchantable log. This amount can be calculated from the component biomass estimates but requires assumptions that are not made in this analysis. The Washington Forest Biomass Supply Assessment and Waste to Wisdom projects assumed residual harvested biomass included biomass from live branches, dead branches, foliage, and a proportion of the stem due to breakage and defect (10% was assumed in each project). These studies also included stem biomass from small non-merchantable trees.

For this study, stem biomass and volume were broken out into several categories to support multiple economic assumptions. Mill infrastructure (including proximity to a mill and log size specifications for a mill) and market conditions (e.g. log prices) determine in part whether small logs are merchantable or should be counted as residual harvested biomass. Small logs come from trees with small DBH's and from the top log of larger trees. This study used a nine-inch DBH to identify potentially non-merchantable trees. For trees smaller than nine inches, both stem biomass and board feet were reported. Trees larger than nine inches were always assumed to have a merchantable stem. Similarly, stem biomass was broken out for the stem between six- and four-inches in diameter. Board foot volume was not reported for this material; however, it might be considered merchantable as part of a pulp or chip-and-saw log.

In the previous studies, residual harvested biomass was further categorized into "scattered throughout the harvest unit" and "piled at the roadside and landing." This was calculated using owner survey information about harvest systems (ground or cable based). Recovery factors representing the proportion of residual harvested biomass that reaches the roadside is listed in Table 10. A slope break of 30% was used to delineate ground and cable harvest systems in the previous studies. For the Washington Forest Biomass Supply Assessment, these factors were reported by region in Washington, incorporating different equipment and techniques. The regional factors were averaged and applied as rough estimates for the Waste to Wisdom project. These averages may or may not be useful in California.

Table 10. Recovery factors by harvest system and owner type used in the Waste to Wisdom project.

	Ground	Cable
Private	.94	.78
Federal	.62	.56

7 Transportation

A transportation analysis was conducted to 163 locations in California representing potential biomass processing facilities. A layer with existing, historical, or proposed power plant and wood processing facilities was developed in part from mill locations collected by Prestemon et al. (2005) and Spelter et al. (2009). The ArcGIS Network Analyst Service Area tool was used with a road network layer from ESRI Business Analyst to calculate miles and minutes from each location in California to each facility. Results were accumulated in five mile or minute intervals. Maximum values of either 240 miles or minutes were allowed, with the limiting factor being 240 minutes for the vast majority of locations. Each service layer was converted into time and distance rasters, totaling 326 transportation rasters.

Because the Business Analyst road network does not include all forest roads, a distance to road raster was created using the ArcGIS Spatial Analyst Euclidean Distance tool. The distance to roads was report in meters. This straight-line distance could be multiplied by a factor representing road travel time or distance and added to the transportation rasters to estimate total travel.

8 Forest Class Cluster Analysis

A clustering analysis was performed to identify groupings within the 2018 pre-harvest forest classes. A representative forest class was selected for each group. The clustering analysis was completed to allow project partners to work with a smaller dataset for subsequent analyses.

First, a dominant species class was determined for each forest class. FCID's with greater than 80% basal area in a single species were classified by that species (i.e. “DF” for Douglas fir). Stands with less than 80% were classified as mixed (prepended with an “M”), followed by the species with the majority or plurality of basal area, followed by other species with at least 20% basal area in descending order (i.e. “MDF” for mixed Douglas fir with minor species, “MDFBO” for mixed Douglas fir with a significant black oak component (> 20% by basal area)). All species groups that made up at least 1% of forest area in California were identified. The remaining species groups were generalized by first keeping the majority/plurality species but lumping minor species into hardwoods or softwoods (i.e. “MDFOS” for mixed Douglas fir with other softwoods or “MDFOH” for mixed Douglas fir with other hardwoods). Finally, species groups that still didn’t make up at least 1% of forest area were further generalized into “MOSOH” (mixed other softwoods with other hardwoods) or “MOHOS” (mixed other hardwoods with other softwoods).

Next, within each dominant species class, k-means clustering was used to group FCID's with similar structural attributes (R Core Team, 2017). Centering and scaling was used to normalize trees per acre, quadratic mean diameter, stand height, snag tons per acre, and downed woody debris tons per acre. Elbow plots of within groups sums-of-squares were produced using 1 to 15 clusters. The optimal number of clusters was identified as the breakpoint that results in a segmented linear model that minimizes the variance amongst all possible segmented models. This decision criteria approximates an analyst manually implementing the “elbow method” to identify the optimal number of clusters, whereby adding addition clusters improves the variation explained by only a small amount (Thorndike 1953).

Finally, for each species-structure group, a representative forest class was identified. This was the forest class with the minimum Euclidean distance from the mean values in normalized space. A total of 177 groups and representative stands were identified. Raster and tabular datasets were developed to link the representative forest class to the 2018 forest class. Tree, snag, and downed woody debris data was provided for each representative stand as a Microsoft Access database.

9 Simulating Harvests to Match Historical Levels

Historical timber harvest data was obtained from the University of Montana Bureau of Business and Economic Research, which provided annual harvested board foot volume by county and owner. Average board foot volume was calculated for each county and owner for years 2012 to 2016 and multiplied by 10 to simulate harvesting over a decade. To characterize silvicultural methods across California, private timber harvest plans and Forest Service activities were intersected with counties and the acres for clear-cuts and thins were summed. Thins were assumed to produce half the volume of clear-cuts. New harvest targets by activity were then calculated by apportioning the county and owner targets by the activity acres and thinning weight.

A thin treatment was identified for each FCID from the simulated treatments and using the basal area requirements in the California Forest Practice Rules. Thins were always assumed to be from below by DBH. Conditions for residual basal area target (125, 100, 75, and 50 square feet per acre) and minimum harvested volume (4000, 3000, 2000, and 1000 board feet per acre) were then considered in pairs. For each FCID, the treatment that removed at least the minimum volume and retained the basal area target was identified. If no treatment satisfied the condition, the next pair of values was considered. If no treatment satisfied the conditions the FCID was not eligible to be treated. Clear-cuts removed 100% of the trees and were required to remove at least 5000 board feet per acre of volume.

After identifying treatments, the parcels were prioritized for thins by calculating the average harvested volume per acre from the parcel. Only forested segments that were in a managed zone with ages between 20 and 150 years old. Age data came from the GNN dataset. Riparian forests and permanently unmanaged forest segments were removed from the analysis. Parcels were then selected for harvest until the thin target was achieved for each county and owner. Next, parcels not harvested with thins were prioritized to be clear-cut in the same way.

A file geodatabase of harvested parcel data was provided. The geodatabase includes the harvested parcel points and tables with distance to road, miles and minutes to each facility, and harvested segments. The harvested segments table identifies the FCID, representative FCID, treatment applied, slope, and acres for each segment. Finally, the treatment summary fields for both residual standing and cut trees were provided. The harvested volume, biomass, and transportation data (and linkage to the representative FCID for other analyses) should support a life-cycle assessment.

10 Data Sources

10.1 Parcels and Ownership

1. Parcels: Waste to Wisdom project acquisition
2. Major Public Ownership: https://gapanalysis.usgs.gov/padus/

10.2 Forest Class

1. GNN: https://lemma.forestry.oregonstate.edu

10.3 Watercourses, Waterbodies, and Wetlands

1. Watercourses and waterbodies: https://www.wildlife.ca.gov/Data/GIS/Clearinghouse
2. National Wetlands Inventory: https://www.fws.gov/wetlands/data/Mapper.html

10.4 Timber Harvest Activity

1. Forest Service Activity: https://data.fs.usda.gov/geodata/edw/datasets.php
2. California Private Timber Harvest Plans: http://www.fire.ca.gov/resource_mgt/resource_mgt_forestpractice_thpstatus

10.5 Fire

1. MTBS: https://www.mtbs.gov/
2. RAVG: https://www.fs.fed.us/postfirevegcondition
3. Perimeters: https://www.geomac.gov/

10.6 Tree Mortality

1. Tree Mortality: http://egis.fire.ca.gov/treemortalityviewer/

10.7 Transportation

1. Facility locations (in part): https://www.srs.fs.usda.gov/econ/data/mills/
2. Transportation: ESRI Business Analyst (2016)

10.8 Historical Timber Harvest Data

1. http://www.bber.umt.edu/FIR/H_harvest.asp

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APPENDIX B
Decay Methodology Details

Much of the work in this appendix was pulled from a masters thesis which was completed for the C-BREC model. Refer to (Blasdel, 2020) for additional details.

B.1 Detailed Forest Residue In-Field Decay Equations

This section provides details of the spatial- and time-explicit equations used to calculate emissions from the decay of forest residues.

B.1.1 Description of Variables

i: subscript indicates that the variable is spatially derived from the i^{th} raster

x: subscript denotes the size class. This is either Coarse Woody Debris – Standing (CS) or – Down (CD), Fines (F), Litter (L), or Duff (D)

y: subscript denotes the state of the residue as piled (p) or scattered (s)

α_i: climate multiplier on k_i. The value of α_i used in the equations below is an average of all α_i values associated with all raster cells [unitless]

$f_d = 0.02$: fraction of mass lost (in all size classes) that is moved to duff [unitless]

$f_a = 1 - f_d = 0.98$: fraction of mass lost (in all size classes) that decays to the atmosphere [unitless]

$f_{y,i}$: fraction of mass $M_{0,x,i}$ that is piled (p) or scattered (s) [unitless]

$k_{x,y,i}$: decay constant of material size class x in state y, where x is either CWD – Standing, CWD – Down, Fine, or Litter, and y is either scattered or piled [$^1/_{yr}$] (Note the decay constant for duff does not vary spatially. y does not apply to CWD – Standing)

$k_D = 0.002$: decay constant of duff [unitless] (Note that the value is from FVS which does not have units of [$^1/_{yr}$]. FVS assumes the first order series approximation of an exponential $(1 - k_D) \approx \left(\sum_{i=0}^{\infty} \frac{(-k_D)^i}{i!} = e^{-k_D} = \frac{M_{t+1}}{M_t} = \frac{M_0 e^{-k_D(t+1)}}{M_0 e^{-k_D t}}\right)$. However, the deviation between the exponential form and the series approximation form is negligible in this context, and k_D is used in both forms).

$M_{0,x,i}$: initial mass of residue at year zero of size class x, where x is either CWD, Fine, Litter, or Duff [bone dry tons (BDT)]

B.1.2 Residues on the Ground – Piled or Scattered

Table 48: Decay Equations for Forest Residues – Piled or Scattered

	Mass Remaining ($MR_{x,i}$)	Mass Lost to Atmosphere ($MA_{x,i}$)	Mass Moved to Duff ($MD_{x,i}$)
CWD (CD)	year / Eq 0 / $M_{0,CD,i}$ … / $M_{0,CD,i}\sum_{y=p,s}\left(f_{y,i}\cdot e^{-\alpha_i k_{CD,y,i} t}\right)$	year / Eq 0 / 0 … / $M_{0,CD,i} f_a \sum_{y=p,s}\left[f_{y,i}\left(e^{-\alpha_i k_{CD,y,i}(t-1)} - e^{-\alpha_i k_{CD,y,i} t}\right)\right]$	year / Eq 0 / 0 … / $M_{0,CD,i} f_d \sum_{y=p,s}\left[f_{y,i}\left(e^{-\alpha_i k_{CD,y,i}(t-1)} - e^{-\alpha_i k_{CD,y,i} t}\right)\right]$
Fine (F)	year / Eq 0 / $M_{0,F,i}$ … / $M_{0,F,i}\sum_{y=p,s}\left(f_{y,i}\cdot e^{-\alpha_i k_{F,y,i} t}\right)$	year / Eq 0 / 0 … / $M_{0,F,i} f_a \sum_{y=p,s}\left[f_{y,i}\left(e^{-\alpha_i k_{F,y,i}(t-1)} - e^{-\alpha_i k_{F,y,i} t}\right)\right]$	year / Eq 0 / 0 … / $M_{0,F,i} f_d \sum_{y=p,s}\left[f_{y,i}\left(e^{-\alpha_i k_{F,y,i}(t-1)} - e^{-\alpha_i k_{F,y,i} t}\right)\right]$

Litter (L)	year / Eq
	0 / $M_{0,L,i}$
	… / IF$\left(e^{-\alpha_i k_{L,y,i} t} > 0.5\right)${
	$M_{0,L,i}\sum_{y=p,s}\left(f_{y,i}\cdot e^{-\alpha_i k_{L,y,i} t}\right)$
	} ELSE {
	0
	}
		year / Eq
		0 / 0
		… / IF$\left(e^{-\alpha_i k_{L,y,i} t} > 0.5\right)${
		$M_{0,L,i} f_a \sum_{y=p,s}\left[f_{y,i}\left(e^{-\alpha_i k_{L,y,i}(t-1)} - e^{-\alpha_i k_{L,y,i} t}\right)\right]$
		} ELSE {
		$M_{0,L,i} = 0$
		}
			year / Eq
			0 / 0
			$1 \le t \le T$ / IF$\left(e^{-\alpha_i k_{L,y,i} t} > 0.5\right)${
			$M_{0,L,i} f_d \sum_{y=p,s}\left[f_{y,i}\left(e^{-\alpha_i k_{L,y,i}(t-1)} - e^{-\alpha_i k_{L,y,i} t}\right)\right]$
			} ELSE {
			$T = t$
			$M_{0,L,i}\sum_{y=p,s}\left(f_{y,i}\cdot e^{-\alpha_i k_{L,y,i} t}\right)$
			}
			$> T$ / 0

Duff (D)	year / Eq 0 / 0 … / $\left(MR_{D,i}^{t-1} + \sum_{x=CD,F,L} MD_{x,i}^{t}\right) - MA_{D,i}^{t}$	year / Eq 0 / 0 … / $\left(MR_{D,i}^{t-1} + \sum_{x=CD,F,L} MD_{x,i}^{t}\right)\alpha_i k_D$	N/A

B.2 Detailed Agricultural Residue In-Field Decay Equations

This section provides details of the spatial- and time-explicit equations used to calculate emissions from the decay of agricultural residues.

B.2.1 Description of Variables

x: subscript denotes the size class. This is either Fines (F) or Litter (L)

y: subscript denotes the state of the residue as tilled (T), non-tilled (NT), or reduced (or conservation) tilled (RT). Applies to straw residues only.

s: subscript denotes the specific crop. This is either almond, walnut, grape, corn, cotton, rice, or wheat.

$f_d = 0.02$: fraction of mass lost (in all size classes) that is moved to duff [unitless]

$f_a = 1 - f_d = 0.98$: fraction of mass lost (in all size classes) that decays to the atmosphere [unitless]

$k_{x,s,y}$: decay constant of material size class x for species s in state y, where x is either Fine or Litter, and y is either tilled, non-tilled, or conservation tilled. [$^1/_{yr}$]

$M_{0,x,i}$: initial mass of residue at year zero of size class x, where x is either Fine or Litter [bone dry tons (BDT)]

B.2.2 Decay Equations for Straw Agricultural Residues

Table 49: Decay Equations for In-Field Agricultural Straw Residues

	Mass Remaining ($MR_{x,s}$)		Mass Lost to Atmosphere ($MA_{x,s}$)	
	year	Eq	year	Eq
Straw	0	$M_{0,L,s}$	0	0
	…	IF $\left(e^{-k_{L,s,y}t} < 0.5\right)$ { $M_{0,L,i}\left(e^{-k_{L,s,y}t}\right)$ } ELSE {0}	…	IF $\left(e^{-k_{L,s,y}t} < 0.5\right)$ { $M_{0,L,i}f_a\left[\left(e^{-k_{L,s,y}(t-1)} - e^{-k_{L,s,y}t}\right)\right]$ } ELSE {0}

B.2.3 Decay Equations for Woody Agricultural Residues

Table 50: Decay Equations for In-Field Agricultural Woody Residues

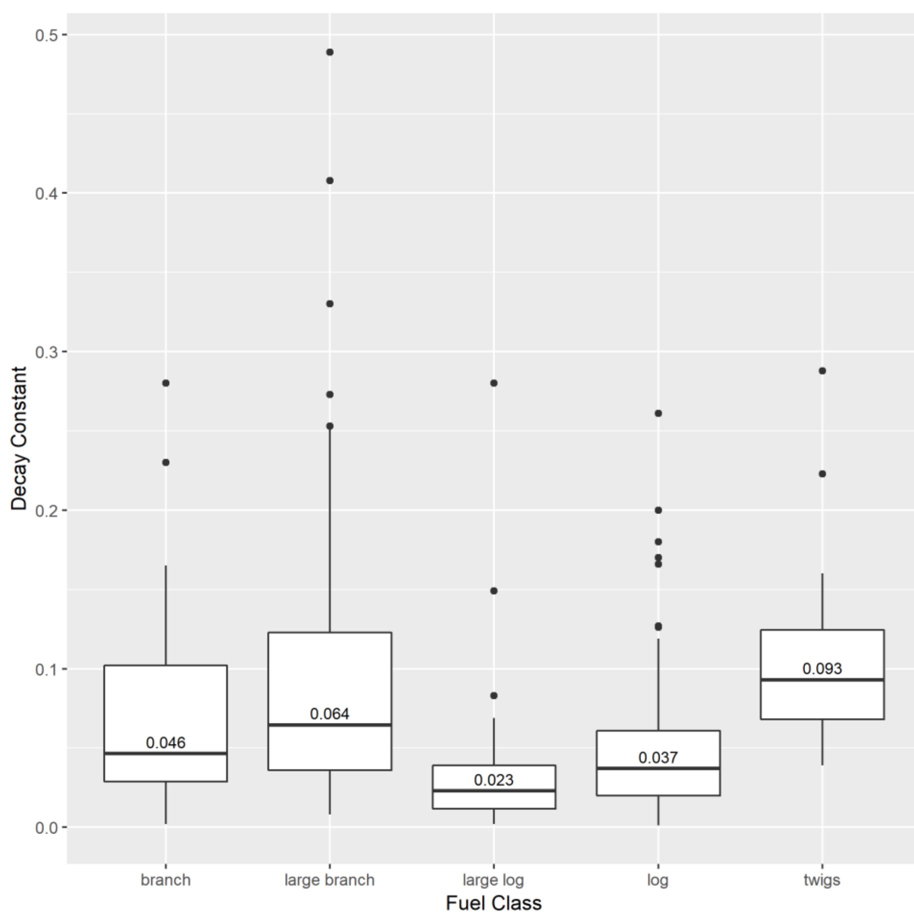
	Mass Remaining ($MR_{x,s}$)	Mass Lost to Atmosphere ($MA_{x,s}$)
Coarse Debris (CD)	No woody residue in this size class	
Fine (F)	year: 0 — Eq: $M_{0,L,s}$ year: … — Eq: IF ($e^{-k_{F,s}t} < 0.5$) { $M_{0,L,i}(e^{-k_{F,s}t})$ } ELSE {0}	year: 0 — Eq: 0 year: … — Eq: IF ($e^{-k_{F,s}t} < 0.5$) { $M_{0,L,i}f_a\left[\left(e^{-k_{F,s}(t-1)} - e^{-k_{F,s}t}\right)\right]$ } ELSE {0}
Litter (L)	No woody residue in this size class	
Duff	Not included in the Agriculture residue decay model	

B.3 Size Class Comparison of Decay Constants for Woody Biomass

Past studies have shown conflicting data on the correlation between size class and decay rates (Mackensen & Bauhus, 1999; Xiwei Yin, 1999; Zell et al., 2009). One theory is that smaller pieces of woody debris have a greater surface area to volume ratio, providing more area for primary decomposing fungi to infiltrate. Another theory being smaller pieces of wood have less water holding capacity and are prone to drying out, which inhibits and stalls decay (McColl & Powers, 2003).

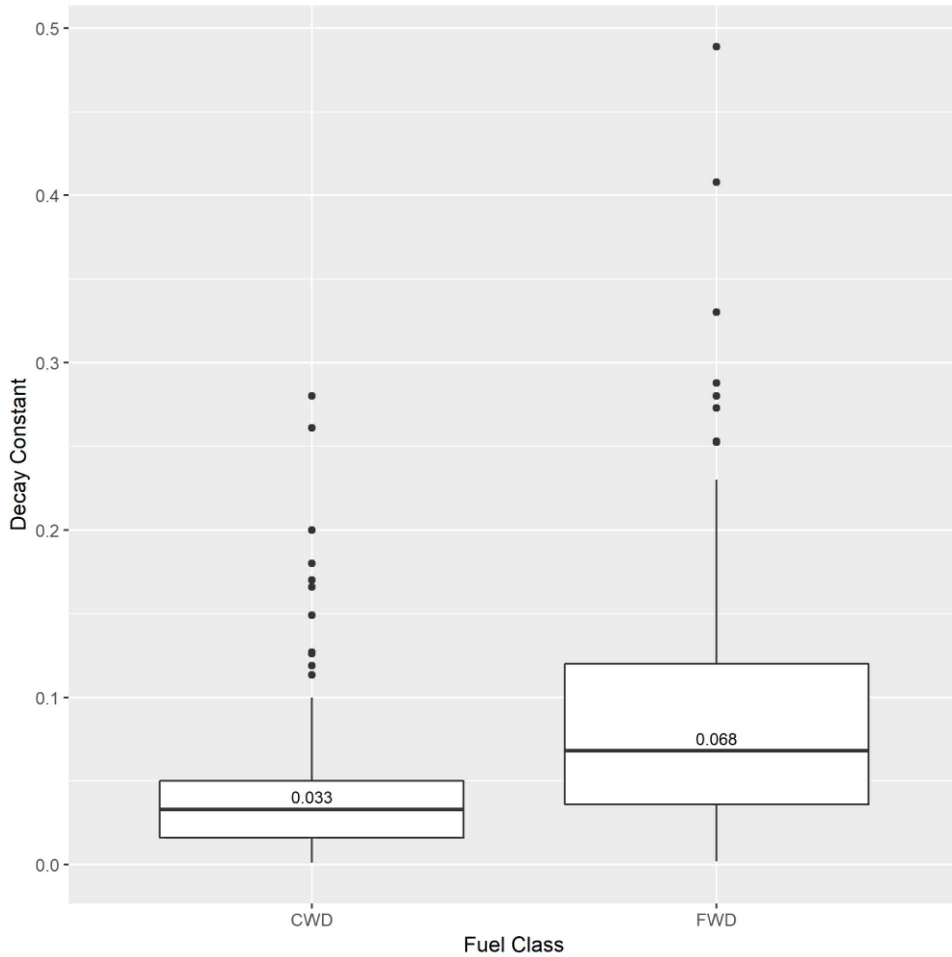
An analysis of decomposition by size class showed no clear trend with the progressively increasing size classes (Figure 19). Large branches have greater decay values than smaller materials, while the smallest materials (twigs) have the greatest decay rates. Differentiating decay along five size classes seems unsupported by this data.

Figure 19: Variation in Decay Constant across Multiple Size Class



Materials between 0-7.62 cm are considered FWD and anything larger is considered CWD (Woodall & Liknes, 2008). Grouping the data by FWD and CWD produces a clearer distinction between the size classes (Figure 20). This supports the idea that there are classes of fine woody debris and coarse woody debris, which behave differently from one another, but distinctions beyond that scope are unsupported by the data.

Figure 20: Variation in Decay Constant by CWD and FWD



B.4 Addressing Missing Decay Rate Values in Literature

There is a relationship between decay rates of CWD and FWD of the same species as there is less variation for decay rates within smaller taxonomic orders (Pietsch et al., 2014). A correlation test was performed on the decay values of CWD and FWD for species that had values from both classes (Table 51).

Table 51: Statistics Associated with Correlation between CWD and FWD Decay Constants

Correlation Test	P-value	Correlation Coefficient
Spearman	0.000817	0.605
Pearson	0.00386	0.528

A linear regression model used to derive a coefficient value to fill in the missing data (Figure 21). The residuals from the linear model were inspected and found to have a normal distribution (Figure 22).

Figure 21: Linear Regression Result to Correlate CWD and FWD

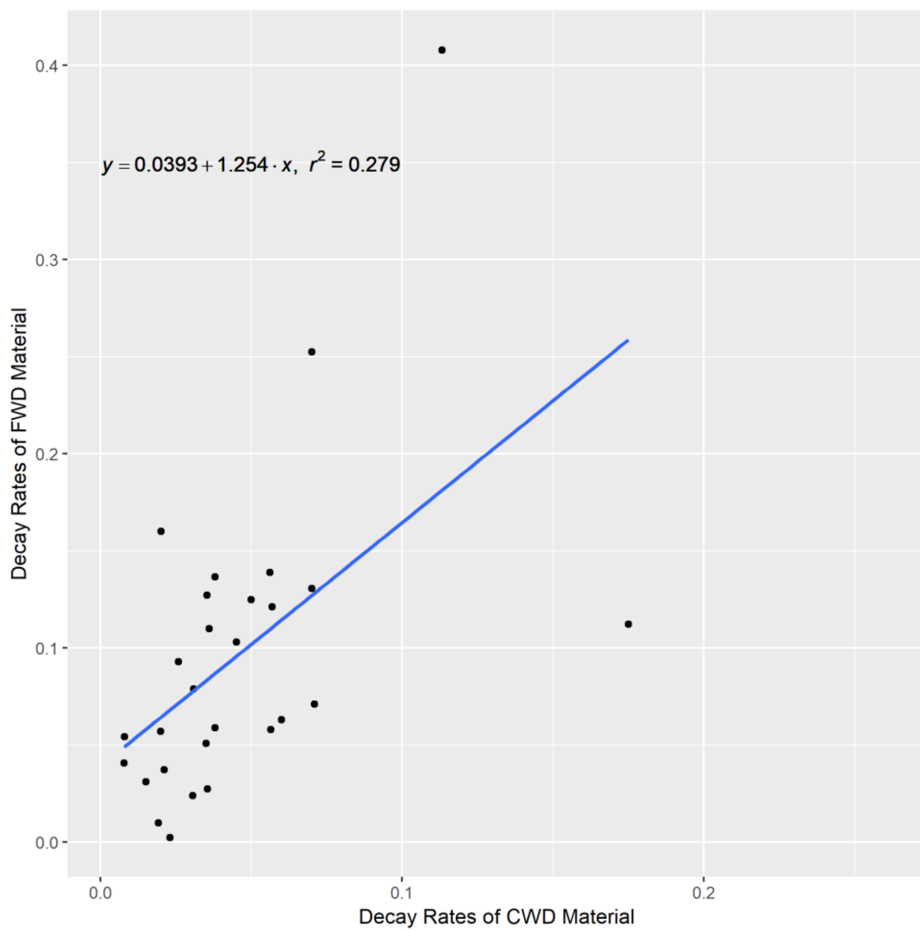
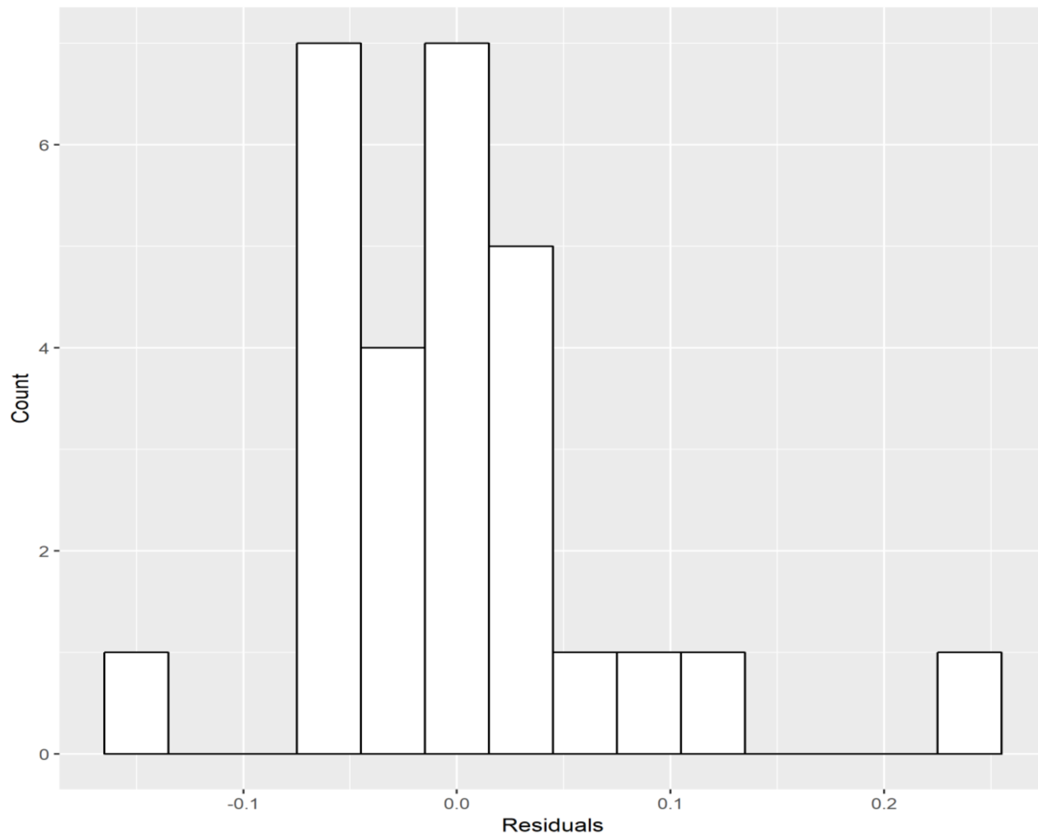


Figure 22: Residuals of Linear Regression between CWD and FWD



This model simply states that there is a correlation between the decay values of CWD and FWD from the same taxonomic order. Missing values from the literature were filled in by multiplying known values by the coefficient from the linear model. Normally distributed residuals show that the variation in the true values from the predicted values are equally distributed throughout the data.

B.5 Pile Composition of Forest Residues

(C. Miller & Boston, 2017) measured slash piles from different harvests throughout Oregon. With their data and an assumed paraboloid shape, the average pile height is roughly 3.1 meters.

Table 52: Literature Values Supporting the Derivation of Average Pile Height

Data Source	Pile Height [m]
(C. Miller & Boston, 2017)	3.51
	2.54
	2.35
	2.58
	5.50
	2.12
Average	3.10

Slash piles have been shown to vary widely depending on the logging system used, but generally resemble a paraboloid shape (Wright et al., 2017). Using average values from different harvest systems will give a rough approximation of a typical pile size. Pile size is commonly approximated using a geometric paraboloid with the formula:

$$V = \frac{\pi * H * W^2}{8}$$

where H is the height and W is the width of the pile (Hardy, 1996). (C. Miller & Boston, 2017) measured slash piles from different harvests throughout Oregon. With their data and an assumed paraboloid shape, the average pile height is roughly 3.1 meters. This number is in line with previous research concerning typical maximum pile heights for forestry practices (Winterbourne, 2016).

Material is classified as AG or GC based on the positioning in the pile. Under the assumption that material within a given distance of the forest floor is considered GC, a shorter paraboloid can be subtracted from a larger paraboloid to get the volume of GC material.

$$V_{gc} = \frac{\pi * H * W^2}{8} - \frac{\pi * (H - x) * W^2}{8}$$

where x is the assumed distance from the ground and V_{gc} is the volume of GC material. The x value is an estimated variable that represents the distance at which material is considered in contact with the forest floor and can be varied to test sensitivity in the model. Using the above equation, a typical pile will have roughly 89.2% AG material and 10.8% as GC (Table 53).

Table 53: Pile Mass Fraction of AG and GC

Pile Volume (m3)	Pile Height (m3)	AG material (m3)	GC material (m3)	% AG	% GC
1142	3.1	1018.8	123.2	89.2	10.8

For this model, material that is within one foot (0.305 meters) of the ground will be considered GC with all other material treated as AG. The proportions of AG and GC are dependent on the assumption of distance from the ground. The effect of this assumption is shown in Table 54. (Barber & Van Lear, 1984) proposed 20% GC which is close to using a half meter as the distance from the ground.

Table 54: Literature Date on GC Fractions and Associated Distance from Ground

AG %	GC %	Distance from ground (m)
89.4	10.6	0.3
85.9	14.1	0.4
82.3	17.7	0.5
78.8	21.2	0.6
75.2	24.8	0.7
71.7	28.3	0.8
68.2	31.8	0.9
64.6	35.4	1.0

Taking a weighted average approach for the piled material decay constants is an approximation used for model simplicity. While this produces different values than treating AG and GC materials differently through time, the maximum difference is never greater than ~0.3% and represents a relatively small source of error in a much larger modeling project (Figure 23). Only select years are shown to highlight that there is a difference in the two methods. The difference is variable and changes over time with a distinct maximum (Figure 24).

Figure 23: Differences in Calculating Pile Decay by Method

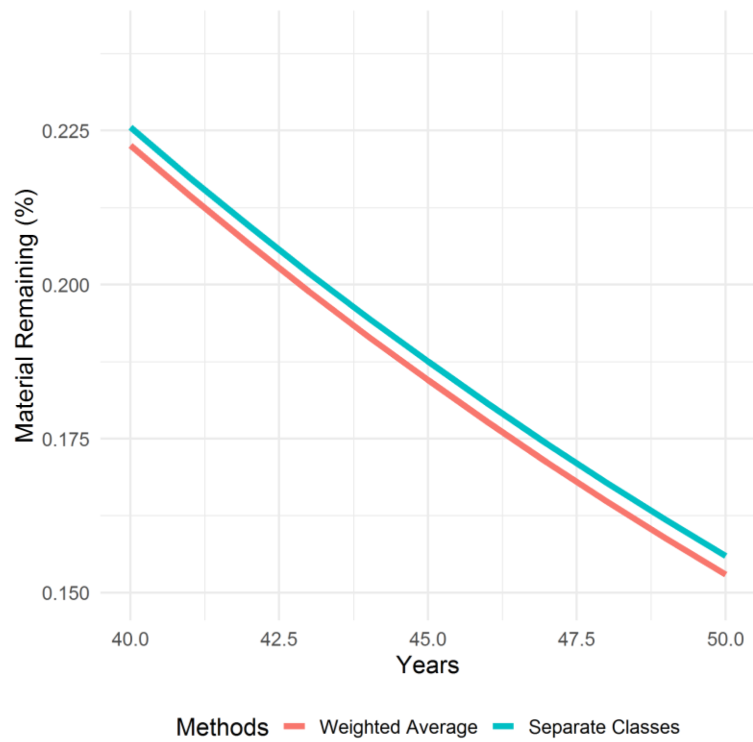
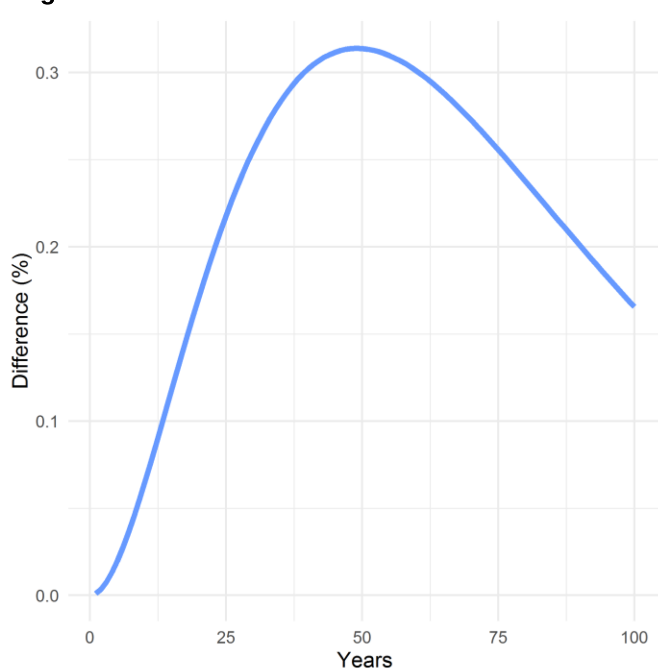


Figure 24: Percent Difference in Methods Overtime



B.6 Details on Climate Modifiers Applied to Forest Residues

Climate modifiers were applied to the decay rates of species data for all of California. The basic structure of the climate modifier models are a set of functions, representing environmental variables, which affect decomposition constants. This is expressed through the decay function as a factor that multiplies the k constant:

$$N_t = N_i * E^{(-k*C_m)*t}.$$

In most models the climate modifier is the product of temperature and a moisture dependent function, expressed through the equation:

$$C_m = f(T) * f(M),$$

where C_m is the climate modifier affecting the decay rate (Sierra et al., 2015). The climate modifier is applied to the species-specific decay values through the following equation:

$$k_m = k * C_m,$$

where k is a given decay rate and k_m is the modified decay value. The C_m value is derived from models that quantify the effect of climate on decay (Adair et al., 2008).

Many climate modifier frameworks use an optimal or reference value where the climate modifier equals 1 (Sierra et al., 2015). This method presents a problem when species specific decay constants are used since species natural ranges exist along different climate gradients.

Some species will only be found in cold and relatively dry areas of California. The empirically derived k values for these species will most likely also have come from cold and dry areas. Applying a climate modifier will have the effect of further decreasing the decay values for these species.

Applying the climate modifier to individual species assumes that the k values have not been affected by the climate in which they were calculated in. This methodology takes the opposite approach by treating every empirically derived k value as having been altered by climate. A k value where there was a neutral effect of climate on the materials is then calculated by rearranging to the following:

$$\frac{k_m}{C_m} = k.$$

Climate metrics were recorded from a literature review of past individual studies to calculate the climate effect for each study. The literature reported decay rates were then divided by the climate modifier to derive a decay constant that is unaffected by climate.

B.6.1 Climate Equations

The effect of temperature on decay was quantified with a equation that models the change in biological respiration rates as temperature increases (Lloyd & Taylor, 1994).

$$f(T) = \exp\left[308.56 * \left(\frac{1}{56.02} - \frac{1}{(273+T) - 227.13}\right)\right].$$

T is given in kelvin and returns a value of 1 when the temperature equals 10°. The temperature equation is based off a Q10 equation that describes how biological processes speed up given a 10° increase in temperature (Lloyd & Taylor, 1994).

While $Q10$ can vary in different conditions, a value of 1.6 was found from a meta-analysis of in situ studies on decomposition and will be used for this analysis (Zell et al., 2009).

There are concerns with using a constant $Q10$ as this factor can vary significantly at high and low temperatures (Wang et al., 2002). When testing this function on LIDET data, it was found to perform the worst in areas with extreme temperatures, although it outperformed other temperature equations (Adair et al., 2008).

The effect of moisture on decomposition is quantified with an equation that models the limiting effect of moisture content on decomposition.

$$f(PPT, PET) = \frac{1.0}{1.0 + 30 * \ exp^{-8.5 * \frac{PPT}{PET}}}$$

In the above equation, PPT is the annual precipitation for an area and PET is the annual potential evapotranspiration. This equation produces a unitless factor between 0 and 1, which acts to limit the rate of decay in areas where the PET is significantly greater than the PPT. Unlike the temperature function, this moisture function can only reduce the decay values. PET is a derived variable calculated with the Penman-Monteith method by the maintainers of the gridMET data set (Abatzoglou, 2013).

B.6.2 Climate Data

The gridMET data was downloaded from the website: http://thredds.northwestknowledge.net:8080/thredds/reacch_climate_MET_catalog.html and accessed with R statistical software using the nc4 and raster packages. The gridMET rasters have a 4km^2 resolution and cover the entire United States. All metrics from the gridMET data have a daily temporal resolution.

Data to determine the PET for studies outside the US was downloaded from the website:

https://earlywarning.usgs.gov/fews/product/81

The yearly data comes in daily .bil files and was compiled with the raster package in R. The data covers the entire globe with a 1 degree ground resolution. PET is a derived variable and is calculated from Global Data Assimilation System analysis fields using the Penman-Monteith method..

B.6.3 Data usage

While yearly means for climate metrics were used in this study, some past studies have focused on climate metrics from January and June to capture seasonal variation (Xiwei Yin, 1999). Decay of woody material almost certainly fluctuates throughout the year with temperature and moisture variation. Yearly means were used since the C-BREC model outputs yearly time series data on various metrics.

B.7 Spatially Explicit Processing of Forest Residue Decay Constants in R

To derive climate values of species at spatially explicit locations, the NRSIG data was parsed into individual rasters showing where a species has a measured basal area. Each raster had a value between 0 and 1 representing the proportional abundance in that cell as calculated from reported basal area. These rasters also show the range of every species in the data.

The individual rasters are then reclassified to the corresponding decay values for each species or genus producing rates of decay for each species. The decay values used to reclassify the rasters have been already modified by the climate and the effect of climate on those decay rates has been calculated out through the above climate equations.

The individual species rasters are then multiplied by the climate modifier which represents the climate conditions of California based on a ten-year average. This produces spatially variable decay rates for each species based on climate conditions. These rasters were then combined as a weighted average into a single decay raster based on proportional abundance of a given cell. These steps were taken for CWD and FWD to produce two rasters showing each size class of fuel.

A simplified approach was taken with the size class of foliage. The decay rates of foliage are only varied by the angiosperm/gymnosperm distinction. The proportional abundance of angiosperms and gymnosperms was calculated for each cell and the previous steps were repeated to create spatially variable decay rates of foliage. Processing of spatial data was done in R Studio with the raster package.

B.8 Literature Review of Forest Residue Decay Constants by Tree Species

Table 55: Decay Constants by Tree Species

K constant	Genus	Species	Size Class (cm)	Reference	Fuel Class	Classification	Notes
0.002	Abies	amabilis	1.5	Erickson et al. 1985	branch	Gymnosperm	suspended material
0.009	Abies	amabilis	10	Erickson et al. 1985	log	Gymnosperm	suspended material
0.003	Abies	amabilis	1.5	Erickson et al. 1985	branch	Gymnosperm	on ground
0.009	Abies	amabilis	10	Erickson et al. 1985	log	Gymnosperm	on ground
0.033	Abies	balsamea	12.5	Foster & Lang 1982	log	Gymnosperm	averaged bole size
0.038	Abies	balsamea	12.5	Foster & Lang 1982	bark	Gymnosperm	bark
0.049	Abies	concolor	20	Harmon 1987	large log	Gymnosperm	
0.039	Abies	concolor	branch	Harmon 1987	branch	Gymnosperm	
0.027	Abies	concolor	bark	Harmon 1987	bark	Gymnosperm	bark
0.035	Abies	lasiocarpa	52	Harmon 2005	large log	Gymnosperm	
0.051	Abies	amabilis	52	Harmon 2005	large log	Gymnosperm	
0.035	Abies	concolor	52	Harmon 2005	large log	Gymnosperm	
0.043	Abies	magnifica	52	Harmon 2005	large log	Gymnosperm	
0.038	Abies	grandis	52	Harmon 2005	large log	Gymnosperm	
0.051	Abies	concolor	52	Harmon 2005	large log	Gymnosperm	
0.03	Abies	procera	52	Harmon 2005	large log	Gymnosperm	
0.072	Abies	spp.	log	Janish 2005	log	Gymnosperm	
0.004	Abies	spp.	bark	Janish 2005	bark	Gymnosperm	
0.128	Abies	grandis	foliage	Keane et al. 2008	foliage	Gymnosperm	
0.063	Abies	grandis	twigs (1hr)	Keane et al. 2008	twigs	Gymnosperm	
0.072	Abies	grandis	branch (10hr)	Keane et al. 2008	branch	Gymnosperm	
0.042	Abies	grandis	large branch (100hr)	Keane et al. 2008	large branch	Gymnosperm	
0.0299	Abies	balsamea	8	Lambert et al. 1980	log	Gymnosperm	averaged bole size

K constant	Genus	Species	Size Class (cm)	Reference	Fuel Class	Classification	Notes
0.032	Abies	spp.	8	Shorohova and Kapitsa	log	Gymnosperm	greater than 8cm
0.13	Abies	concolor	litter	Stohlgren 1988	twigs	Gymnosperm	excludes initial 0.7 years, first fall and winter will give better description of long term litter decay
0.14	Abies	concolor	litter	Stohlgren 1988	twigs	Gymnosperm	excludes initial 0.7 years, first fall and winter will give better description of long term litter decay
0.0353	Abies	lasiocarpa	branch	Taylor et al. 1991	branch	Gymnosperm	Finds lignin content to be best predictor of litter decay rate
0.062	Abies	lasiocarpa	twigs (1hr)	Taylor et al. 1991	twigs	Gymnosperm	
0.0933	Abies	lasiocarpa	needles	Taylor et al. 1991	foliage	Gymnosperm	
0.15	Abies	lasiocarpa	foliage	Keane et al. 2008	foliage	Gymnosperm	
0.082	Abies	lasiocarpa	twigs (1hr)	Keane et al. 2008	twigs	Gymnosperm	
0.037	Abies	lasiocarpa	branch (10hr)	Keane et al. 2008	branch	Gymnosperm	
0.038	Abies	lasiocarpa	large branch (100hr)	Keane et al. 2008	large branch	Gymnosperm	
0.08	Acer	rubrum	10	Harmon 1982	log	Angiosperm	
0.053	Acer	spp.	31	Kahl et al. 2017	large log	Angiosperm	
0.0452	Acer	spp.	18	MacMillan 1988	log	Angiosperm	
0.081	Acer	rubrum	14.5	Mattson 1987	log	Angiosperm	CWD size found not to affect decomp rate

K constant	Genus	Species	Size Class (cm)	Reference	Fuel Class	Classification	Notes
0.072	Allocasuarina	fraseriana	bole and branch	Brown et al. 1996		Angiosperm	These values are boles and branches together for each species. Since this study did find an inverse relationship between CWD size I will use the ratio of bole to branch to infer the decay rates for the size classes of each species.
0.136615	Allocasuarina	fraseriana	4	Brown et al. 1996	large branch	Angiosperm	Derived values
0.037946	Allocasuarina	fraseriana	12.5	Brown et al. 1996	log	Angiosperm	Derived values
0.23	Alnus	rubra	1.5	Edmonds et al. 1986	branch	Angiosperm	surface
0.122	Alnus	rubra	5	Edmonds et al. 1986	large branch	Angiosperm	surface
0.088	Alnus	rubra	10	Edmonds et al. 1986	log	Angiosperm	surface
0.115	Alnus	rubra	1.5	Edmonds et al. 1986	branch	Angiosperm	surface
0.109	Alnus	rubra	5	Edmonds et al. 1986	large branch	Angiosperm	surface
0.04	Alnus	rubra	10	Edmonds et al. 1986	log	Angiosperm	surface
0.146	Alnus	rubra	1.5	Edmonds et al. 1986	branch	Angiosperm	elevated
0.086	Alnus	rubra	5	Edmonds et al. 1986	large branch	Angiosperm	elevated
0.119	Alnus	rubra	10	Edmonds et al. 1986	log	Angiosperm	elevated
0.145	Alnus	rubra	1.5	Edmonds et al. 1986	branch	Angiosperm	elevated
0.093	Alnus	rubra	5	Edmonds et al. 1986	large branch	Angiosperm	elevated
0.035	Alnus	rubra	10	Edmonds et al. 1986	log	Angiosperm	elevated

K constant	Genus	Species	Size Class (cm)	Reference	Fuel Class	Classification	Notes
0.083	Alnus	rubra	25	Harmon 2005	large log	Angiosperm	https://andrewsforest.oregonstate.edu/sites/default/files/lter/pubs/webdocs/reports/decomp/cwd_decomp_web.htm
0.055	Alnus	rubra	25	Harmon 2005	large log	Angiosperm	
0.69	Artemisia	tridentata	litter	Comaner and Staffeldt 1979	foliage	Angiosperm	
0.6	Artemisia	tridentata	litter	Murray 1975	foliage	Angiosperm	
0.133	Banksia	grandis	bole and branch	Brown et al. 1996		Angiosperm	
0.252359	Banksia	grandis	4	Brown et al. 1996	large branch	Angiosperm	Derived values
0.070095	Banksia	grandis	12.5	Brown et al. 1996	log	Angiosperm	Dervied values
0.053	Betula	papyrifera	logs	Brais 2006	log	Angiosperm	>10cm
0.046	Betula	pendula	logs	Harmon 2000	log	Angiosperm	
0.042	Betula	spp.	31	Kahl et al. 2017	large log	Angiosperm	
0.045	Betula	spp.	log	Krankina & Harmon 1995	log	Angiosperm	>10 cm
0.149	Betula	lenta	21.5	Mattson 1987	large log	Angiosperm	CWD size found not to affect decomp rate
0.066	Betula	spp.	8	Shorohova and Kapitsa	log	Angiosperm	greater than 8cm
0.13	Betula	pendula	branch	Swift et al. 1976	branch	Angiosperm	CWD greater than 2cm
0.148	Betula	pendula	branch	Swift et al. 1976	branch	Angiosperm	CWD greater than 2cm
0.088	Betula	spp.	10	Tarasov and Birdsey 2001	log	Angiosperm	
0.039	Betula	spp.	37.5	Tarasov and Birdsey 2001	large log	Angiosperm	

K constant	Genus	Species	Size Class (cm)	Reference	Fuel Class	Classification	Notes
0.023	Betula	spp.	bark	Tarasov and Birdsey 2001	bark	Angiosperm	
0.054	Betula	pendula	log	Yatskov et al. 2003	log	Angiosperm	>10 cm
0.061	Betula	pendula	log	Yatskov et al. 2003	log	Angiosperm	>10 cm
0.042	Betula	pendula	log	Yatskov et al. 2003	log	Angiosperm	>10 cm
0.078	Betula	pendula	log	Yatskov et al. 2003	log	Angiosperm	>10 cm
0.03	Betula	costata	log	Yatskov et al. 2003	log	Angiosperm	>10 cm
0.027	Betula	pendula	snag	Yatskov et al. 2003	snag	Angiosperm	>10 cm
0.056	Betula	pendula	snag	Yatskov et al. 2003	snag	Angiosperm	>10 cm
0.052	Betula	pendula	snag	Yatskov et al. 2003	snag	Angiosperm	>10 cm
0.088	Betula	pendula	snag	Yatskov et al. 2003	snag	Angiosperm	>10 cm
0.081	Betula	costata	snag	Yatskov et al. 2003	snag	Angiosperm	>10 cm
0.02	Calocedrus	decurrens	52	Harmon 2005	large log	Gymnosperm	
0.16	Calocedrus	decurrens	litter	Stohlgren 1988	twigs	Gymnosperm	excludes initial 0.7 years, first fall and winter will give better description of long term litter decay
0.083	Carpinus	spp.	31	Kahl et al. 2017	large log	Angiosperm	
0.08	Carya	spp.	10	Harmon 1982	log	Angiosperm	
0.035	Carya	spp.	29.66667	MacMillan 1988	large log	Angiosperm	
0.166	Carya	spp.	13	Mattson 1987	log	Angiosperm	CWD size found not to affect decomp rate
0.041	Castanea	dentata	7.6	Mattson 1987	large branch	Angiosperm	CWD size found not to affect decomp rate
0.05	Cornus	florida	10	Harmon 1982	log	Angiosperm	
0.125	Cornus	florida	6.3	Mattson 1987	large branch	Angiosperm	CWD size found not to affect decomp rate

K constant	Genus	Species	Size Class (cm)	Reference	Fuel Class	Classification	Notes
0.068	Cornus/Quercus		0.5	Mattson 1987	twigs	Angiosperm	FWD
0.092	Cornus/Quercus		2	Mattson 1987	branch	Angiosperm	FWD
0.081	Cornus/Quercus		4	Mattson 1987	large branch	Angiosperm	FWD
0.098	Corylus	avellana	branch	Swift et al. 1976	branch	Angiosperm	CWD greater than 2cm
0.28	Corylus	avellana	branch	Swift et al. 1976	branch	Angiosperm	CWD greater than 2cm
0.261	Diospyros	virginiana	11.6	Mattson 1987	log	Angiosperm	CWD size found not to affect decomp rate
0.215	Eucalyptus	calophylla	bole and branch	Brown et al. 1996		Angiosperm	
0.174	Eucalyptus	diversicolor	bole and branch	Brown et al. 1996		Angiosperm	
0.067	Eucalyptus	marginata	bole and branch	Brown et al. 1996		Angiosperm	
0.407949	Eucalyptus	calophylla	4	Brown et al. 1996	large branch	Angiosperm	Derived values
0.330154	Eucalyptus	diversicolor	4	Brown et al. 1996	large branch	Angiosperm	Derived values
0.127128	Eucalyptus	marginata	4	Brown et al. 1996	large branch	Angiosperm	Derived values
0.113311	Eucalyptus	calophylla	12.5	Brown et al. 1996	log	Angiosperm	Derived values
0.091703	Eucalyptus	diversicolor	12.5	Brown et al. 1996	log	Angiosperm	Derived values
0.035311	Eucalyptus	marginata	12.5	Brown et al. 1996	log	Angiosperm	Derived values
0.041	Eucalyptus	regnans	20	Mackensen and Bauhus 2003	log	Angiosperm	
0.049	Eucalyptus	maculata	20	Mackensen and Bauhus 2003	log	Angiosperm	
0.107	Eucalyptus	diversicolor	0.8	O'connell 1997	twigs	Angiosperm	twigs
0.12	Eucalyptus	diversicolor	1.1	O'connell 1997	branch	Angiosperm	twigs
0.094	Eucalyptus	diversicolor	1.4	O'connell 1997	branch	Angiosperm	twigs
0.046	Eucalyptus	diversicolor	2.5	O'connell 1997	branch	Angiosperm	stem
0.03	Eucalyptus	diversicolor	4.3	O'connell 1997	large branch	Angiosperm	stem
0.022	Eucalyptus	diversicolor	8.4	O'connell 1997	log	Angiosperm	stem

K constant	Genus	Species	Size Class (cm)	Reference	Fuel Class	Classification	Notes
0.288	Fagus	sylvatica	twigs	Cotrufo 2000	twigs	Angiosperm	
0.223	Fagus	sylvatica	twigs	Cotrufo 2000	twigs	Angiosperm	
0.069	Fagus	spp.	31	Kahl et al. 2017	large log	Angiosperm	
0.0189	Fagus	spp.	15	MacMillan 1988	log	Angiosperm	
0.019	Fraxinus	spp.	31	Kahl et al. 2017	large log	Angiosperm	
0.071	Fraxinus	profunda	13.75	Rice et al. 1997	log	Angiosperm	values are averages of ranges of diameter
0.071	Fraxinus	profunda	1.5	Rice et al. 1997	branch	Angiosperm	values are averages of ranges of diameter
0.019	Fraxinus	excelsior	branch	Swift et al. 1976	branch	Angiosperm	CWD greater than 2cm
0.165	Fraxinus	excelsior	branch	Swift et al. 1976	branch	Angiosperm	CWD greater than 2cm
0.16	Juniperus	occidentalis	litter	Bates et al. 2007	foliage	Gymnosperm	cut treatment
0.09	Juniperus	occidentalis	litter	Bates et al. 2007	foliage	Gymnosperm	uncut treatment
0.008	Juniperus	communis	7.5	Devries and Kuyper 1988	large branch	Gymnosperm	branches
0.027	Juniperus	communis	7.5	Devries and Kuyper 1988	large branch	Gymnosperm	branches
0.044	Juniperus	communis	7.5	Devries and Kuyper 1988	large branch	Gymnosperm	branches
0.025	Juniperus	communis	7.5	Devries and Kuyper 1988	large branch	Gymnosperm	branches
0.06	Juniperus	communis	7.5	Devries and Kuyper 1988	large branch	Gymnosperm	branches
0.055	Juniperus	communis	7.5	Devries and Kuyper 1988	large branch	Gymnosperm	branches

K constant	Genus	Species	Size Class (cm)	Reference	Fuel Class	Classification	Notes
0.037	Kalmia	latifolia	8.5	Mattson 1987	log	Angiosperm	CWD size found not to affect decomp rate
0.004	Larix	spp.	31	Kahl et al. 2017	large log	Gymnosperm	
0.023	Larix	siberica	log	Yatskov et al. 2003	log	Gymnosperm	>10 cm
0.031	Larix	siberica	log	Yatskov et al. 2003	log	Gymnosperm	>10 cm
0.015	Larix	dahurica	log	Yatskov et al. 2003	log	Gymnosperm	>10 cm
0.004	Larix	siberica	snag	Yatskov et al. 2003	snag	Gymnosperm	>10 cm
0.01	Larix	siberica	snag	Yatskov et al. 2003	snag	Gymnosperm	>10 cm
0.009	Larix	dahurica	snag	Yatskov et al. 2003	snag	Gymnosperm	>10 cm
0.8	Larrea	tridentata	litter	Whitford et al. 1986	foliage	Angiosperm	
0.107	Liriodendron	tulipifera	6.4	Mattson 1987	large branch	Angiosperm	CWD size found not to affect decomp rate
0.0062	mixed		<45	MacMillan 1988	large log	Angiosperm	Analysis by size class regardless of spp.
0.0099	mixed		45	MacMillan 1988	large log	Angiosperm	Analysis by size class regardless of spp.
0.0051	mixed		25	MacMillan 1988	large log	Angiosperm	Analysis by size class regardless of spp.
0.0241	mixed		34.5	MacMillan 1988	large log	Angiosperm	Analysis by size class regardless of spp.
0.0099	mixed		45	MacMillan 1988	large log	Angiosperm	Analysis by size class regardless of spp.
0.0063	mixed		20	MacMillan 1988	large log	Angiosperm	Analysis by size class regardless of spp.
0.0027	mixed		30.5	MacMillan 1988	large log	Angiosperm	Analysis by size class regardless of spp.

K constant	Genus	Species	Size Class (cm)	Reference	Fuel Class	Classification	Notes
0.0098	mixed		50.5	MacMillan 1988	large log	Angiosperm	Analysis by size class regardless of spp.
0.0337	mixed		70.5	MacMillan 1988	large log	Angiosperm	Analysis by size class regardless of spp.
0.01	mixed		81	MacMillan 1988	large log	Angiosperm	Analysis by size class regardless of spp.
0.078	mixed species			Brown et al. 1996	log		
0.148	mixed species			Brown et al. 1996	branch		
0.2	Nyssa	sylvatica	10	Harmon 1982	log	Angiosperm	
0.126	Nyssa	sylvatica	10.8	Mattson 1987	log	Angiosperm	CWD size found not to affect decomp rate
0.05	Oxydendrum	arboreum	10	Harmon 1982	log	Angiosperm	
0.033	Oxydendrum	arboreum	12.7	Mattson 1987	log	Angiosperm	CWD size found not to affect decomp rate
0.071	Picea	glauca	12.7	Alban and Pastor 1993	log	Gymnosperm	
0.038	Picea	glauca	logs	Brais 2006	log	Gymnosperm	>10cm
0.033	Picea	rubens	12.5	Foster & Lang 1982	log	Gymnosperm	
0.027	Picea	rubens	20	Foster & Lang 1982	large log	Gymnosperm	
0.032	Picea	rubens	25	Foster & Lang 1982	large log	Gymnosperm	
0.011	Picea	rubens	12.5	Foster & Lang 1982	bark	Gymnosperm	bark
0.014	Picea	rubens	20	Foster & Lang 1982	bark	Gymnosperm	bark
0.022	Picea	rubens	25	Foster & Lang 1982	bark	Gymnosperm	bark
0.0096	Picea	sitchensis	>60	Graham and Cromack 1982	large log	Gymnosperm	
0.0119	Picea	sitchensis	<60	Graham and Cromack 1982	large log	Gymnosperm	

K constant	Genus	Species	Size Class (cm)	Reference	Fuel Class	Classification	Notes
0.0111	Picea	sitchensis	all	Graham and Cromack 1982	large log	Gymnosperm	
0.033	Picea	abies	logs	Harmon 2000	log	Gymnosperm	
0.028	Picea	engelmannii	52	Harmon 2005	large log	Gymnosperm	
0.023	Picea	sitchensis	52	Harmon 2005	large log	Gymnosperm	
0.0054	Picea	engelmannii	10	Johnson and Green 1991	log	Gymnosperm	boles
0.0025	Picea	engelmannii	10	Johnson and Green 1991	log	Gymnosperm	boles
0.035	Picea	spp.	31	Kahl et al. 2017	large log	Gymnosperm	
0.034	Picea	spp.	log	Krankina & Harmon 1995	log	Gymnosperm	>10 cm
0.0013	Picea	engelmannii	15.6	Kueppers et al. 2004	log	Gymnosperm	boles
0.0015	Picea	engelmannii	15.6	Kueppers et al. 2004	log	Gymnosperm	boles
0.0275	Picea	abies	10	Naesset 1999	large branch	Gymnosperm	less than 10
0.0342	Picea	abies	12.5	Naesset 1999	log	Gymnosperm	
0.0435	Picea	abies	18	Naesset 1999	log	Gymnosperm	
0.0391	Picea	abies	23	Naesset 1999	large log	Gymnosperm	
0.0412	Picea	abies	25	Naesset 1999	large log	Gymnosperm	greater than 25
0.059	Picea	abies	12.5	Tarasov and Birdsey 2001	log	Gymnosperm	
0.022	Picea	abies	30	Tarasov and Birdsey 2001	large log	Gymnosperm	
0.0215	Picea	abies	50	Tarasov and Birdsey 2001	large log	Gymnosperm	
0.017	Picea	abies	bark	Tarasov and Birdsey 2001	bark	Gymnosperm	

K constant	Genus	Species	Size Class (cm)	Reference	Fuel Class	Classification	Notes
0.027	Picea	abies	coarse roots	Tarasov and Birdsey 2001		Gymnosperm	
0.0265	Picea	engelmannii	branch	Taylor et al. 1991	branch	Gymnosperm	
0.0549	Picea	engelmannii	twigs (1hr)	Taylor et al. 1991	twigs	Gymnosperm	
0.1828	Picea	engelmannii	needles	Taylor et al. 1991	foliage	Gymnosperm	
0.026	Picea	abies	log	Yatskov et al. 2003	log	Gymnosperm	>10 cm
0.049	Picea	obovata	log	Yatskov et al. 2003	log	Gymnosperm	>10 cm
0.028	Picea	ajanensis	log	Yatskov et al. 2003	log	Gymnosperm	>10 cm
0.066	Picea	abies	snag	Yatskov et al. 2003	snag	Gymnosperm	>10 cm
-0.0006	Picea	obovata	snag	Yatskov et al. 2003	snag	Gymnosperm	>10 cm
0.035	Picea	ajanensis	snag	Yatskov et al. 2003	snag	Gymnosperm	>10 cm
0.055	Pinus	resinosa	14.4	Alban and Pastor 1993	log	Gymnosperm	
0.042	Pinus	banksiana	14.4	Alban and Pastor 1993	log	Gymnosperm	
0.058	Pinus	taeda	small	Barber and Van Lear 1984	branch	Gymnosperm	ground contact
0.081	Pinus	taeda	medium	Barber and Van Lear 1984	large branch	Gymnosperm	ground contact
0.068	Pinus	taeda	large	Barber and Van Lear 1984	log	Gymnosperm	ground contact
0.036	Pinus	taeda	small	Barber and Van Lear 1984	branch	Gymnosperm	aerial
0.057	Pinus	taeda	medium	Barber and Van Lear 1984	large branch	Gymnosperm	aerial
0.045	Pinus	taeda	large	Barber and Van Lear 1984	log	Gymnosperm	aerial
0.02	Pinus	banksiana	logs	Brais 2006	log	Gymnosperm	>10cm
0.049	Pinus	pinaster	bole and branch	Brown et al. 1996		Gymnosperm	
0.092974	Pinus	pinaster	4	Brown et al. 1996	large branch	Gymnosperm	Dervied values

K constant	Genus	Species	Size Class (cm)	Reference	Fuel Class	Classification	Notes
0.025824	Pinus	pinaster	12.5	Brown et al. 1996	log	Gymnosperm	Dervied values
0.027	Pinus	contorta	25	Busse 1994	large log	Gymnosperm	
0.022	Pinus	sylvestris	7.5	Devries and Kuyper 1988	large branch	Gymnosperm	branches
0.134	Pinus	sylvestris	7.5	Devries and Kuyper 1988	large branch	Gymnosperm	branches
0.054	Pinus	sylvestris	7.5	Devries and Kuyper 1988	large branch	Gymnosperm	branches
0.042	Pinus	sylvestris	7.5	Devries and Kuyper 1988	large branch	Gymnosperm	branches
0.113	Pinus	sylvestris	7.5	Devries and Kuyper 1988	large branch	Gymnosperm	branches
0.109	Pinus	sylvestris	7.5	Devries and Kuyper 1988	large branch	Gymnosperm	branches
0.013	Pinus	ponderosa	10	Erickson et al. 1985	log	Gymnosperm	suspended material
0.012	Pinus	ponderosa	10	Erickson et al. 1985	log	Gymnosperm	on ground
0.005	Pinus	ponderosa	1.5	Erickson et al. 1985	branch	Gymnosperm	suspended material
0.009	Pinus	ponderosa	1.5	Erickson et al. 1985	branch	Gymnosperm	on ground
0.0163	Pinus	contorta	15	Fahey 1983	log	Gymnosperm	
0.06	Pinus	rigida	10	Harmon 1982	log	Gymnosperm	
0.04	Pinus	virginiana	10	Harmon 1982	log	Gymnosperm	
0.035	Pinus	sylvestris	logs	Harmon 2000	log	Gymnosperm	
0.042	Pinus	contorta	52	Harmon 2005	large log	Gymnosperm	
0.035	Pinus	monticola	52	Harmon 2005	large log	Gymnosperm	
0.011	Pinus	ponderosa	52	Harmon 2005	large log	Gymnosperm	
0.042	Pinus	jefferyi	52	Harmon 2005	large log	Gymnosperm	

K constant	Genus	Species	Size Class (cm)	Reference	Fuel Class	Classification	Notes
0.036	Pinus	lambertiana	52	Harmon 2005	large log	Gymnosperm	
0.37	Pinus	ponderosa	litter	Hart et al. 1992	foliage	Gymnosperm	clearcut
0.17	Pinus	ponderosa	litter	Hart et al. 1992	foliage	Gymnosperm	forested
0.19	Pinus	ponderosa	litter	Hart et al. 1992	foliage	Gymnosperm	young forest
0.08	Pinus	ponderosa	litter	Hart et al. 1992	foliage	Gymnosperm	old forest
0.0171	Pinus	contorta	10	Johnson and Green 1991	log	Gymnosperm	boles
0.0299	Pinus	contorta	10	Johnson and Green 1991	log	Gymnosperm	boles
0.0153	Pinus	contorta	10	Johnson and Green 1991	log	Gymnosperm	boles
0.0045	Pinus	contorta	10	Johnson and Green 1991	log	Gymnosperm	boles
0.0035	Pinus	contorta	10	Johnson and Green 1991	log	Gymnosperm	boles
0.016	Pinus	spp.	31	Kahl et al. 2017	large log	Gymnosperm	
0.226	Pinus	albicaulis	foliage	Keane et al. 2008	foliage	Gymnosperm	
0.195	Pinus	contorta	foliage	Keane et al. 2008	foliage	Gymnosperm	
0.111	Pinus	ponderosa	foliage	Keane et al. 2008	foliage	Gymnosperm	
0.083	Pinus	albicaulis	twigs (1hr)	Keane et al. 2008	twigs	Gymnosperm	
0.093	Pinus	contorta	twigs (1hr)	Keane et al. 2008	twigs	Gymnosperm	
0.039	Pinus	ponderosa	twigs (1hr)	Keane et al. 2008	twigs	Gymnosperm	
0.069	Pinus	albicaulis	branch (10hr)	Keane et al. 2008	branch	Gymnosperm	
0.045	Pinus	contorta	branch (10hr)	Keane et al. 2008	branch	Gymnosperm	
0.028	Pinus	ponderosa	branch (10hr)	Keane et al. 2008	branch	Gymnosperm	
0.05	Pinus	albicaulis	large branch (100hr)	Keane et al. 2008	large branch	Gymnosperm	
0.041	Pinus	contorta	large branch (100hr)	Keane et al. 2008	large branch	Gymnosperm	

K constant	Genus	Species	Size Class (cm)	Reference	Fuel Class	Classification	Notes
0.075	Pinus	ponderosa	large branch (100hr)	Keane et al. 2008	large branch	Gymnosperm	
0.033	Pinus	spp.	log	Krankina & Harmon 1995	log	Gymnosperm	>10 cm
0.0029	Pinus	ponderosa	15.6	Kueppers et al. 2004	log	Gymnosperm	boles
0.0016	Pinus	ponderosa	15.6	Kueppers et al. 2004	log	Gymnosperm	boles
0.127	Pinus	radiata	20	Mackensen and Bauhus 2003	log	Gymnosperm	diameter given as range between 10 and 30cm
0.063	Pinus	rigida	6.9	Mattson 1987	large branch	Gymnosperm	CWD size found not to affect decomp rate
0.12	Pinus	pinaster	litter	Moro and Domingo 2000	foliage	Gymnosperm	
0.17	Pinus	nigra	litter	Moro and Domingo 2000	foliage	Gymnosperm	
0.027	Pinus	sylvestris	8	Shorohova and Kapitsa	log	Gymnosperm	greater than 8cm
0.014	Pinus	sibirica	8	Shorohova and Kapitsa	log	Gymnosperm	greater than 8cm
0.12	Pinus	lambertiana	litter	Stohlgren 1988	twigs	Gymnosperm	excludes initial 0.7 years, first fall and winter will give better description of long term litter decay
0.1	Pinus	lambertiana	litter	Stohlgren 1988	twigs	Gymnosperm	excludes initial 0.7 years, first fall and winter will give better description of long term litter decay
0.041	Pinus	sylvestris	10	Tarasov and Birdsey 2001	log	Gymnosperm	
0.0185	Pinus	sylvestris	25	Tarasov and Birdsey 2001	large log	Gymnosperm	

K constant	Genus	Species	Size Class (cm)	Reference	Fuel Class	Classificat ion	Notes
0.018	Pinus	sylvestri s	45	Tarasov and Birdsey 2001	large log	Gymnosp erm	
0.009	Pinus	sylvestri s	bark	Tarasov and Birdsey 2001	bark	Gymnosp erm	
0.0521	Pinus	contorta	branch	Taylor et al. 1991	branch	Gymnosp erm	
0.0549	Pinus	contorta	twigs (1hr)	Taylor et al. 1991	twigs	Gymnosp erm	
0.1151	Pinus	contorta	needles	Taylor et al. 1991	foliage	Gymnosp erm	
0.027	Pinus	sylvestri s	log	Yatskov et al. 2003	log	Gymnosp erm	>10 cm
0.044	Pinus	sylvestri s	log	Yatskov et al. 2003	log	Gymnosp erm	>10 cm
0.036	Pinus	sylvestri s	log	Yatskov et al. 2003	log	Gymnosp erm	>10 cm
0.019	Pinus	siberica	log	Yatskov et al. 2003	log	Gymnosp erm	>10 cm
0.015	Pinus	koraiens is	log	Yatskov et al. 2003	log	Gymnosp erm	>10 cm
0.037	Pinus	sylvestri s	snag	Yatskov et al. 2003	snag	Gymnosp erm	>10 cm
-0.02	Pinus	sylvestri s	snag	Yatskov et al. 2003	snag	Gymnosp erm	>10 cm
0.004	Pinus	sylvestri s	snag	Yatskov et al. 2003	snag	Gymnosp erm	>10 cm
0.003	Pinus	siberica	snag	Yatskov et al. 2003	snag	Gymnosp erm	>10 cm
0.003	Pinus	koraiens is	snag	Yatskov et al. 2003	snag	Gymnosp erm	>10 cm
0.235	Pinus	contorta	litter	Yavitt and Fahey 1986	foliage	Gymnosp erm	
0.05	Pinus	ponderosa		Avery et al. 1976	log	Gymnosp erm	
0.4	Pinus	contorta		Keenan et al. 1996	foliage	Gymnosp erm	
0.023	Pinus	contorta	52	Harmon 2005	large log	Gymnosp erm	
0.08	Populu s	tremuloi des	15.3	Alban and Pastor 1993	log	Angiosper m	
0.06	Populu s	tremuloi des	logs	Brais 2006	log	Angiosper m	>10cm
0.055	Populu s	spp.	31	Kahl et al. 2017	large log	Angiosper m	

K constant	Genus	Species	Size Class (cm)	Reference	Fuel Class	Classification	Notes
0.295	Populus	tremuloides	litter	Louiser and Parkinson 1976	foliage	Angiosperm	
0.071	Populus	tremula	15	Tarasov and Birdsey 2001	log	Angiosperm	
0.044	Populus	tremula	42.5	Tarasov and Birdsey 2001	large log	Angiosperm	
0.018	Populus	tremula	bark	Tarasov and Birdsey 2001	bark	Angiosperm	
0.031	Prunus	spp.	31	Kahl et al. 2017	large log	Angiosperm	
0.036	Psuedotsuga	menziesii	1.5	Edmonds et al. 1986	branch	Gymnosperm	surface
0.027	Psuedotsuga	menziesii	5	Edmonds et al. 1986	large branch	Gymnosperm	surface
0.013	Psuedotsuga	menziesii	10	Edmonds et al. 1986	log	Gymnosperm	surface
0.038	Psuedotsuga	menziesii	1.5	Edmonds et al. 1986	branch	Gymnosperm	surface
0.013	Psuedotsuga	menziesii	5	Edmonds et al. 1986	large branch	Gymnosperm	surface
0.019	Psuedotsuga	menziesii	10	Edmonds et al. 1986	log	Gymnosperm	surface
0.033	Psuedotsuga	menziesii	1.5	Edmonds et al. 1986	branch	Gymnosperm	elevated
0.022	Psuedotsuga	menziesii	5	Edmonds et al. 1986	large branch	Gymnosperm	elevated
0.007	Psuedotsuga	menziesii	10	Edmonds et al. 1986	log	Gymnosperm	elevated
0.029	Psuedotsuga	menziesii	1.5	Edmonds et al. 1986	branch	Gymnosperm	elevated
0.016	Psuedotsuga	menziesii	5	Edmonds et al. 1986	large branch	Gymnosperm	elevated
0.012	Psuedotsuga	menziesii	10	Edmonds et al. 1986	log	Gymnosperm	elevated
0.016	Psuedotsuga	menziesii	10	Erickson et al. 1985	log	Gymnosperm	suspended material
0.037	Psuedotsuga	menziesii	10	Erickson et al. 1985	log	Gymnosperm	on ground
0.004	Psuedotsuga	menziesii	1.5	Erickson et al. 1985	branch	Gymnosperm	suspended material
0.011	Psuedotsuga	menziesii	1.5	Erickson et al. 1985	branch	Gymnosperm	on ground
0.015	Psuedotsuga	menziesii	52	Harmon 2005	large log	Gymnosperm	

K constant	Genus	Species	Size Class (cm)	Reference	Fuel Class	Classification	Notes
0.014	Psuedo tsuga	menziesii	52	Harmon 2005	large log	Gymnosperm	
0.016	Psuedo tsuga	menziesii	log	Janish 2005	log	Gymnosperm	
0.002	Psuedo tsuga	spp.	31	Kahl et al. 2017	large log	Gymnosperm	
0.12	Psuedo tsuga	menziesii	foliage	Keane et al. 2008	foliage	Gymnosperm	
0.084	Psuedo tsuga	menziesii	twigs (1hr)	Keane et al. 2008	twigs	Gymnosperm	
0.031	Psuedo tsuga	menziesii	branch (10hr)	Keane et al. 2008	branch	Gymnosperm	
0.142	Psuedo tsuga	menziesii	large branch (100hr)	Keane et al. 2008	large branch	Gymnosperm	
0.0063	Psuedo tsuga	menziesii	logs	Means et al. 1985	large log	Gymnosperm	greater than 50
0.007	Psuedo tsuga	menziesii	logs	Means et al. 1985	large log	Gymnosperm	greater than 50
0.01	Psuedo tsuga	menziesii	logs	Sollins et al. 1987	large log	Gymnosperm	median 55
0.029	Psuedo tsuga	menziesii	logs	Spies et al. 1988	log	Gymnosperm	10cm to 60cm
0.022	Psuedo tsuga	menziesii	logs	Stone et al. 1997	large log	Gymnosperm	all diameters
0.067	Psuedo tsuga	menziesii	20	Stone et al. 1997	log	Gymnosperm	
0.056	Psuedo tsuga	menziesii	30	Stone et al. 1997	large log	Gymnosperm	
0.021	Psuedo tsuga	menziesii	60	Stone et al. 1997	large log	Gymnosperm	
0.012	Psuedo tsuga	menziesii	80	Stone et al. 1997	large log	Gymnosperm	
0.1244	Quercus	prinus	0.5	Abbott and Crossley 1982	twigs	Angiosperm	
0.1144	Quercus	prinus	2	Abbott and Crossley 1982	branch	Angiosperm	
0.0978	Quercus	prinus	4	Abbott and Crossley 1982	large branch	Angiosperm	
0.26	Quercus	spp.	litter	Christensen 1977	foliage	Angiosperm	
0.066	Quercus	robur	7.5	Devries and Kuyper 1988	large branch	Angiosperm	branches

K constant	Genus	Species	Size Class (cm)	Reference	Fuel Class	Classification	Notes
0.273	Quercus	robur	7.5	Devries and Kuyper 1988	large branch	Angiosperm	branches
0.489	Quercus	robur	7.5	Devries and Kuyper 1988	large branch	Angiosperm	branches
0.253	Quercus	robur	7.5	Devries and Kuyper 1988	large branch	Angiosperm	branches
0.151	Quercus	robur	7.5	Devries and Kuyper 1988	large branch	Angiosperm	branches
0.175	Quercus	robur	7.5	Devries and Kuyper 1988	large branch	Angiosperm	branches
0.1	Quercus	coccinea	10	Harmon 1982	log	Angiosperm	
0.18	Quercus	prinus	10	Harmon 1982	log	Angiosperm	
0.021	Quercus	spp.	31	Kahl et al. 2017	large log	Angiosperm	
0.0175	Quercus	spp.	43	MacMillan 1988	large log	Angiosperm	size classes are averages by species
0.05	Quercus	coccinea	14.9	Mattson 1987	log	Angiosperm	CWD size found not to affect decomp rate
0.063	Quercus	alba	11.4	Mattson 1987	log	Angiosperm	CWD size found not to affect decomp rate
0.17	Quercus	prinus	8.7	Mattson 1987	log	Angiosperm	CWD size found not to affect decomp rate
0.28	Quercus	spp.	30	Schowalter 1992	large log	Angiosperm	
0.069	Quercus	spp.	30	Schowalter 1998	large log	Angiosperm	
0.088	Quercus	robur	branch	Swift et al. 1976	branch	Angiosperm	CWD greater than 2cm
0.067	Quercus	robur	branch	Swift et al. 1976	branch	Angiosperm	CWD greater than 2cm
0.059	Rhododendron	maximum	6	Mattson 1987	large branch	Angiosperm	CWD size found not to affect decomp rate

K constant	Genus	Species	Size Class (cm)	Reference	Fuel Class	Classification	Notes
0.015	Robinia	pseudoacacia	9.7	Mattson 1987	log	Angiosperm	CWD size found not to affect decomp rate
0.2	Salvia	mellifera	litter	Schlesinger 1985	foliage	Angiosperm	
0.024	Sequoia	sempervirens	10	Busing and Fijumori 2005	large branch	Gymnosperm	size classes below 10cm
0.07	Sequoiadendron	giganteum	litter	Stohlgren 1988	twigs	Gymnosperm	excludes initial 0.7 years, first fall and winter wil give better description of long term litter decay
0.007	Thuja	plicata	52	Harmon 2005	large log	Gymnosperm	
0.165	Thuja	plicata	foliage	Keane et al. 2008	foliage	Gymnosperm	
0.093	Thuja	plicata	twigs (1hr)	Keane et al. 2008	twigs	Gymnosperm	
0.047	Thuja	plicata	branch (10hr)	Keane et al. 2008	branch	Gymnosperm	
0.023	Thuja	plicata	large branch (100hr)	Keane et al. 2008	large branch	Gymnosperm	
0.009	Thuja	plicata	logs	Sollins et al. 1987	large log	Gymnosperm	median 30
0.035	Tilia	spp.	31	Kahl et al. 2017	large log	Angiosperm	
0.024	Tsuga	heterophylla	10	Erickson et al. 1985	log	Gymnosperm	suspended material
0.036	Tsuga	heterophylla	10	Erickson et al. 1985	log	Gymnosperm	on ground
0.01	Tsuga	heterophylla	1.5	Erickson et al. 1985	branch	Gymnosperm	suspended material
0.01	Tsuga	heterophylla	1.5	Erickson et al. 1985	branch	Gymnosperm	on ground
0.0079	Tsuga	heterophylla	>30	Graham and Cromack 1982	large log	Gymnosperm	
0.023	Tsuga	heterophylla	<30	Graham and Cromack 1982	large log	Gymnosperm	
0.01	Tsuga	heterophylla	all	Graham and Cromack 1982	large log	Gymnosperm	

K constant	Genus	Species	Size Class (cm)	Reference	Fuel Class	Classification	Notes
0.0118	Tsuga	heterophylla	35	Grier 1978	large log	Gymnosperm	
0.04	Tsuga	canadensis	10	Harmon 1982	log	Gymnosperm	
0.023	Tsuga	heterophylla	52	Harmon 2005	large log	Gymnosperm	
0.026	Tsuga	heterophylla	52	Harmon 2005	large log	Gymnosperm	
0.018	Tsuga	heterophylla	52	Harmon 2005	large log	Gymnosperm	
0.015	Tsuga	heterophylla	log	Janish 2005	log	Gymnosperm	
0.024	Tsuga	canadensis	7.6	Mattson 1987	large branch	Gymnosperm	CWD size found not to affect decomp rate
0.016	Tsuga	heterophylla	logs	Sollins et al. 1987	large log	Gymnosperm	median 30
0.021	Tsuga	canadensis	30	Tyrrell and Crow 1994	large log	Gymnosperm	
0.029			litter	Rosswall 1975	foliage		mixed pine and beech
0.0245			litter	Rosswall 1975	foliage		mixed pine and beech
0.0318			litter	Rosswall 1975	foliage		mixed pine and beech
0.029			litter	Rosswall 1975	foliage		mixed pine and beech

APPENDIX C
Fire Methodology Details

Additional fire methodology details here. Wind adjustment factors are calculated using the decision tree shown in Figure 25.

Additional details on fire methodology can be found in a separate document labeled “Appendix C Fire Methodology Report.pdf”.

Fuel loading is predicted using regression trees that are used to partitioned forest residue according to the proportions of each time-lag size class in the existing FCCS fuelbed. Regression trees are grown so every node contains a single fuel model. An example regression tree is shown in Figure 26.

Figure 25: Wind Adjustment Factors for Site Characteristics

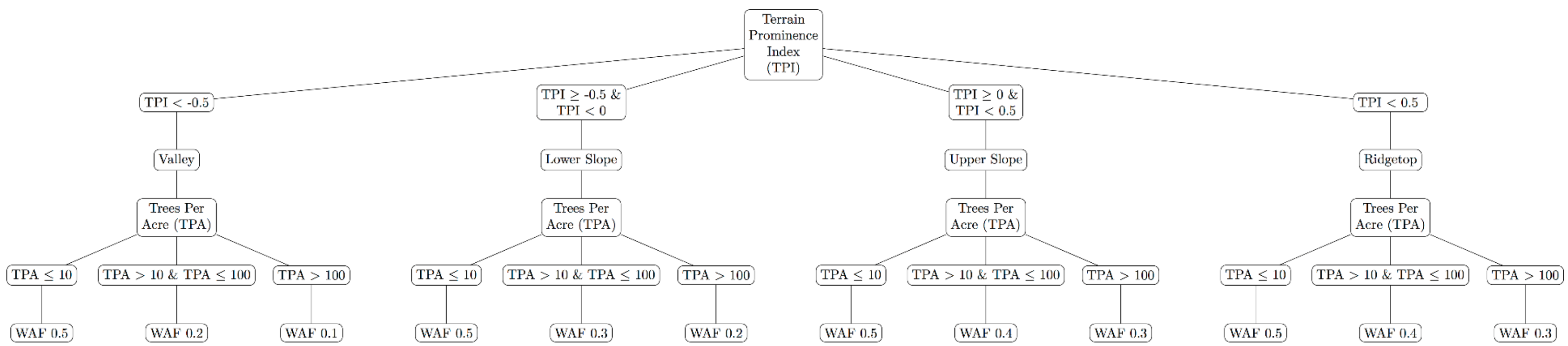
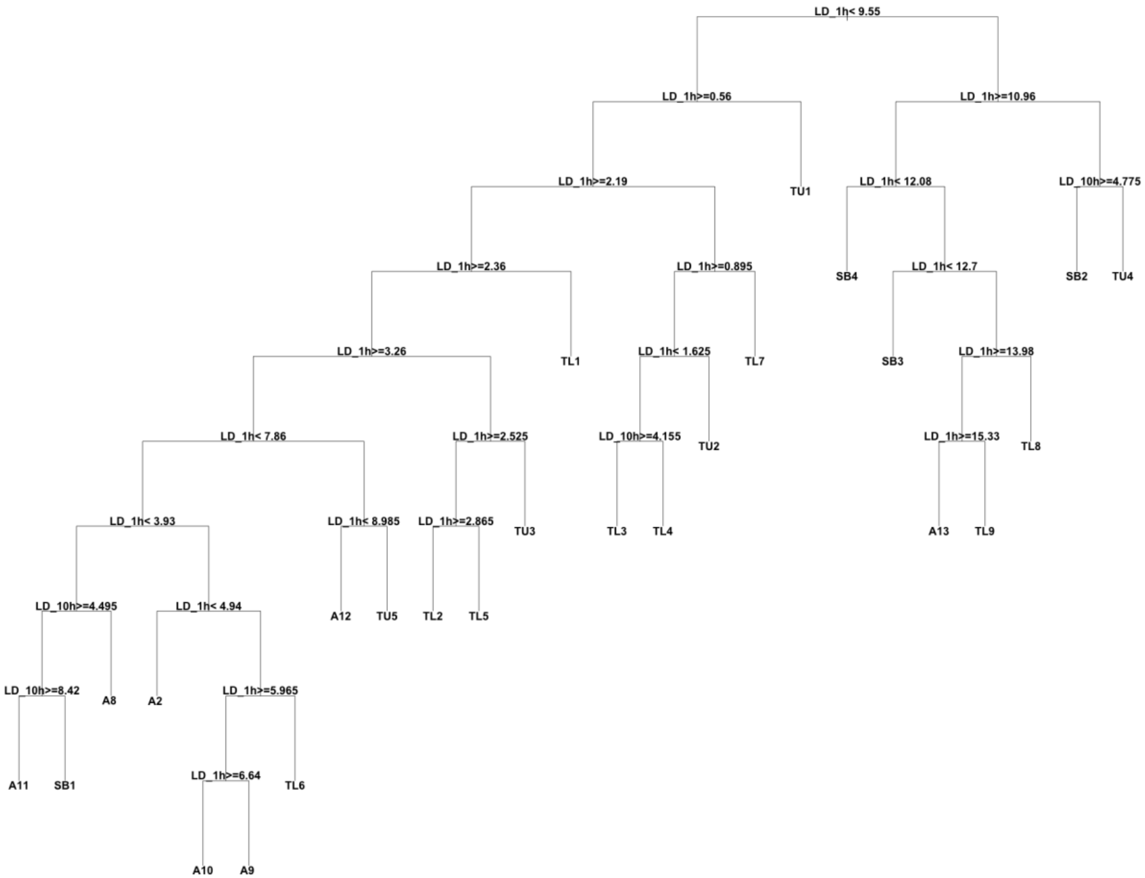


Figure 26: Example Fuel Model Prediction Regression Tree



C.1 Comparison in Crown Biomass Between C-BREC Data Set, FVS, and FCCS

During the decision process for whether or not to use FVS or FCCS for developing fueling loading for in-field combustion, an analysis was conducted to estimate how reasonably these two data sets correlate with the forest biomass residue amounts developed by NRSIG for the C-BREC Model. This analysis is included on the following pages.

Compare Crown Biomass: FCCS, FVS, & UW

Micah Wright

July 12, 2018

Purpose

This document performs a small analysis on the differences in crown fuel loading between the FCCS, UW, and FVS (representative stand) data sets.

Assumptions, probably wrong:

1. The sum of the FCCS overstory, midstory, and understory crown loadings are approximating roughly the same thing as the sum of the cut branches and foliage from the UW raster, and the live foliage and live 0-3" in the represenatative stands fuel database.
2. The relationships in the sample area reflect broader relationships at the state level. This is almost certainly untrue, I suspect that these relationships vary considerably by forest type. However, the computation time is much lower when we use a small study area, and I believe gives at least a rough Idea of what we're dealing with.

Setup

Load the necessary packages. Most of this is done in base R to avoid conficts with the raster package.

```
library(raster)
library(rgdal)
```

Data import and processing

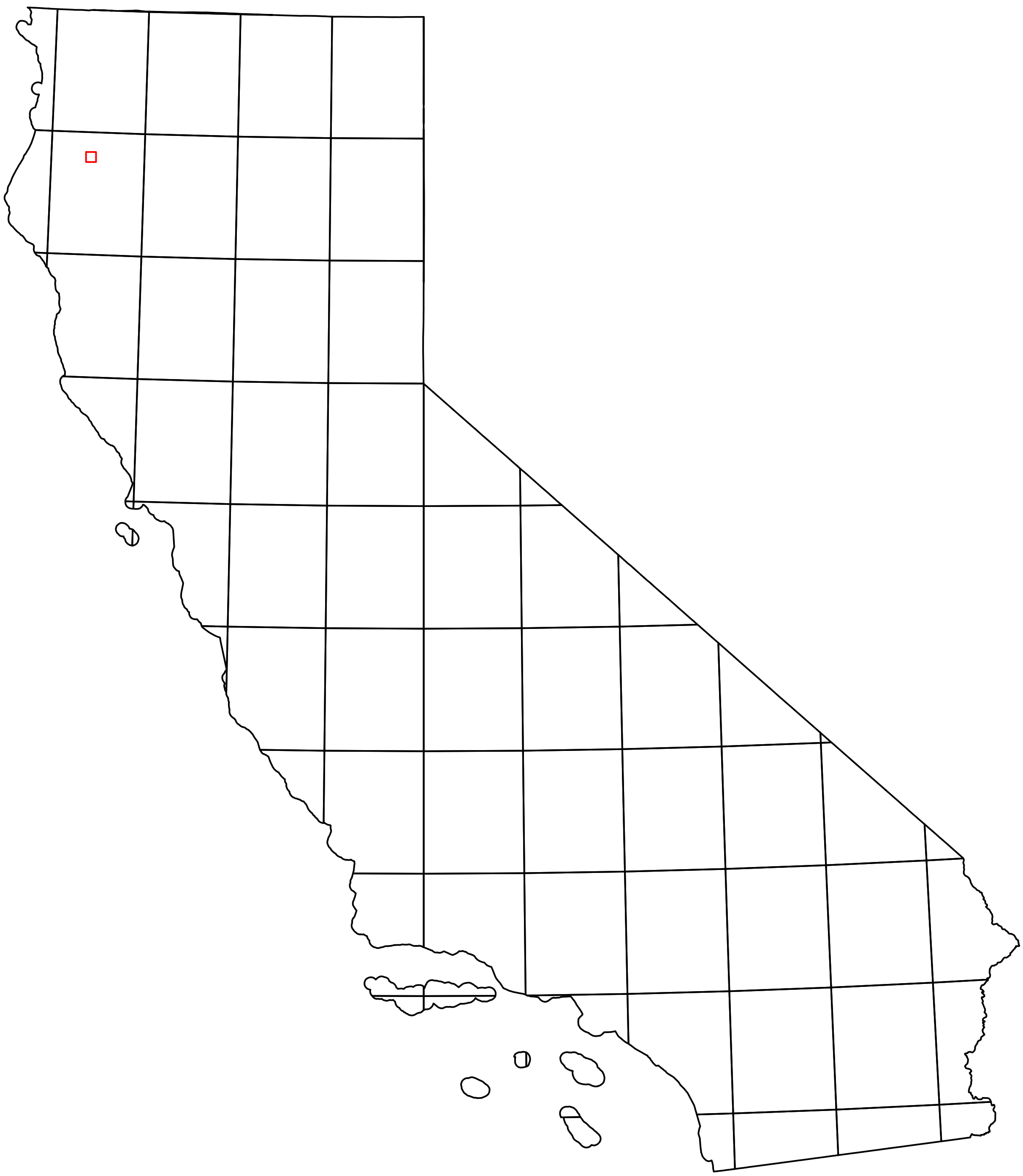
Create a somewhat arbitrary extent to crop the rasters. It's a small area near the Humboldt-Trinity border, plotted in red below.

```
small <- extent(c(-306191.6, -297114.6, 310269.4, 319346.4))
```

```
plot(spTransform(readOGR("data/Other/srtm_1_deg",
             "srtm_1_deg"),
             crs(raster("data/FCCS/spatial/FCCS_NAD83.tif"))))
```

```
## OGR data source with driver: ESRI Shapefile
## Source: "data/Other/srtm_1_deg", layer: "srtm_1_deg"
## with 69 features
## It has 1 fields
```

```
plot(small, add = TRUE, col = "red")
```



FCCS data

Load the FCCS raster and crop it.

```
FCCS <- raster("data/FCCS/spatial/FCCS_NAD83.tif")

FCCS <- crop(FCCS, small)
```

Load the FCCS fuel model data from Landfire.

```
FL <- read.csv("data/FCCS/tabular/LF_consume.csv",
                 stringsAsFactors = FALSE,
                 header = FALSE)
```

The csv is in a Consume-specific format (header row is not column names- they're on the second row) that we need to change for R to understand the column names. First, get the header rows, which contain the actual column names in the second row.

```
KeepHead <- FL[1:2, ]
```

Subset the data frame so it only contain the loading values (no header rows). Reassign the column names from the previous chunk.

```
FL <- FL[3:nrow(FL), ]

names(FL) <- KeepHead[2, ]
```

Select only the columns of interest, and convert them to numeric. Fuelbed number corresponds to pixel value, the others are crown loading columns.

```
FL <- subset(FL, select = c(fuelbed_number,
                            overstory_loading:understory_loading))
FL[] <- lapply(FL, function(x) as.numeric(x))
```

Calculate the total crown fuel load, converting to pounds per acre (FCCS is in tons per acre, while UW is in pounds).

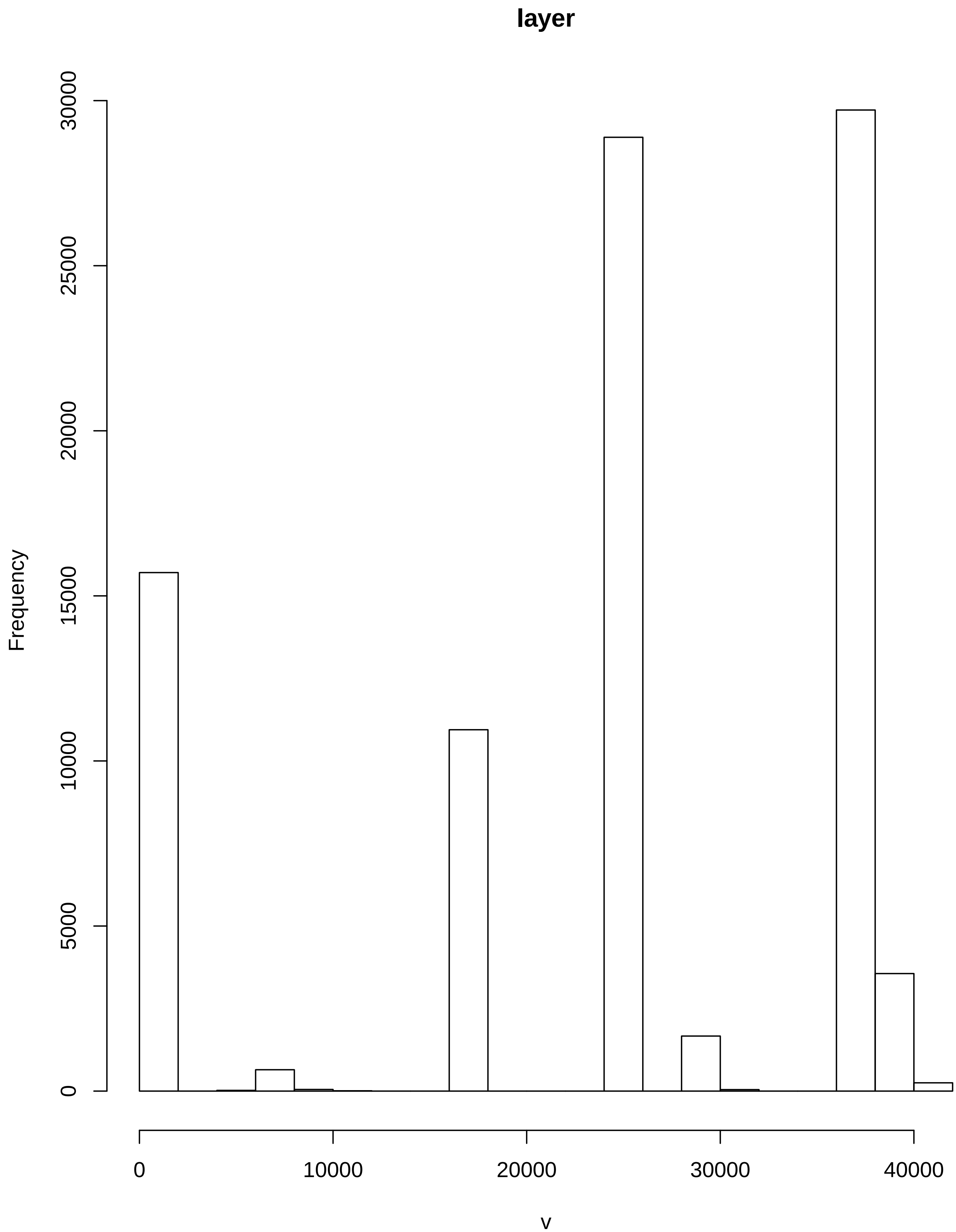
```
FL$total_crown_load <- base::rowSums(subset(FL, select = overstory_loading:understory_loading)) * 2000
```

Make a matrix to reclassify the raster. Pixel values will represent total crown load.

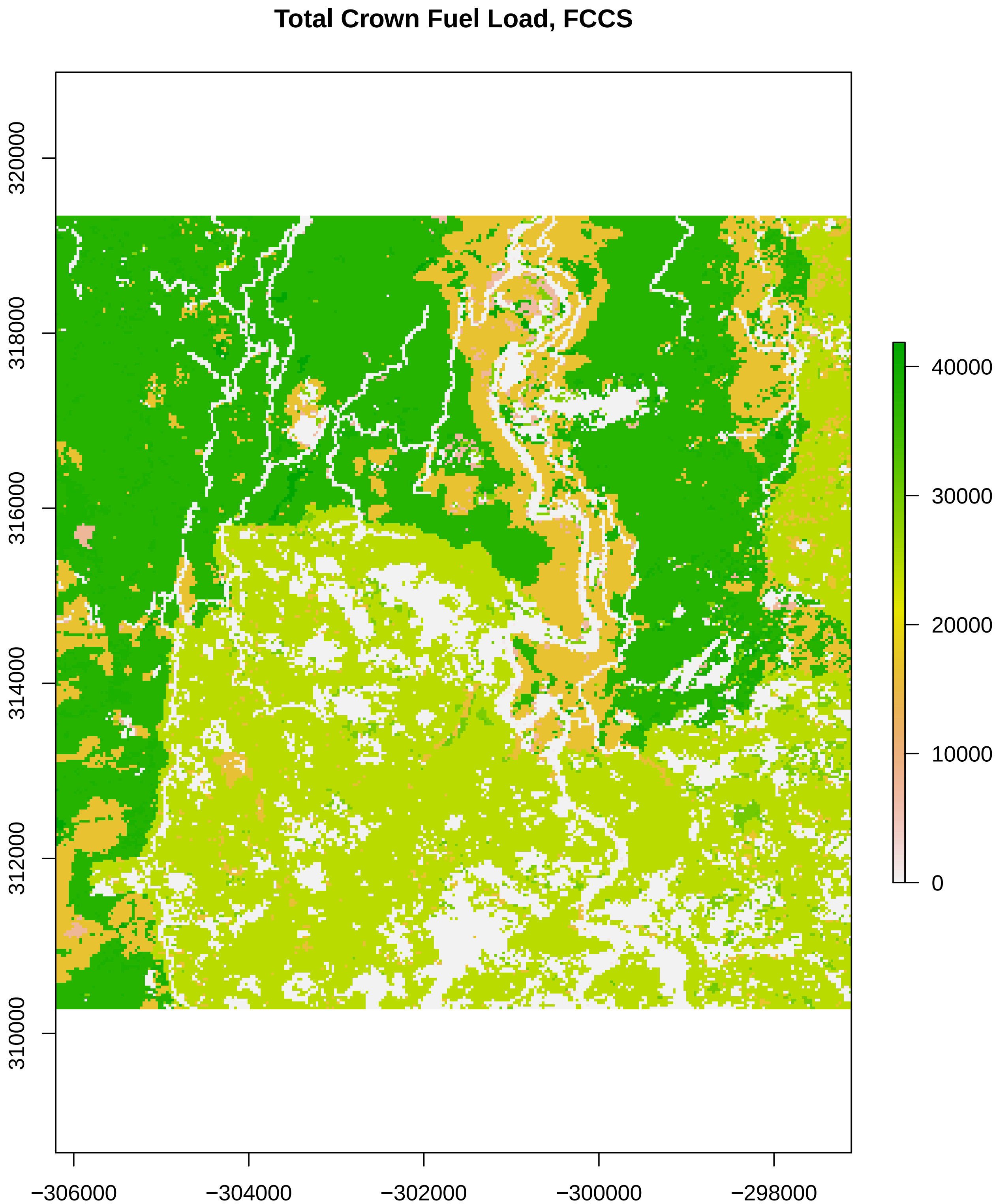
```
fccs_recl <- cbind(FL$fuelbed_number, FL$total_crown_load)

FCCS_Crown <- reclassify(FCCS, fccs_recl)
```

Check out a histogram and plot the raster.

```
hist(FCCS_Crown)
```




```r
plot(FCCS_Crown)
title(main = "Total Crown Fuel Load, FCCS")
```



The catagorical nature of the FCCS fuelbeds is pretty obvious here.

UW data

Load the UW raster and crop it.

```r
UW <- raster("data/UW/UW_FCID.tif")

UW <- crop(UW, small)
```

Load the clearcut (removed 100%) attribute table.

```r
CC <- foreign::read.dbf("data/UW/batch_out/Treatment_Remove100Percent.dbf", as.is = TRUE)
```

Select the columns of interest and filter out the rows not in the raster.

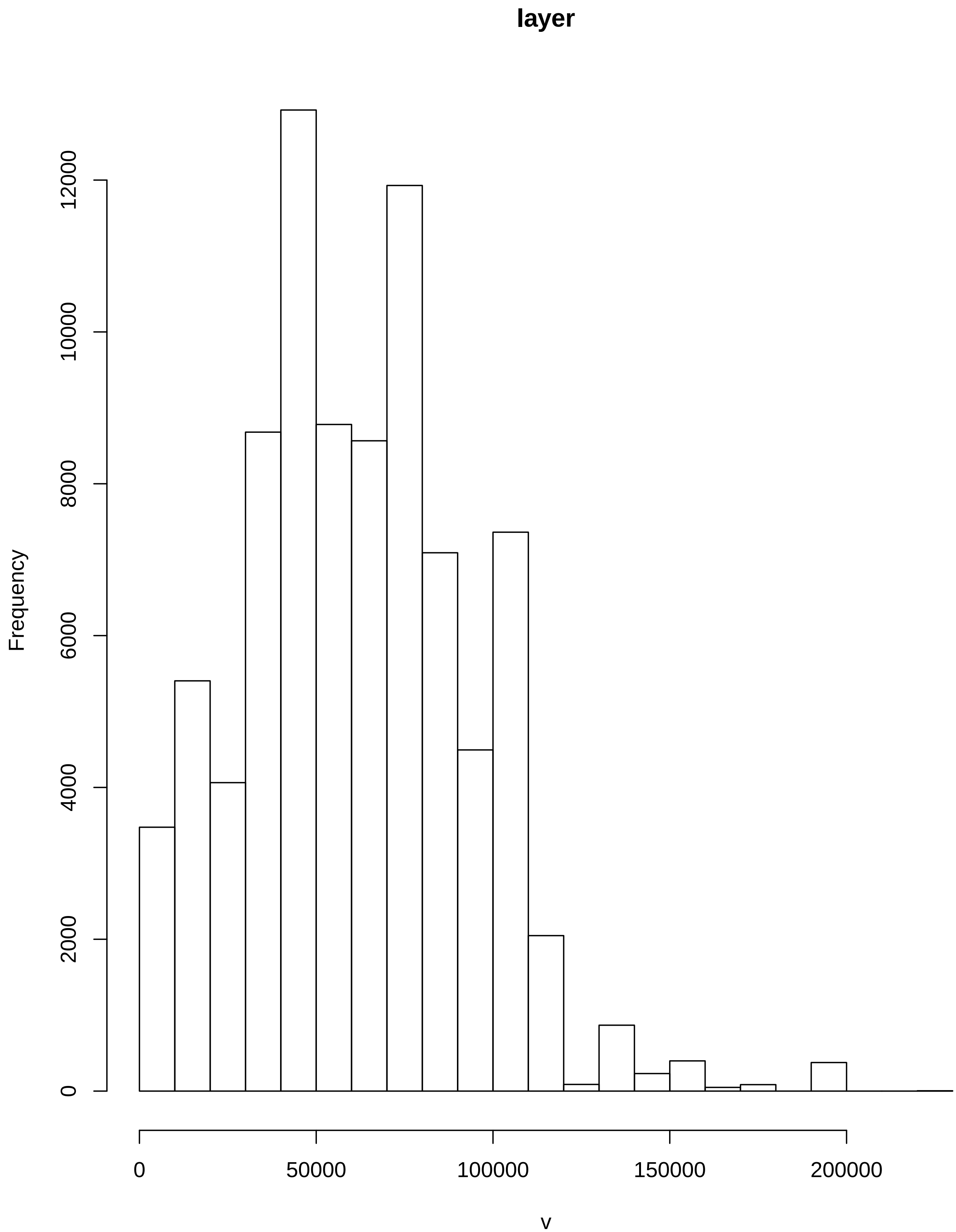
```r
CC <- subset(CC, select = c(Value, CutBranchB, CutFoliage))

CC <- CC[CC$Value %in% unique(values(UW)), ]
```

Calculate total crown load, and reclassify the raster.

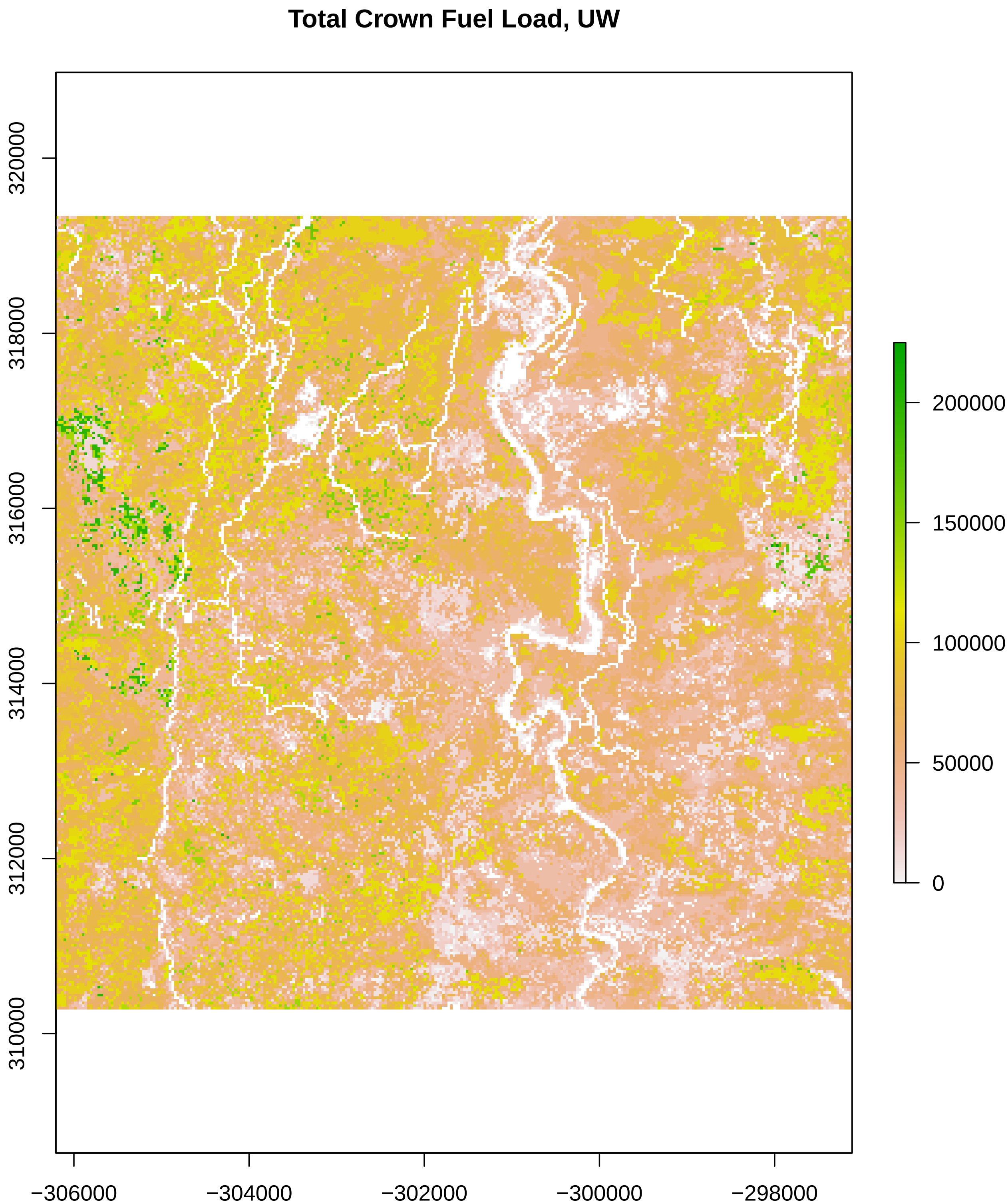
```r
CC$total_crown_load <- base::rowSums(subset(CC, select = c(CutBranchB, CutFoliage)))

cc_recl <- cbind(CC$Value, CC$total_crown_load)

UW_Crown <- reclassify(UW, cc_recl)
```

Check the histogram and plot.

```r
hist(UW_Crown)
```




```r
plot(UW_Crown)
title(main = "Total Crown Fuel Load, UW")
```



FVS data

Load the fuel data for the representative stands, estimated with FVS. Incidentally, this was also processed by UW, but it makes more sense (at least to me) to name it this way.

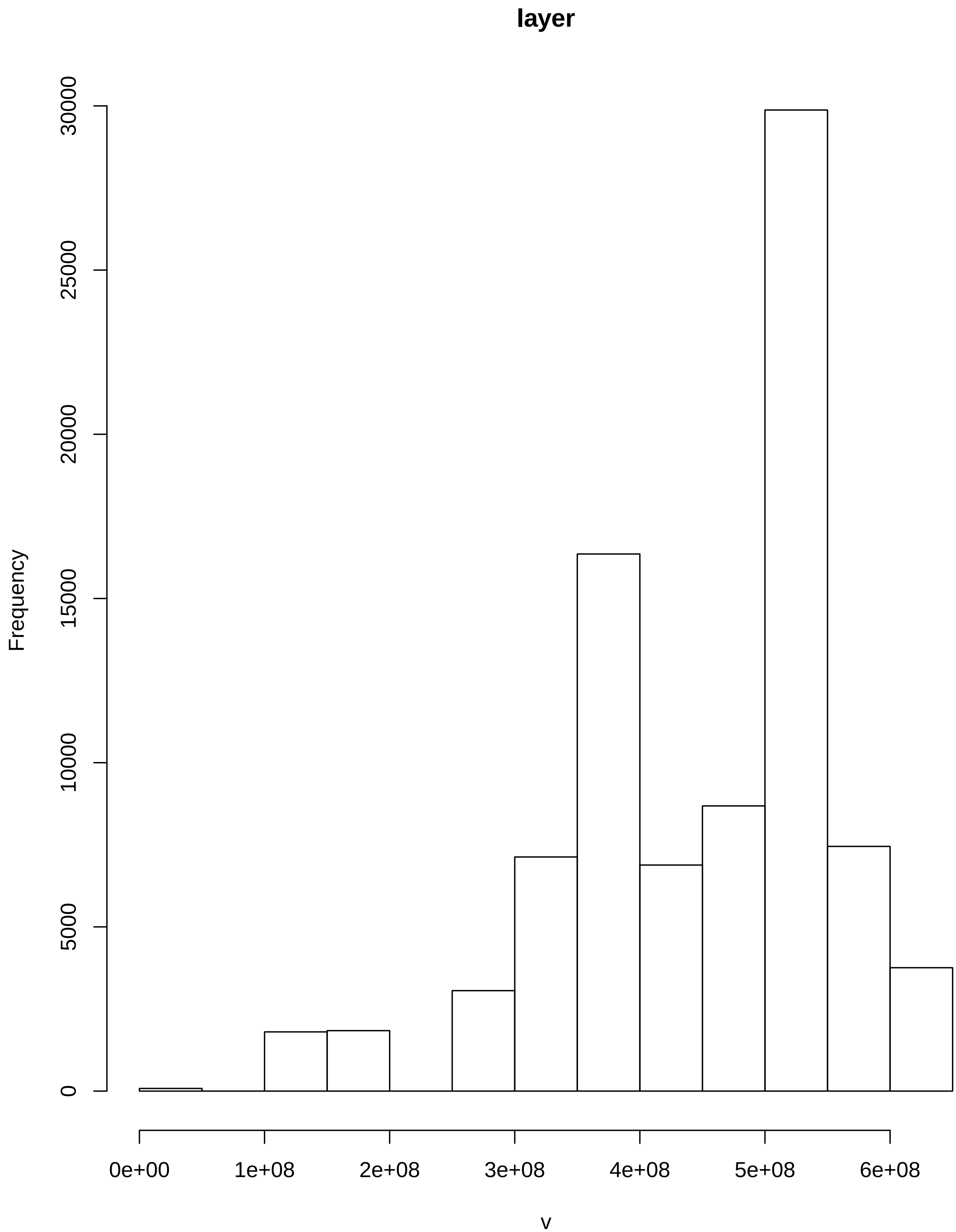
```
FVS <- readxl::read_xlsx("data/UW/Fuels.xlsx")
```

Select the live foliage and 0-3" material, calculate total crown load, and reclassify the raster. I've left out material >3", because even though stem wood is included in 0-3", it's probably a better comparison without including >3". It should be noted that this may be a poor representation of crown fuel loading. However, I'm assuming that the correlations should be roughly the same.

```
FVS$total_crown_load <- base::rowSums(subset(FVS, select = c(LiveFoliage, Live0To3)))

fvs_recl <- cbind(FVS$FCID, FVS$total_crown_load)

FVS_Crown <- reclassify(UW, fvs_recl)
```

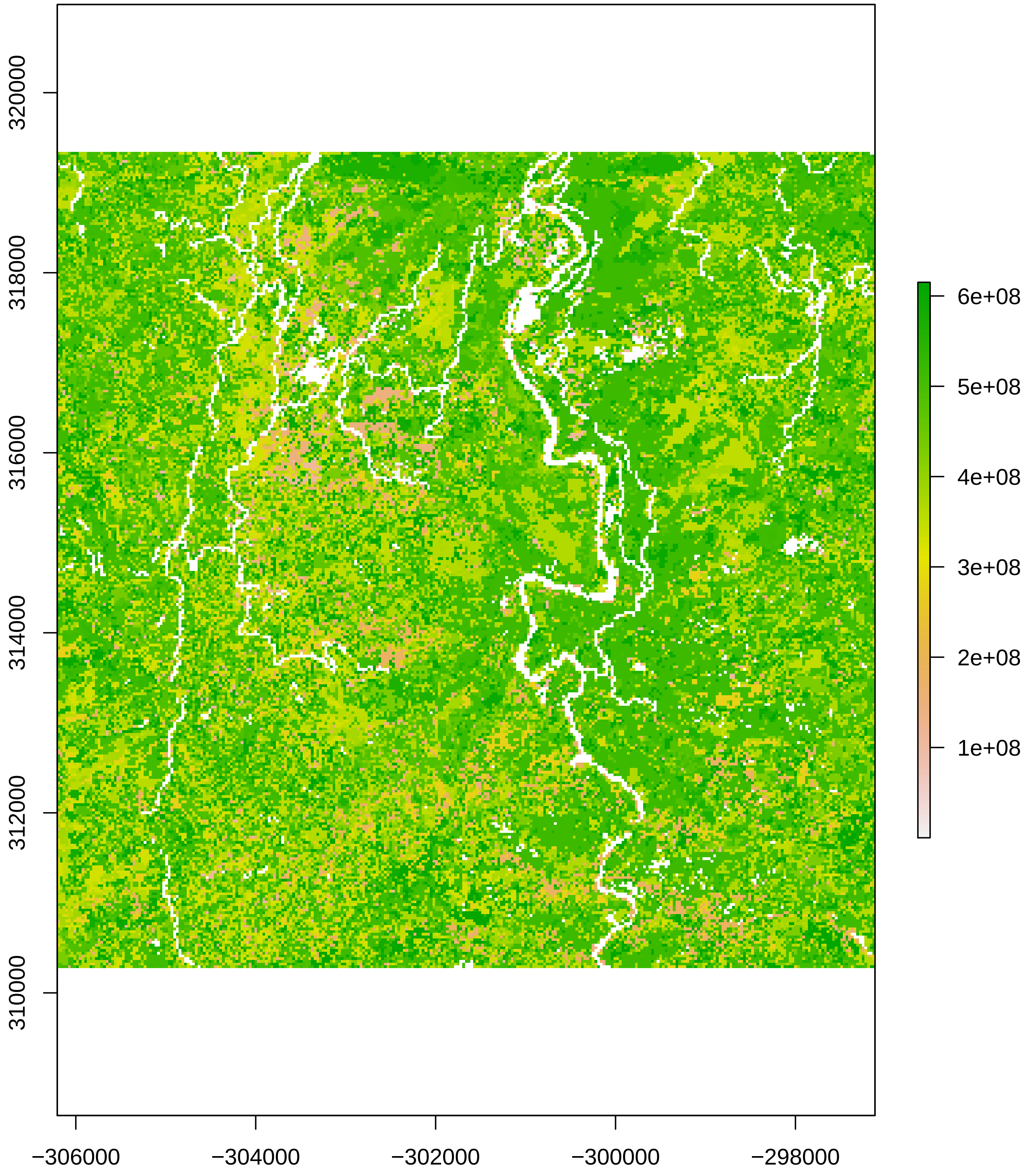
Check the histogram and plot.

```
hist(FVS_Crown)
```




```r
plot(FVS_Crown)
title(main = "Total Crown Fuel Load, Rep Stands")
```

Total Crown Fuel Load, Rep Stands



Analysis

Correlation and modeling

Check correlation coefficient between all the crown load rasters.

```
layerStats(stack(UW_Crown, FCCS_Crown, FVS_Crown),
           stat = "pearson",
           na.rm = TRUE)
```

```
## $`pearson correlation coefficient`
##             layer.1     layer.2     layer.3
## layer.1 1.00000000 0.303733508 0.084833338
## layer.2 0.30373351 1.000000000 0.004391721
## layer.3 0.08483334 0.004391721 1.000000000
##
## $mean
##      layer.1      layer.2      layer.3
##     61627.52     24129.34 448341553.26
```

UW and FCCS have the highest correlation, though none are very good.

Make a data frame from the rasters, and assign correct names.

```
Crown_df <- as.data.frame(stack(UW_Crown, FCCS_Crown, FVS_Crown))

names(Crown_df) <- c("UW", "FCCS", "FVS")
```

Run some basic linear models. For now, don't worry too much about model assumptions, ect. Use FCCS and FVS as the predictor, because the UW data is the most continuous and normal looking.

```
mod_list <- list("m_FCCS_UW" = lm(UW ~ FCCS, data = Crown_df),
                 "m_FVS_UW" = lm(UW ~ FVS, data = Crown_df),
                 "m_FCCS_FVS" = lm(FVS ~ FCCS, data = Crown_df))
```

Check the model summaries. Note: this is exploratory and may not be the best method. I checked the residual plots previously, but I commented them out here because they inflate the size of the document.

```
lapply(mod_list, summary)
```

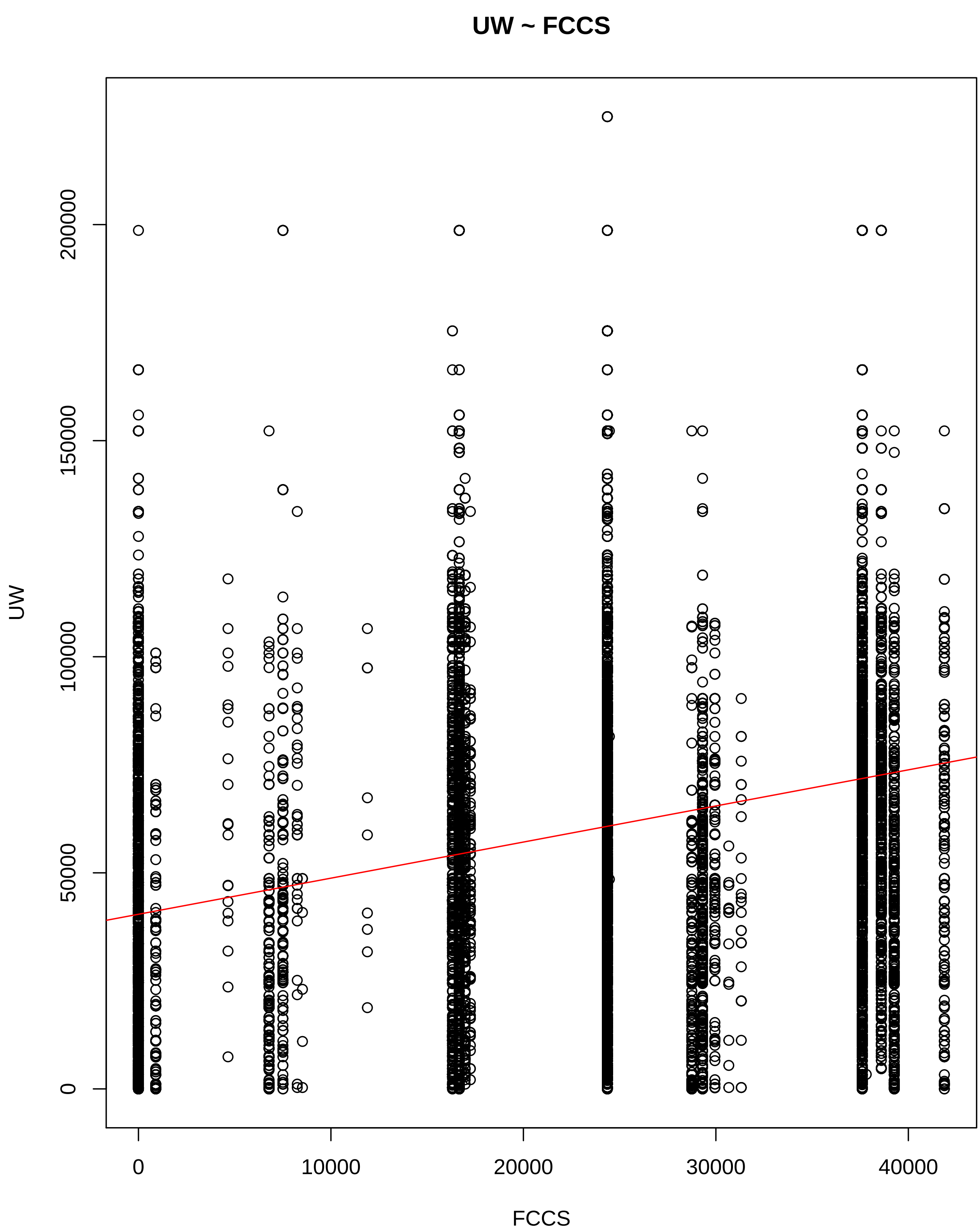
```
## $m_FCCS_UW
##
## Call:
## lm(formula = UW ~ FCCS, data = Crown_df)
##
## Residuals:
##    Min     1Q Median     3Q    Max
## -75392 -20915  -1580  18094 164211
##
## Coefficients:
##              Estimate Std. Error t value Pr(>|t|)
## (Intercept) 4.041e+04  2.329e+02   173.5   <2e-16 ***
## FCCS        8.355e-01  8.235e-03   101.4   <2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 30210 on 86914 degrees of freedom
```

```
##   (4590 observations deleted due to missingness)
## Multiple R-squared:  0.1059, Adjusted R-squared:  0.1059
## F-statistic: 1.029e+04 on 1 and 86914 DF,  p-value: < 2.2e-16
##
##
## $m_FVS_UW
##
## Call:
## lm(formula = UW ~ FVS, data = Crown_df)
##
## Residuals:
##    Min     1Q Median     3Q    Max
## -65794 -22478  -1896  20496 164058
##
## Coefficients:
##              Estimate Std. Error t value Pr(>|t|)
## (Intercept) 5.036e+04  4.619e+02   109.0   <2e-16 ***
## FVS         2.514e-05  1.002e-06    25.1   <2e-16 ***
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 31830 on 86914 degrees of freedom
##   (4590 observations deleted due to missingness)
## Multiple R-squared:  0.007197,   Adjusted R-squared:  0.007185
## F-statistic:   630 on 1 and 86914 DF,  p-value: < 2.2e-16
##
##
## $m_FCCS_FVS
##
## Call:
## lm(formula = FVS ~ FCCS, data = Crown_df)
##
## Residuals:
##        Min         1Q     Median         3Q        Max
## -448839107  -82287854   39582146   69335547  167864890
##
## Coefficients:
##              Estimate Std. Error t value Pr(>|t|)
## (Intercept) 4.473e+08  8.310e+05 538.247   <2e-16 ***
## FCCS        4.076e+01  2.939e+01   1.387    0.165
## ---
## Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
##
## Residual standard error: 107800000 on 86914 degrees of freedom
##   (4590 observations deleted due to missingness)
## Multiple R-squared:  2.214e-05,  Adjusted R-squared:  1.063e-05
## F-statistic: 1.924 on 1 and 86914 DF,  p-value: 0.1654
```

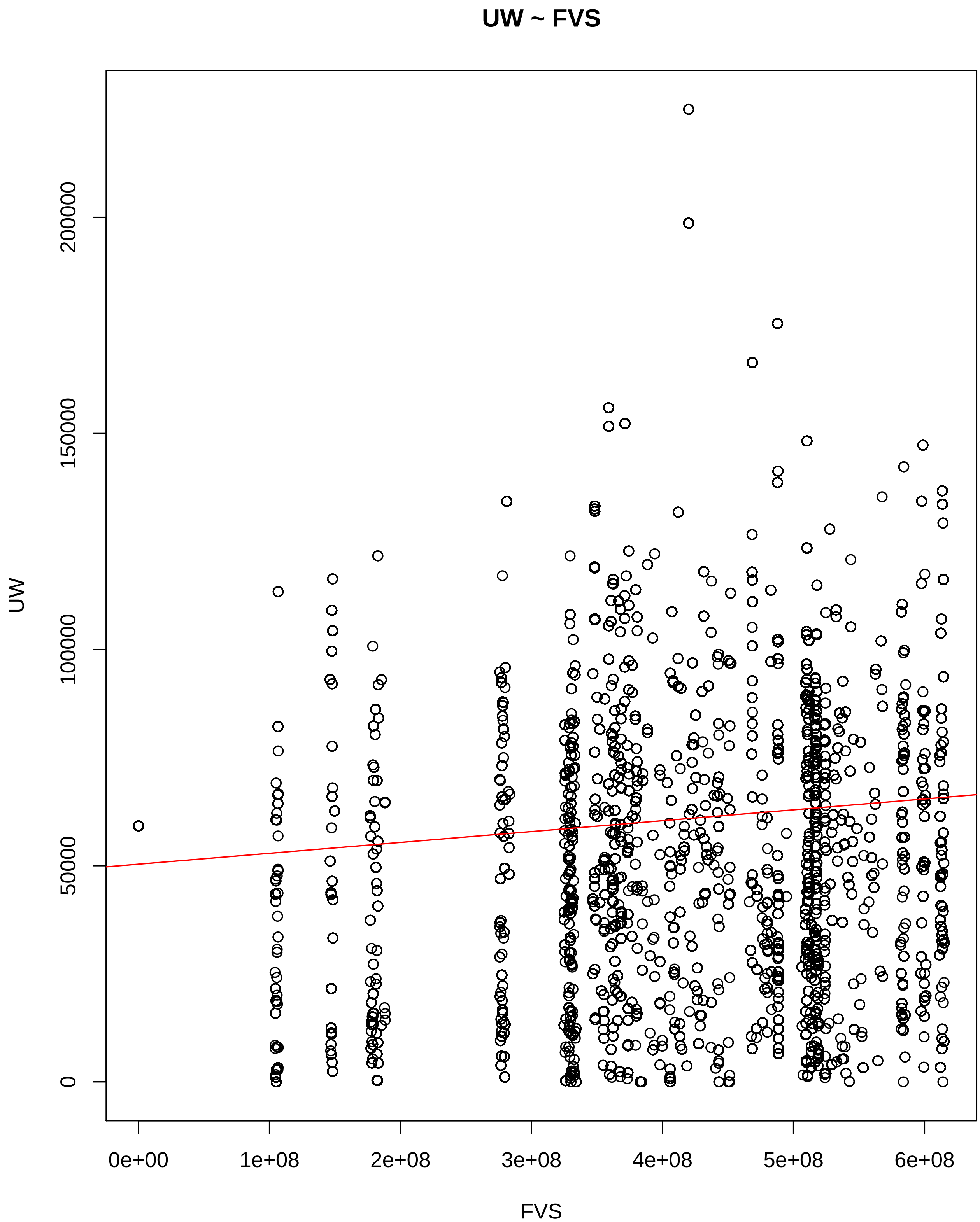
```r
# lapply(mod_list, function(x) plot(x))
```

Plot the results, including a best fit line (red).

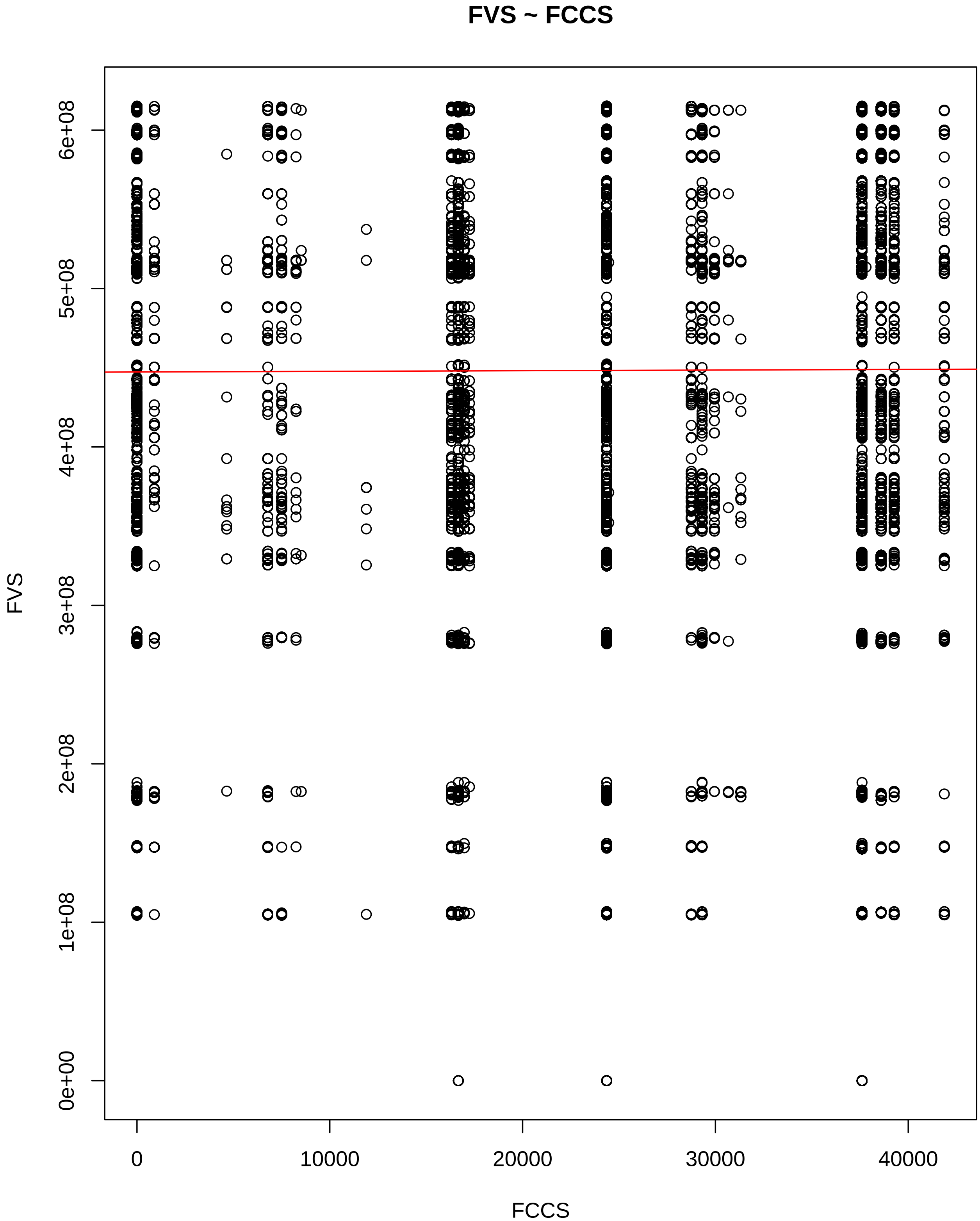
```r
plot(UW ~ FCCS, data = Crown_df)
abline(mod_list$m_FCCS_UW, col = "red")
title(main = "UW ~ FCCS")
```




```r
plot(UW ~ FVS, data = Crown_df)
abline(mod_list$m_FVS_UW, col = "red")
title(main = "UW ~ FVS")
```




```r
plot(FVS ~ FCCS, data = Crown_df)
abline(mod_list$m_FCCS_FVS, col = "red")
title(main = "FVS ~ FCCS")
```



It looks like FCCS and UW are actually more closely related (given the assumptions). I'm not sure how much of this discrepancy has anything to do with how I've characterized crown loading for FVS, or if the FVS fuel just isn't that good at characterizing crown fuels. It does include stems 3" and less, which probably inflates it somewhat.

Difference

Get difference rasters for each combination. First, make a function that calculates the difference raster.

```
diff_fun <- function(x) {
        overlay(x[[1]], x[[2]], fun = function(r1, r2){return(r1-r2)})
        }
```

Make a named list for each combination. I've subtracted all the rasters based on general loading, the raster with the least gets subtracted from the raster with the most.

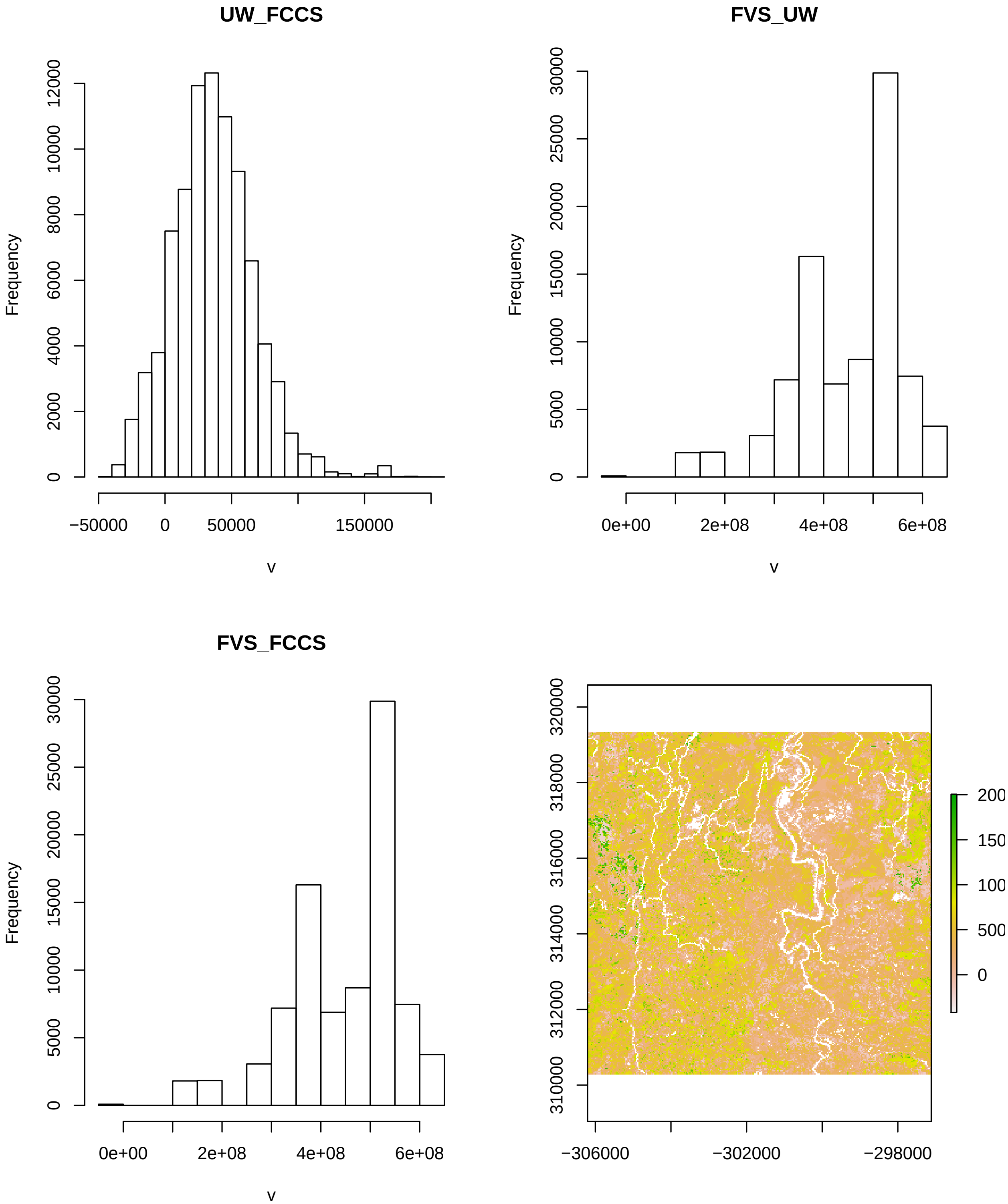
```
combo <- list("UW_FCCS" = c(UW_Crown, FCCS_Crown),
              "FVS_UW" = c(FVS_Crown, UW_Crown),
              "FVS_FCCS" = c(FVS_Crown, FCCS_Crown))
```

Run the difference function on the list and make a stack of the results.

```
diff_list <- lapply(combo, diff_fun)

diff_stack <- stack(diff_list)
```

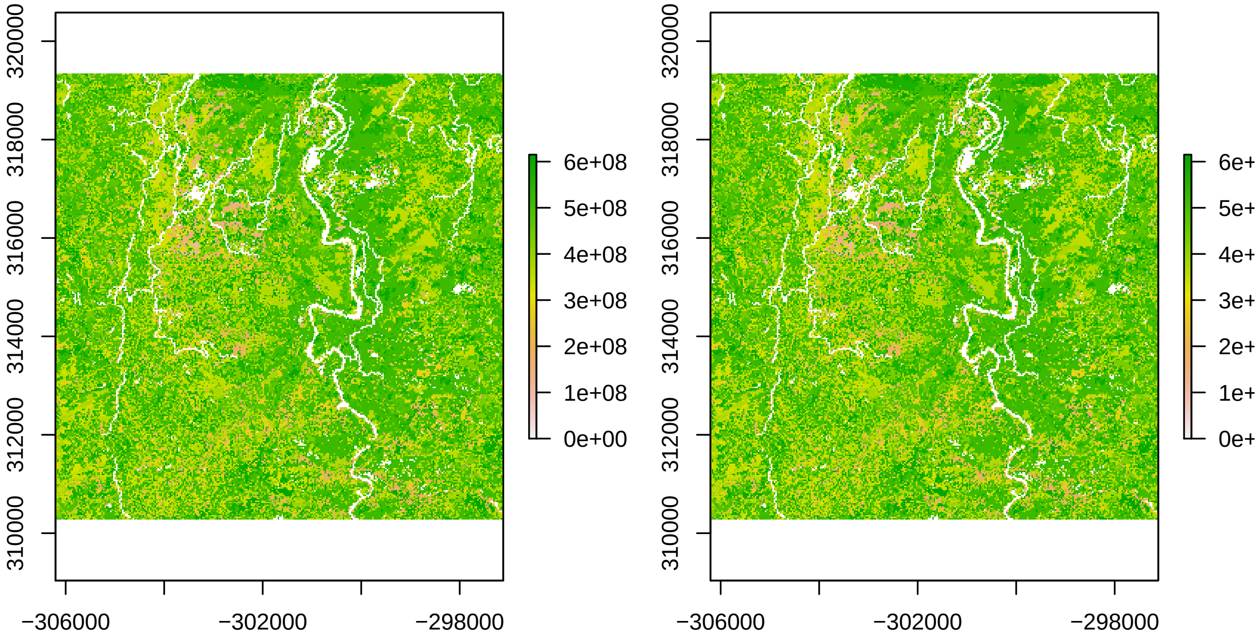
Check a histogram and plot the results

```
hist(diff_stack)

lapply(diff_list, plot)
```




```
## $UW_FCCS
## NULL
##
## $FVS_UW
## NULL
##
```

```
## $FVS_FCCS
## NULL
```



Again, it appears that the best agreement is between UW and FCCS.

C.2 Biomass Discrepancy Analysis Between C-BREC Data Set and FCCS

Follow the decision to pursue FCCS for fuel loading values, an analysis on the discrepancy between the forest biomass resource developed by NRSIG for the C-BREC Model and FCCS was conducted. The results of this analysis are included in the following pages.

Untitled

Micah Wright

July 10, 2018

Purpose

This document performs a small analysis on the (dis)agreement between the FCCS and UW rasters. The FCCS and UW raster data sets are made with different models, and thus do not perfectly agree with each other, specifically in reference to whether or not a pixel is forested. In FCCS_reclass.R, I reclassified the FCCS raster to create a mask for what should be forested areas. First, I masked any class that contained the words "Urban", "Barren", "Water"", or"Field". I also masked any class where the Wood_tpa ("Total combustible wood, including downed wood, rotten and lightered stumps, and piled wood."- FCCS metadata) values were less than 0.5. I experimented with removing classes based on the keywords"grass" and "shrub", but those selections were too conservative.

Setup

Load the necessary packages .

```
library(raster)
library(rgdal)
library(raster)
```

Load the FCCS mask, created in FCCS_reclass.R. I need to rename this file to better reflect what it actually is.

```
FCCS_mask <- raster("data/FCCS/spatial/FCCS_reclass.tif")
```

Reclassify the missing values as 0, and all other values as 2. If this isn't done, the pixels from the UW raster will be masked in these areas when they are added, and we won't be able to differenciate the actual missing values from area of overlap. I did not do this in FCCS_reclass.R because I wanted the raster to ulitimately function as a mask.

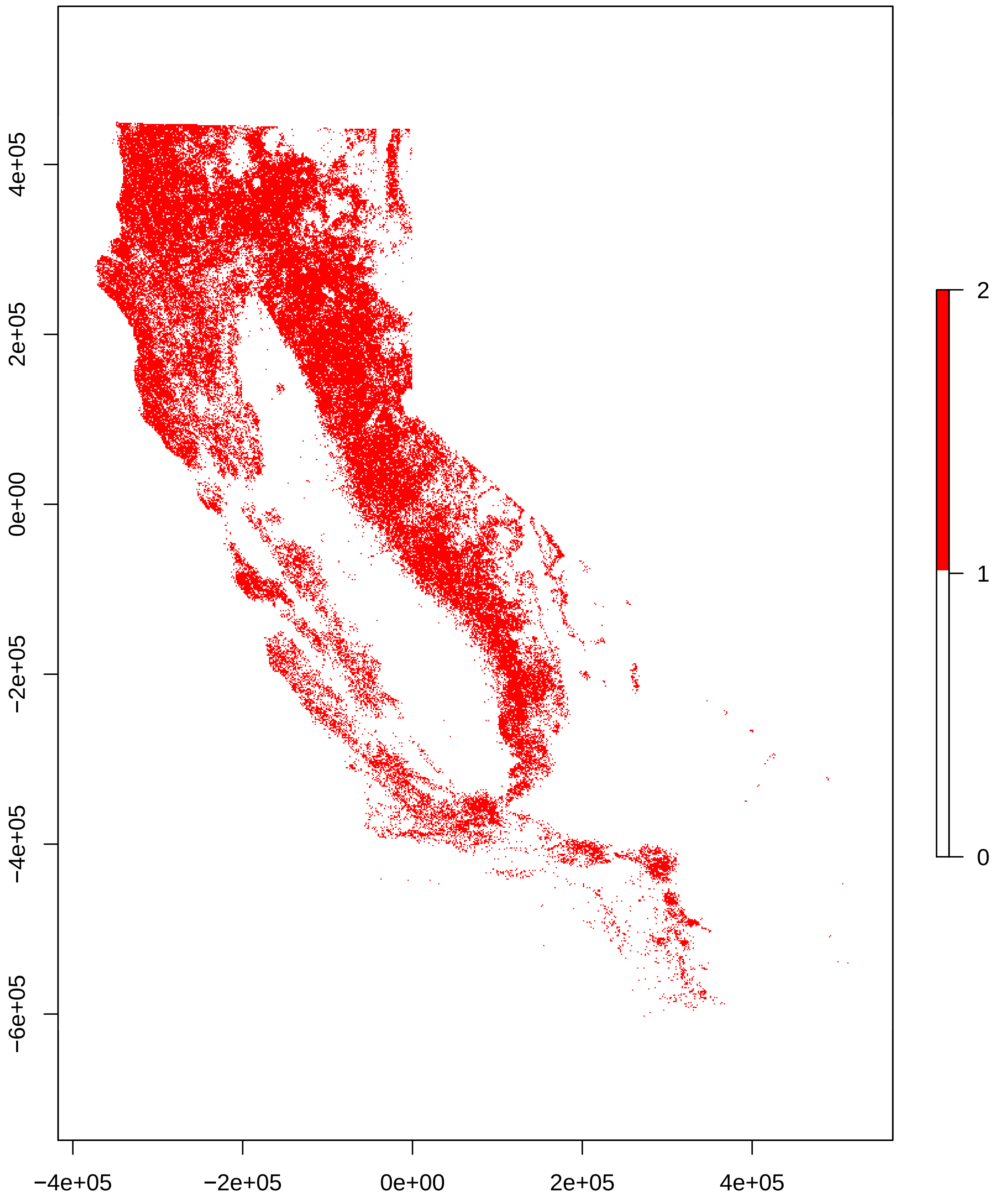
```
recl <- cbind(c(NA, 1), c(0, 2))
FCCS_mask <- reclassify(FCCS_mask, recl)
```

Inspect the raster min and max values and plot it. There should only be 2s and 0s.

```
FCCS_mask
```

```
## class       : RasterLayer
## dimensions  : 35840, 32768, 1174405120  (nrow, ncol, ncell)
## resolution  : 30, 30  (x, y)
## extent      : -417385.6, 565654.4, -618851.6, 456348.4  (xmin, xmax, ymin, ymax)
## coord. ref. : +proj=aea +lat_1=34 +lat_2=40.5 +lat_0=0 +lon_0=-120 +x_0=0 +y_0=-4000000 +ellps=GRS80
## data source : /private/var/folders/gw/89brfqbx24s2k81fp7s_16mc0000gn/T/RtmpvBwwzQ/raster/r_tmp_2018-(
## names       : layer
## values      : 0, 2  (min, max)
```

```
plot(FCCS_mask,
     breaks = c(0, 1, 2),
     col = c("white", "red"))
```

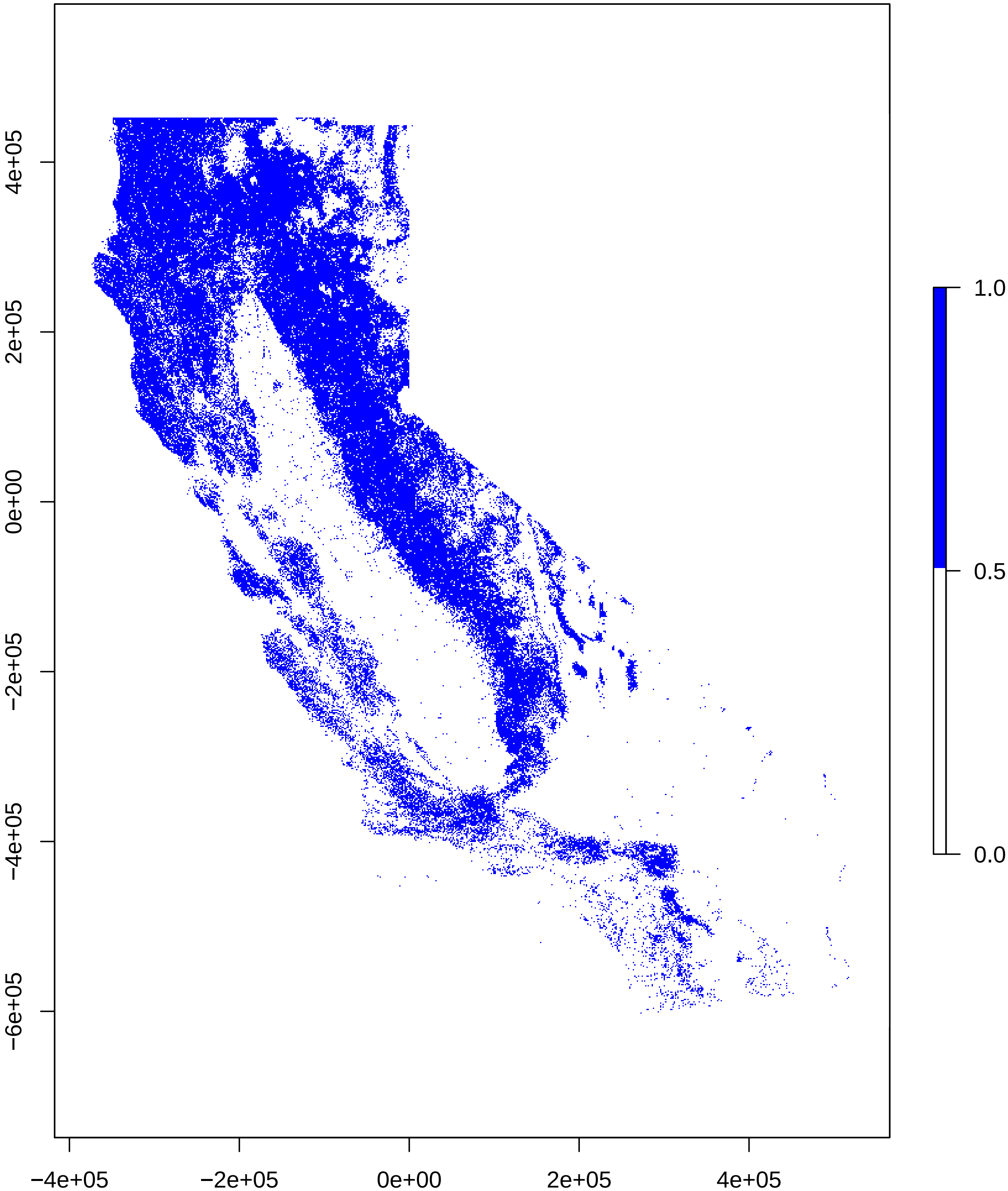


Load the UW raster.

```
UW <- raster("data/UW/UW_reclass.tif")
```

Inspect the raster, all forested pixels have a value of 1.

```r
plot(UW,
     breaks = c(0, 0.5, 1),
     col = c("white", "blue"))
```



Double check that the rasters have the same extent, resolution, CRS, etc.

```r
compareRaster(FCCS_mask, UW)
```

```
## [1] TRUE
```

Stack the rasters.

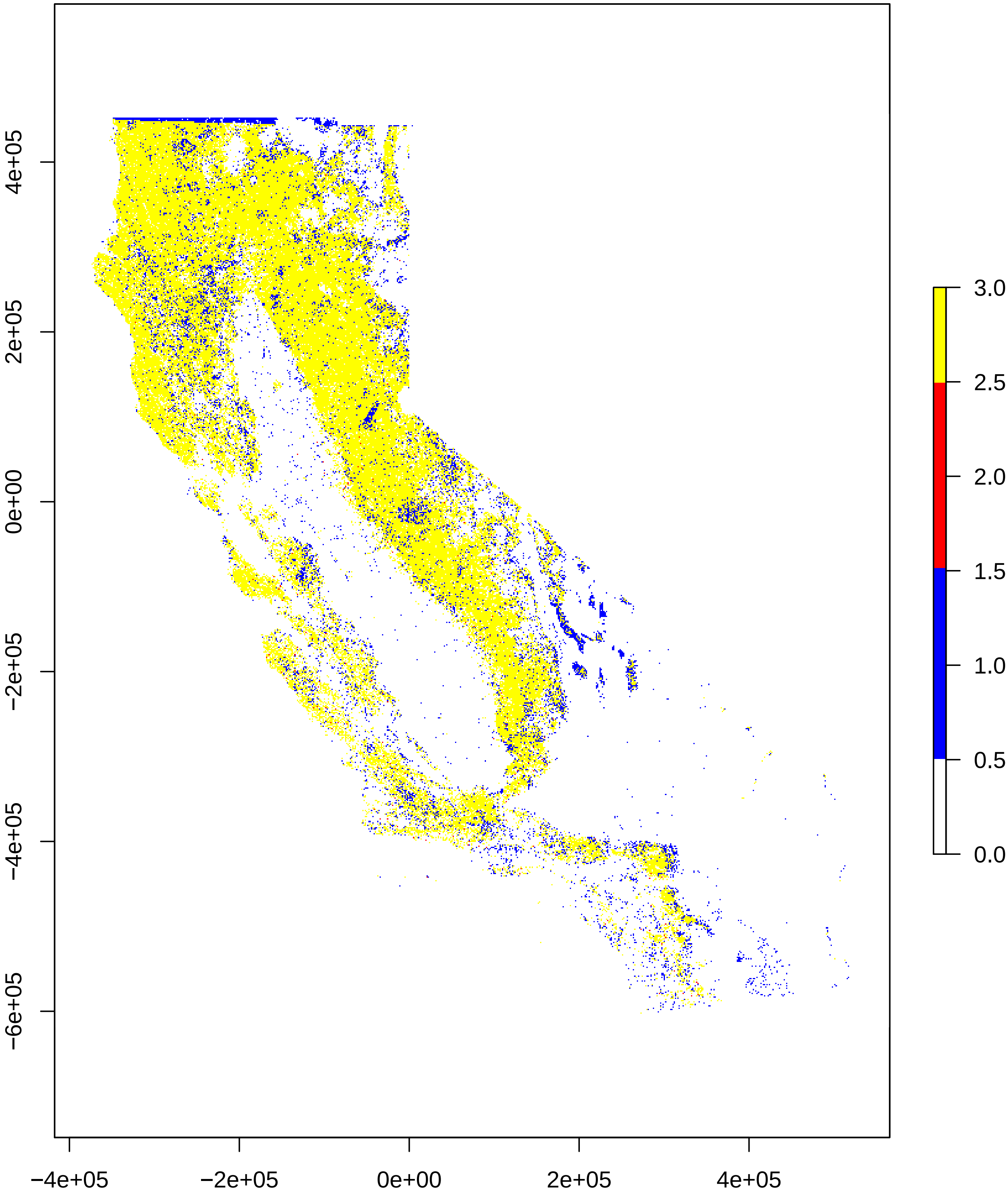
```r
rstack <- stack(FCCS_mask, UW)
```

Sum the raster stack. This will result in a raster with 3 for the overlap, 2 for just FCCS, and 1 for just UW.

```r
diff_raster <- sum(rstack)
```

Inspect the values as before. Pixels that only have values for the UW raster are blue, overlap is yellow, and only FCCS are red. There are very few pixels that only have FCCS values, and they are often isolated, so they are essentially invisible.

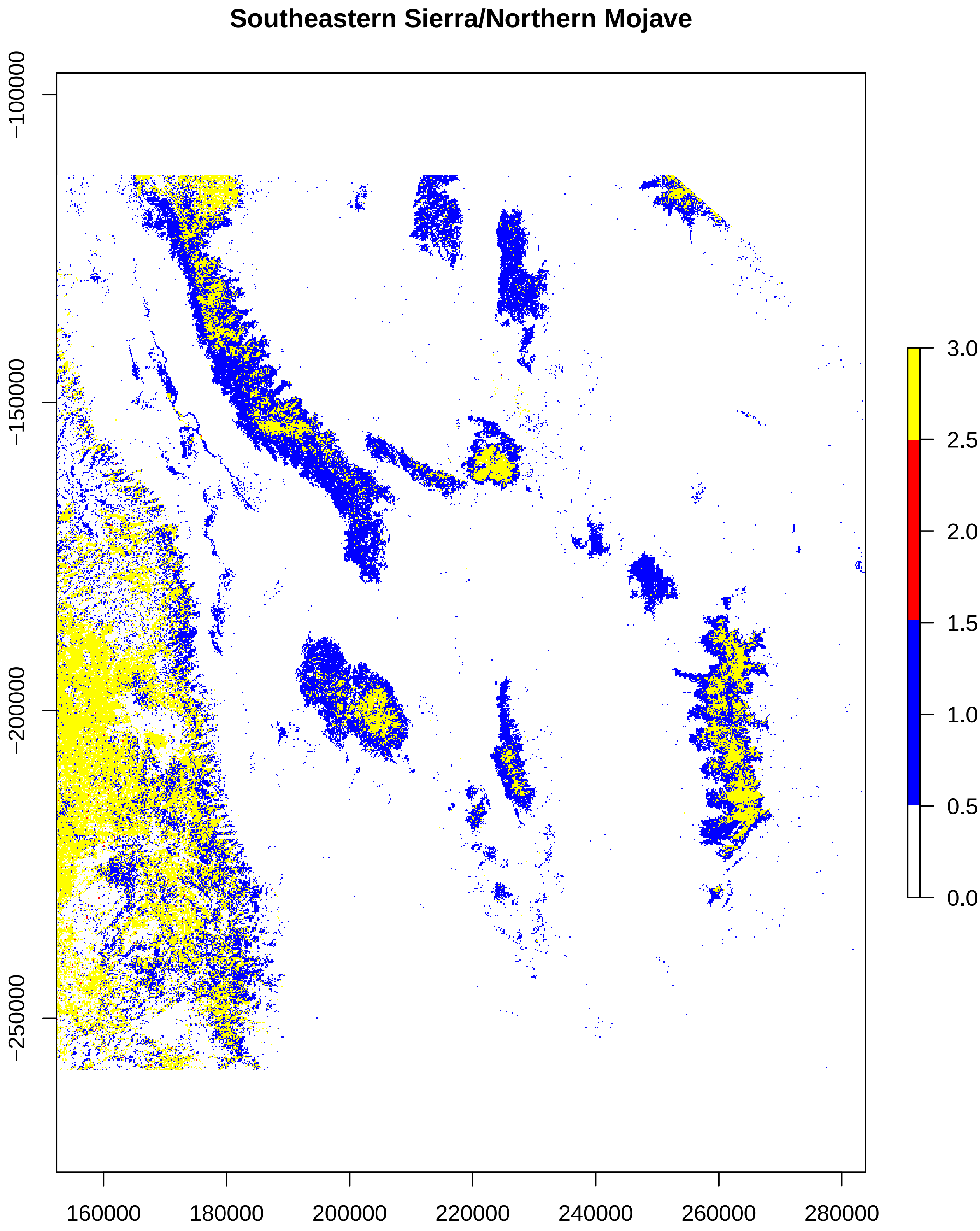
```r
plot(diff_raster,
     breaks = c(0, 0.5, 1, 1.5, 2, 2.5, 3),
     col = c("white", "blue", "blue", "red", "red", "yellow"))
```



It looks like the biggest areas of disagreement between the rasters is the extra cells in Oregon, and in the northern Majave/Southeastern Sierra. Inspect this area.

```
plot(diff_raster,
     breaks = c(0, 0.5, 1, 1.5, 2, 2.5, 3),
     col = c("white", "blue", "blue", "red", "red", "yellow"),
     ext = extent(c(152338.3,
```

```
                    283831.6 ,
                    -258421.5,
                    -113086.8)))
title(main = "Southeastern Sierra/Northern Mojave")
```



It appears that most of the discrepancy is at the lower elevations in this area.

Make a frequency table for the values.

```
freq_tab <- data.frame(table(values(diff_raster)),
                       stringsAsFactors = FALSE)

names(freq_tab) <- c("Pixel_value", "Frequency")

freq_tab$Class <- with(freq_tab,
                       ifelse(Pixel_value == 0, "None",
                              ifelse(Pixel_value == 1, "UW",
                                     ifelse(Pixel_value == 2,
                                            "FCCS", "Overlap"))))

knitr::kable(freq_tab)
```

Pixel_value	Frequency	Class
0	1005965855	None
1	27142190	UW
2	491166	FCCS
3	140805909	Overlap

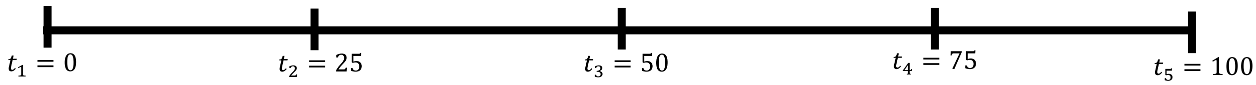
Calculate the proportion of the forested cells in the UW raster occupied by each class.

```
freq_tab$Total_pixels <- sum(freq_tab$Frequency[c(2, 4)])

freq_tab$Proportion_total <- freq_tab$Frequency/freq_tab$Total_pixels

knitr::kable(freq_tab)
```

Pixel_value	Frequency	Class	Total_pixels	Proportion_total
0	1005965855	None	167948099	5.9897424
1	27142190	UW	167948099	0.1616106
2	491166	FCCS	167948099	0.0029245
3	140805909	Overlap	167948099	0.8383894

C.3 Method for Linearly Interpolating Wildfire Emissions Factors Between Modeled Years

Wildfire emissions are calculated in 25-year increments. To obtain annual wildfire emissions we use the following approach.



C.3.1 Year t_1 to Year $(t_2 - 1)$

The following describes the calculations needed for each raster cell

1. Load appropriate .rds files for years t_1 and t_2 for the project area. If there is no prescribed burn, there should only be files with a "first" label. There will not be files with a "second" label. If there is a prescribed burn, load the file with the "second" label.
    a. Subset to appropriate case ID in those files

2. Load the residue carbon fraction for each raster cell = Cf_i [% mass]

3. Load list of carbon fractions of each pollutant species = $Cf_{<p>}$ [% mass]

4. Load the wildfire probabilities for each location and the first 25-year increment = $P_{wf,i}^{t_1}$ [unitless]

5. Calculate total emissions for year t_1 for each pollutant species <g> (where <x> is size-class):

<g>	Equation	Data columns from which year	Units
All Except CO2	$E_{<p>,i}^{t_1} = \left(\sum_{<x>} \text{total\_<x>\_residue\_<g>}\right) \cdot 0.222 \cdot P_{wf,i}^{t_1}$	t_1	metric tons of pollutant <g> / raster cell
CO2	$C_{consumed,i} = Cf_i \cdot \left(\sum_{<x>} \text{total\_<x>\_consumed}\right) \cdot 0.222$ $C_{allocated,i} = \sum_{<p>} \left(Cf_{<g>} \cdot E_{<g>,i}\right) + \sum_{<x>} \text{char\_<x>\_residue} \cdot 0.222$ $E_{CO2,i}^{t_1} = \left(C_{consumed,i} - C_{allocated,i}\right) \cdot Cf_{CO2} \cdot P_{wf,i}^{t_1}$		

6. Except for CO2, calculate a per-tonne consumed residue emissions factor for each size-class <x> and pollutant species <g> combination (including char … not really an emission but we can track it as such) for years t_1 and t_2

<g>	Equation	Data columns from which year	Units
All Except CO2	$Ef^{t_1}_{<x>,<g>,i} = \frac{\text{total\_<x>\_residue\_<g>}}{\text{total\_<x>\_consumed}}$ $Ef^{t_1}_{<x>,char,i} = \frac{\text{char\_<x>\_residue}}{\text{total\_<x>\_consumed}}$	t_1	$\frac{\text{metric tons of pollutant <g>}}{\text{metric tons of consumed residue}}$
	$Ef^{t_2}_{<x>,<g>,i} = \frac{\text{total\_<x>\_residue\_<g>}}{\text{total\_<x>\_consumed}}$ $Ef^{t_2}_{<x>,char,i} = \frac{\text{char\_<x>\_residue}}{\text{total\_<x>\_consumed}}$	t_2	

In addition, calculate a fraction of mass consumed per mass exposed to wildfire for each size class for years t_1 and t_2

<x>	Equation	Data columns from which year	Units
All size classes	$Mfrac^{t_1}_{<x>,i} = \frac{\text{total\_<x>\_consumed}}{\text{total\_<x>\_exposed}}$	t_1	$\frac{\text{metric tons of residue consumed}}{\text{metric tons of residue exposed}}$
	$Mfrac^{t_2}_{<x>,i} = \frac{\text{total\_<x>\_consumed}}{\text{total\_<x>\_exposed}}$	t_2	

7. Calculate linear equation for $Ef^{t}_{<x>,<p>,i}$ between years t_1 and t_2 for each size-class <x> and pollutant species <g> combination (including char … not really an emission but we can track it as such)

<g>	Equation	Units
All Except CO2	$Ef^{t}_{<x>,<g>,i} = \frac{Ef^{t_2}_{<x>,<g>,i} - Ef^{t_1}_{<x>,<g>,i}}{t_2 - t_1}(t - t_1) + Ef^{t_1}_{<x>,<g>,i}$ $Ef^{t}_{<x>,char,i} = \frac{Ef^{t_2}_{<x>,char,i} - Ef^{t_1}_{<x>,char,i}}{t_2 - t_1}(t - t_1) + Ef^{t_1}_{<x>,char,i}$	metric tons of pollutant <g> / metric tons of consumed residue

In addition, calculate the linear equation for $Mfrac^{t}_{<x>,i}$ between years t_1 and t_2 for each size-class <x>

<x>	Equation	Units
All Size Classes	$Mfrac^{t}_{<x>,i} = \frac{Mfrac^{t_2}_{<x>,i} - Mfrac^{t_1}_{<x>,i}}{t_2 - t_1}(t - t_1) + Mfrac^{t_1}_{<x>,i}$	metric tons of residue consumed / metric tons of residue exposed

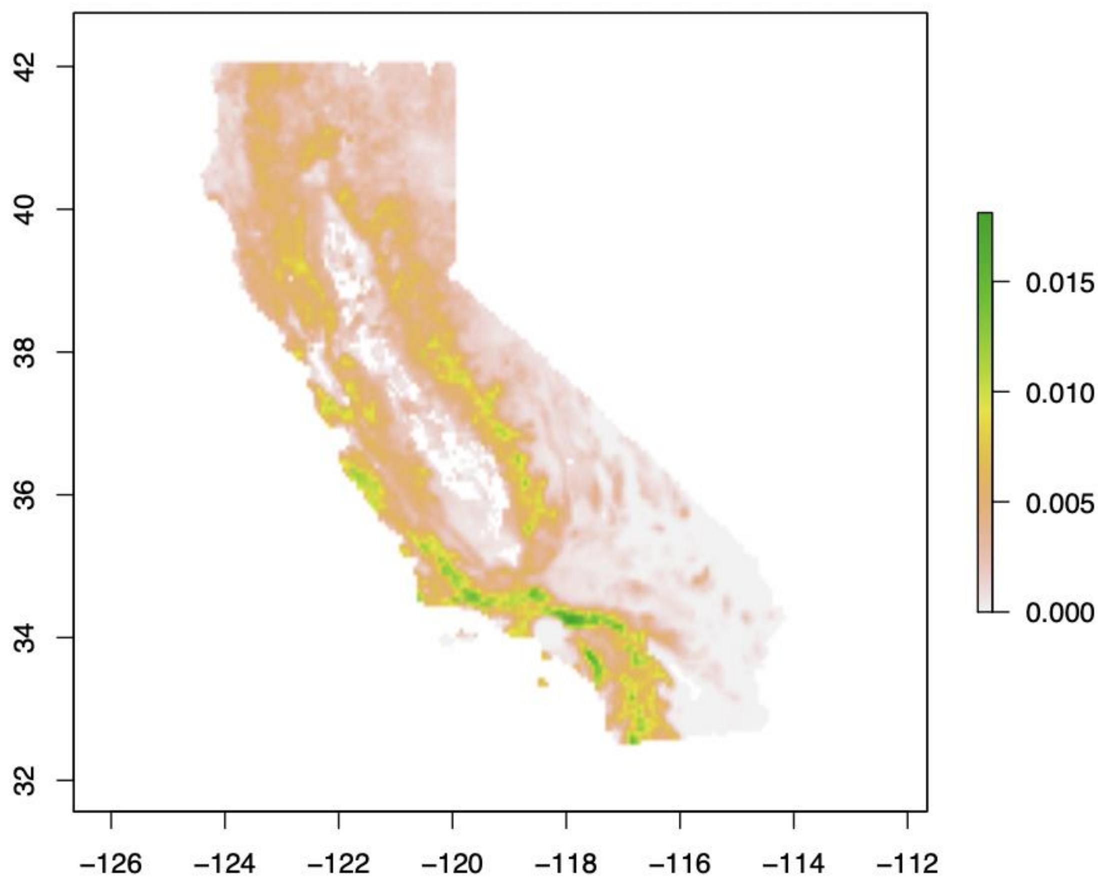
8. For each year t between years $(t_1 + 1)$ and $(t_2 - 1)$ calculate the total emissions (where the function D() is the decay function)

<g>	Equation	Data columns from which year	Units
All Except CO2	$M^{t}_{consumed,<x>} = D^{t}_{<x>}\left(\text{total\_<x>\_consumed} * (1 - P^{t_1}_{wf,i})^{t}\right)$ $E^{t}_{<g>,i} = \left(\sum_{<x>} Ef^{t}_{<x>,<g>,i} \cdot M^{t}_{consumed,<x>}\right) \cdot 0.222 \cdot P^{t_1}_{wf,i}$	t_1	metric tons of pollutant <g> / raster cell
CO2	$C_{consumed,i} = Cf_i \cdot \left(\sum_{<x>} M^{t}_{consumed,<x>}\right) \cdot 0.222$ $C_{allocated,i} = \sum_{<g>}\left((Cf_{<g>} \cdot E^{t}_{<g>,i}) + \left(\sum_{<x>} Ef^{t}_{<x>,char,i} \cdot M^{t}_{consumed,<x>}\right) \cdot 0.222 \right)$ $E^{t}_{CO2,i} = (C_{consumed,i} - C_{allocated,i}) \cdot Cf_{CO2} \cdot P^{t_1}_{wf,i}$	N/A	

C.4 Future Wildfire Probability Data Sources

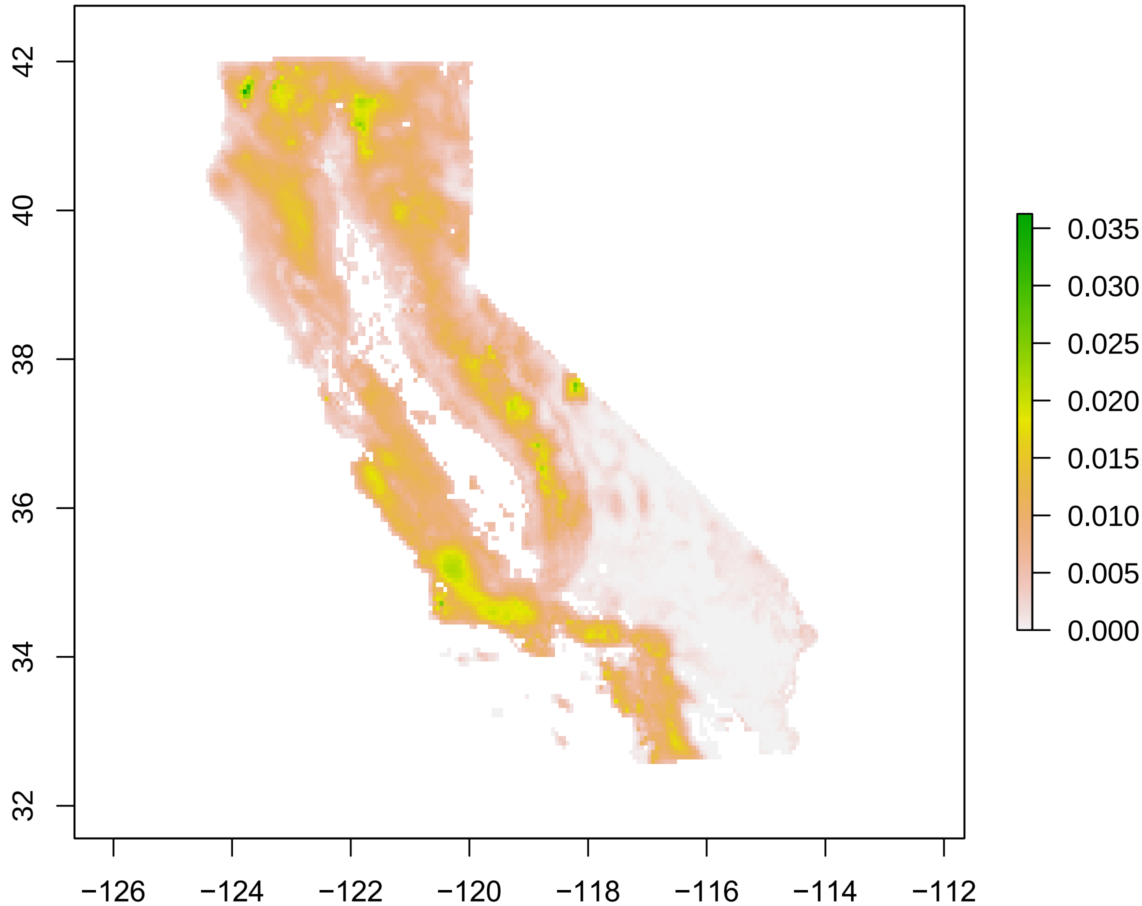
The appendix discusses the choice of data for future wildfire probability projections. The California Department of Forestry and Fire Protection (CALFIRE) publishes a map with the projected annual fire probability between 2026 and 2050 using data from (M. L. Mann et al., 2016) for the Fire Resource and Assessment Program (FRAP). The probability is published as a static percentage for the 25 year interval (Figure 27). Cal-Adapt also publishes future wildfire probability out to 2100 (Anthony Leroy Westerling, 2018). Their data are published in number of hectares burned in each 6 x 6 km grid cell in the state for each year. The area burned was converted into a probability and future trend line as described in Section 6 of the main framework document. To compare against CALFIRE's projection, the Cal Adapt data is shown for year 2038 (Figure 28), which is the median year of the CALFIRE projection interval.

Figure 27. FRAP Fire Probability Between 2026 - 2050.



Data obtained from (California Department of Forestry and Fire Protection, 2019a)

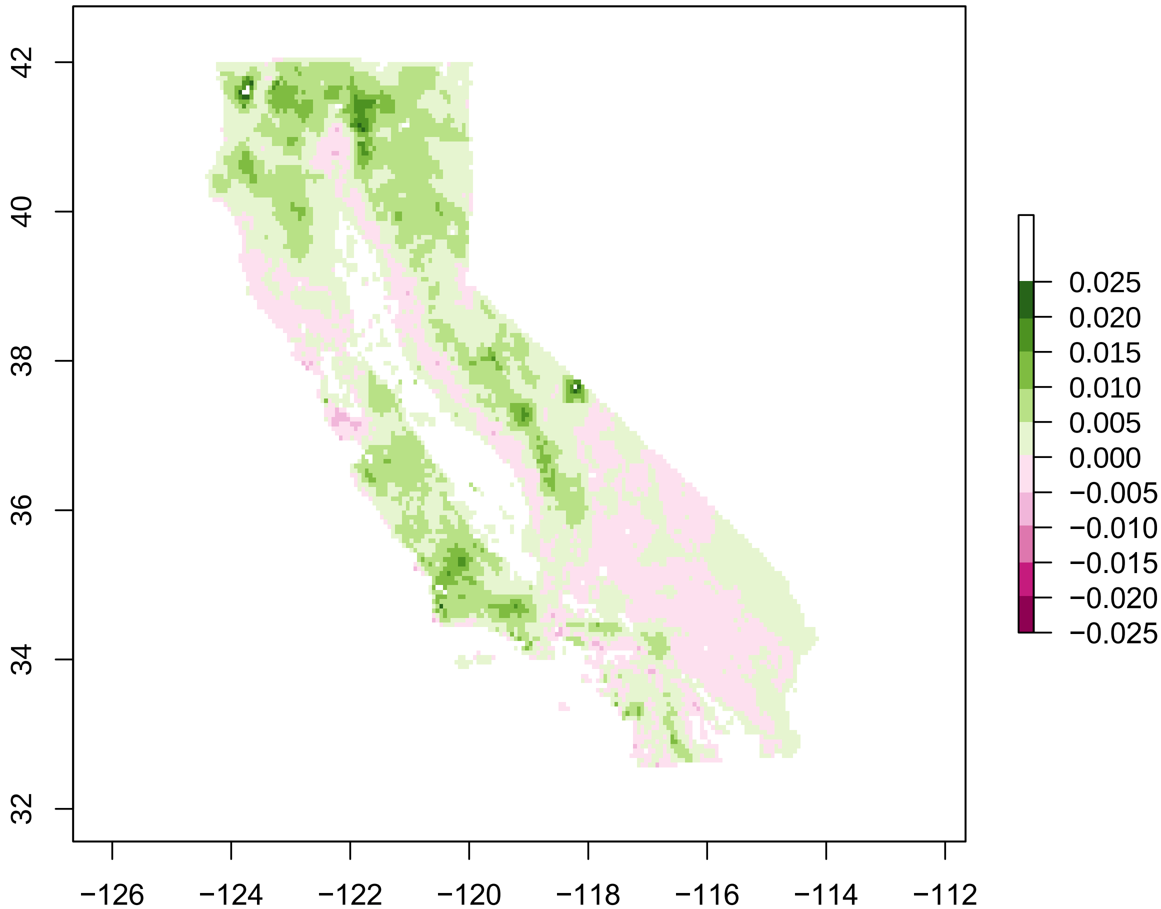
Figure 28. Fire Probability from Cal-Adapt for Year 2038.



Data obtained from cal-adapt.org.

As visible in the two maps, the fire probability estimated from two sources varies by magnitude and spatially across the state. The Cal-Adapt data show higher values up to 3% probability of fire, while FRAP has a maximum near 1.5%. Also the spatial differences are noticeable in the maps, where Cal Adapt shows higher probabilities of fire estimated in the far northern areas of the state. The difference between the two estimations is plotted in Figure 29. Positive values (green) indicate higher Cal-Adapt values.

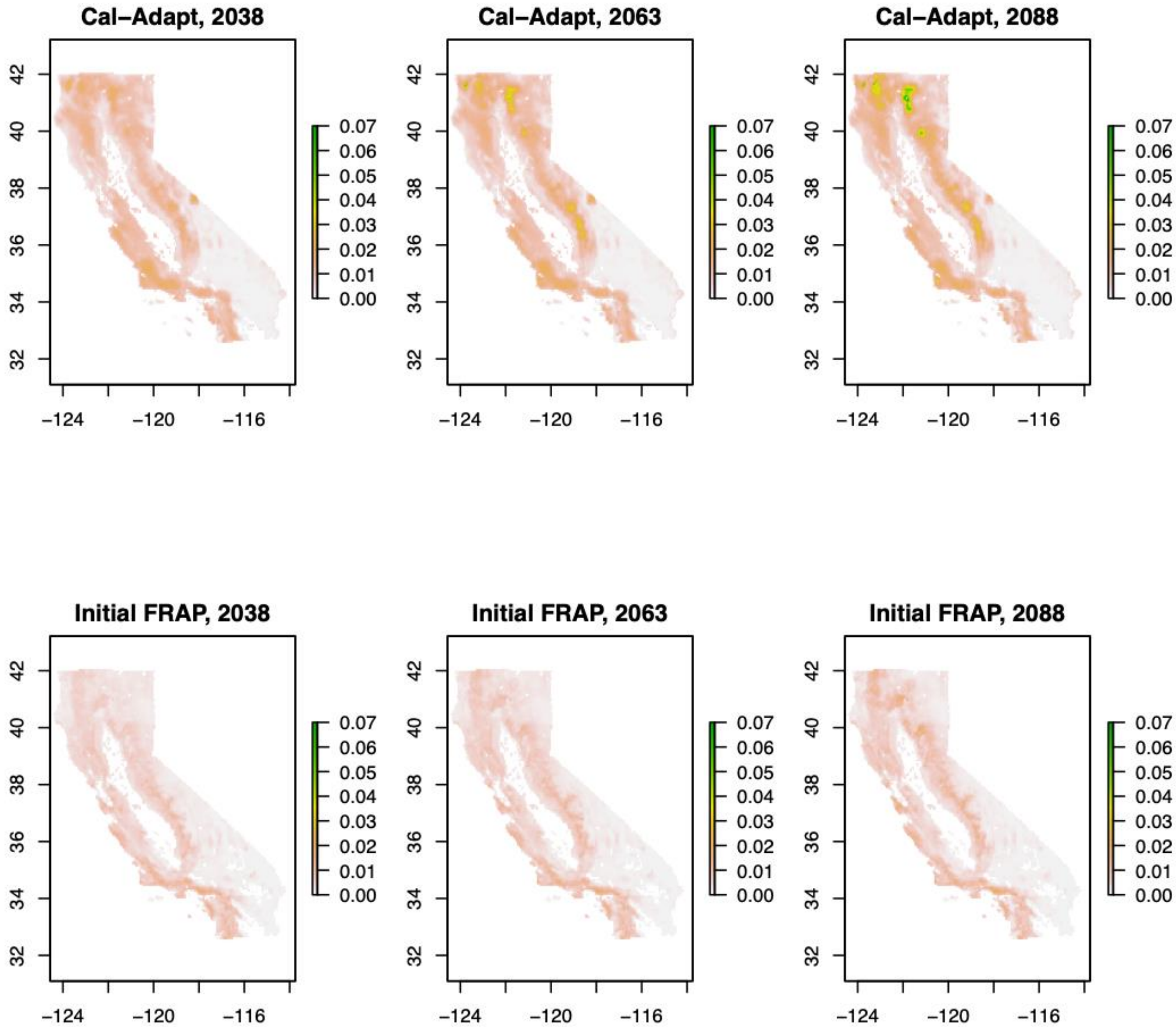
Figure 29. Absolute Difference Between FRAP and Cal-Adapt Fire Probabilities



C-BREC has a 100-year time horizon from 2020 to 2120 and the fire probability projections need to match this timeline. The Cal-Adapt probabilities are easily adapted to a 2120 time horizon. The initial dataset has stochastic annual projections out to 2100. A trend line was fit to these data to estimate a smooth trajectory in wildfire probabilities. To extend beyond the 2100 time frame, the trend line was extrapolated out to 2120.

The data from CALFIRE are presented as a single value representative of the 2026 to 2050 time interval. Fire probabilities were projected further into the future by using the slope of the trend line for each 6 x 6 km grid cell of the Cal Adapt dataset. A comparison of the two datasets in future years is shown in Figure 30. The adjusted FRAP data (bottom row labeled “Initial FRAP”) show significantly lower probabilities, which is expected because of the lower initial values. The adjusted FRAP values follow the trends of Cal Adapt to increase the fire probability in the far north state.

Figure 30. Comparison of Future Year Projections of Fire Probability Datasets



Differences in the values between the two datasets are a results of different modeling processes and assumptions. For this biomass lifecycle assessment, the Cal-Adapt data was used instead of using CALFIRE's FRAP data as the initial starting point. This decision was made because:

- Cal Adapt has a longer time horizon to 2100, which is closer aligned to C-BREC's time horizon of 2120, and therefore required less extrapolation.
- The method to project FRAP estimations into the future using Cal-Adapt trend lines raises issues for data quality and consistency. Using a single data source (Cal-Adapt) for the entire time interval is preferred when compared to combining two data sources (FRAP and Cal-Adapt) to formulate a projection.

C.5 Emission Factors for Prescribed Burning of Agricultural Residues

C.5.1 NO_x and N_2O Emission Factors for Prescribed Burning of Agricultural Residues

NO_x and N_2O emission factors for straw residues were calculated based upon methodology in section 6.5 of (United States Environmental Protection Agency, Office of Atmospheric Programs, 2011). The inventory calculates emissions from the burning of agricultural residues based on the following equations:

Equation 1:

$$N\ released = ABR * CP * RCR * DMF * BE * CE * Frac_N$$

Where:

ABR = Area Burned Ratio (crop area burned / crop area harvested)
CP = Crop Production (Gg crop / year)
RCR = Residue/Crop Ratio (Gg residue / Gg crop)
DMF = Dry Matter Fraction (Gg dry matter / Gg residue)
BE = Burn Efficiency (Gg residue burned / Gg pre-fire dry matter residue)
CE = Combustion Efficiency (Gg N released from burned material / Gg N in burned material)
$Frac_N$ = Fraction of N (Gg N / Gg dry matter)

Equation 2:

$$N_2O\ or\ NO_x\ emissions = (N\ Released) * (ER) * (CF)$$

Where:

ER = Emissions Ratio (grams N [as N_2O or NO_x] / grams N released)
CF = Conversion Factor; molecular weight ratio of N2O-N to N (44/28) or NOx-N to N (30/14)

To get the emissions factor, (N_2O or NO_x emissions ÷ amount of residue burned), we substitute Equation 1 into

Equation *2* and reorganize into Equation 3:

$$N_2O\ or\ NO_x\ emissions = ABR * CP * RCR * DMF * BE * CE * Frac_N * (ER) * (CF)$$

Equation 3:

$$\frac{N_2O\ or\ NO_x\ emissions}{ABR * CP * RCR * DMF} = BE * CE * Frac_N * (ER) * (CF)$$

Where (Area Burned Ratio * Crop Production * Residue/Crop Ratio * Dry Matter Fraction) represents the amount of residue burned. The crop-specific values for Burn Efficiency, Combustion Efficiency, and Nitrogen Fraction are given in Table 56, while the gas-specific Emissions Ratio and Conversion Factor are given in Table 57.

Table 56: Crop-Specific Values for Calculating Agricultural Straw Emissions Factors

Crop	N Fraction	Burning Efficiency (Fraction)	Combustion Efficiency (Fraction)
Corn	0.006	0.93	0.88
Cotton	0.012	0.93	0.88
Rice	0.007	0.93	0.88
Wheat	0.006	0.93	0.88

Table 57: Nitrogen Speciation Values for Agricultural Straw Emissions Factors

Gas	Emissions Ratio	Conversion Factor
N_2O:N	0.007	44/28
NO_x:N	0.121	30/14

The crop-specific emissions factors, calculated using *Equation 3*, are given in Table 58.

Table 58: Crop-Specific N_2O and NO_x Emissions Factors for Agricultural Straw

Crop	Gas	RCR	DMF	$Frac_N$	BE	CE	ER	CF	Emissions Factor
Corn	N_2O:N	1.0	0.91	0.006	0.93	0.88	0.007	44/28	0.000054
	NO_x:N						0.121	30/14	0.0013
Cotton	N_2O:N	1.6	0.90	0.012	0.93	0.88	0.007	44/28	0.00011
	NO_x:N						0.121	30/14	0.0025
Rice	N_2O:N	1.4	0.91	0.007	0.93	0.88	0.007	44/28	0.000063
	NO_x:N						0.121	30/14	0.0015
Wheat	N_2O:N	1.3	0.93	0.006	0.93	0.88	0.007	44/28	0.000054
	NO_x:N						0.121	30/14	0.0013

C.5.2 Cotton Emission Factor Literature Values

Emission factor values from Table 1 of (McCarty, 2011) were used to account for emissions and particulate matter released during prescribed burning of cotton crop residues (excluding NO_x and N_2O, which are described in the preceding section). Note that these values were derived from a number of literature sources. (McCarty, 2011) adhered to the following reporting scheme: when two emission factor values from literature were leveraged, the mean was used and the uncertainty was represented by plus or minus half the range. When three or more emission factor values from literature were leveraged, the mean was used and the uncertainty was represented by plus or minus the standard deviation. Emission factors with a single measurement were reported without an uncertainty estimate. In this work, the minimum and maximum values listed in Table 25 were calculated by adding or subtracting the reported uncertainty estimate, when applicable.

See Table 59 for the range of literature values used to derive cotton emission factors used in (McCarty, 2011) and the current work.

Table 59: Range of Literature Values for Open Field Combustion Emission Factors for Cotton

Crop	Open Field Combustion Products [% residue dry weight]					
	CO	CO2	CH4	SO2	PM10	PM2.5
Cotton	58.0 – 92.0	1520	2.70 – 4.50	0.34 – 3.96	8.87	3.90 – 8.48

Adapted from (McCarty, 2011)

APPENDIX D
Discussion of Soil CO_2 Efflux on Forest Lands

The content in this appendix is taken from a report written by Dr. Garrett Liles and Seth Myrick of California State University Chico. The report was written for the CBI Project, and can be found as a separate document titled "Appendix D Soil Carbon Efflux Report.pdf".

Forests and forest soils cover approximately 30% of our planet's surface and play a critical role in supporting humanity though a variety of ecosystem services. Forests supply water, biodiversity and habitat, recreation opportunities, and play a major role in local through global C cycling in soil and through the production of timber and forest biomass for diverse durable goods and bioenergy. Management actions and other disturbance factors in forests can generate intended positive benefits and unintended consequences through the alteration of the soil physical properties (e.g., compaction, erosion, soil moisture) and removal of biomass (carbon and nutrients). Changes to site and soil properties can be short lived or long lasting and sometimes require considerable time and/or direct mitigation to recover to a desired condition of forest form and function. Forest management focused on biomass removal or salvage of dead or dying trees has become a debated issue when considering the balance between potential benefits and consequences to a site, but nevertheless will be an important tool to support the restoration of forest health and resilient communities across California.

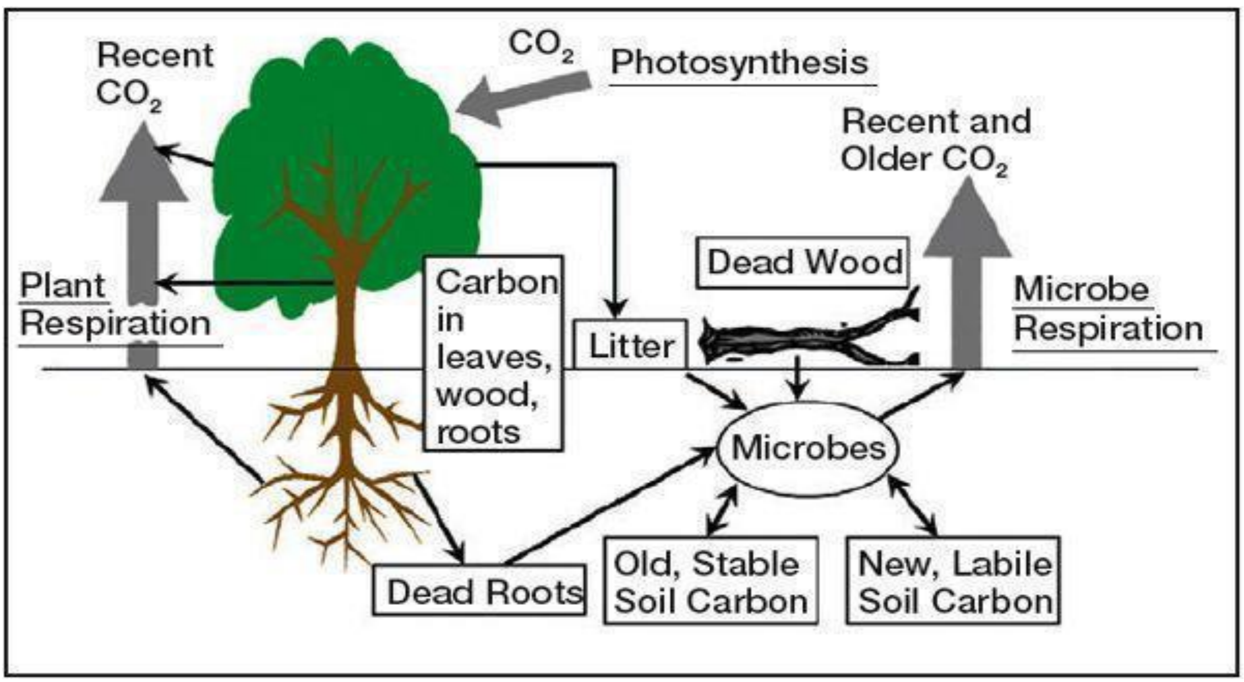
Forests in California and across the Western US are being impacted by a variety of environmental stressors, such as overstocking, drought, pests, disease, and wildfire, which are producing declining forest productivity, extensive mortality, and the loss of life and property as wildfires continue to impact towns and cities across the state. In California, its estimated 129 million trees have died since 2010 due to a variety of disturbances. These conditions are creating a need to treat forest stands and broader landscapes for multiple benefits including resilient forest ecosystems while reducing wildfire risk. Active forest management is a pathway to reduce fuel loading while generating consistent streams of forest biomass for a variety of end uses including the generation of biopower.

The effects of salvage and biomass harvest practices on stand productivity is variable, depending on soil properties (soil organic matter, porosity and moisture content, nutrient capital, etc.), species, and equipment use (surface disturbance and compaction). In general, quantifying the fate of post-disturbance residues (type, size, quantity, etc.) and retained biomass (slash) on the forest floor is an important factor in understanding site quality and stand productivity. A best practice recommendation is the more severe the disturbance (management or natural), the more conservative the management intensity to maintain sufficient biomass substrate for plant and soil recovery (Karr et al., 2004; Peterson & Leach, 2008). For example, more biomass can in general be removed from a wind throw or thinning site than from a site impacted by an intense stand replacing wildfire. This does not imply that biomass cannot be taken from highly-damaged sites, but careful planning, operations, and monitoring should be undertaken to ensure soil properties and habitat are protected.

D.1 Forest Carbon Cycle Concepts

Annually, forests and forest soils support a considerable sink (CO_2 capture and conversion into biomass via photosynthesis) and source of C (soil CO_2 efflux) returning to the atmosphere. These fluxes into biomass and back to the atmosphere as CO_2 are generally balanced each year with a small net C storage in woody biomass and soil organic matter. This simple depiction of an input-output relationship condenses considerable complexity across diverse factors working at varying spatial and temporal scales. This 'simple' relationship plays a considerable role in the C cycle at individual sites through global biogeochemical scales. Understanding potential disturbance and management effects on soil C dynamics are important to help guide planning and actions to achieve sustainable management, climate change mitigation, and resilient forest ecosystems. Figure 1 provides a conceptual diagram of a forest ecosystem with the major C pools and fluxes identified. These are CO_2 capture (photosynthesis), turnover (microbial processes), storage (biomass & soil organic matter), and CO_2 returned to the atmosphere via soil respiration (combined autotrophic and heterotrophic respiration).

Figure 31: Major Forest Ecosystem Carbon Pools and Fluxes



D.2 Soil CO2 Efflux Concepts

The C balance at a forest site is governed by a tight interrelation and long-term balance between inputs from photosynthesis (C and energy capture, and exchange with soil through root exudates and decomposition) and outputs from annual Soil C efflux (autotrophic and heterotrophic sources) with C also stored in soil organic matter and woody biomass. Soil CO_2 efflux is an important site productivity indicator that integrates multiple factors associated with soil health and is directly affected by various treatment and disturbance factors. Although soil CO_2 efflux can appear minor at first glance (micrograms per m^2 per minute) aggregate global soil respiration annually returns 60 billion metric tons of carbon to the atmosphere (about half of all C captured by primary productivity), larger than human emissions from fossil fuel combustion and cement production combined.

Measuring this ecosystem attribute can be difficult due to considerable spatial and temporal variability and the inherent seasonality of the main factors that regulate it. Both autotrophic and heterotrophic respiration are greatly affected by and positively correlated with factors like vegetation type, rainfall, temperature, soil moisture, and elevation. In fact, soil CO_2 efflux tends to be more sensitive to changes in temperature than photosynthesis (C inputs). The transformation of C and energy resources are the primary driver of the soil microbial community and the terrestrial food web. This creates a feedback loop where root exudates (rhizosphere), forest residues, litter fall, native soil organic matter, and the recycling of microbial biomass support the cycling of essential plant nutrients, like nitrogen, which are transformed and made available for uptake by plants which promotes primary productivity and C accumulation in vegetation and soil.

After management or other major disturbances (fire, blowdown, mortality, etc.) significant changes in total CO_2 efflux can occur over the first few years, returning to a reference or steady state condition, as the vegetation community becomes re-established and site temperature, water balance, and C inputs return to pre-disturbance conditions. This being said soil CO_2 efflux can be highly variably inter-annually independent of treatment or disturbance. A study by (Concilio et al., 2006) was conducted over four years measuring a western Sierra Nevada mixed-conifer site, and demonstrating as much as 37% year to year variation regardless of treatment (undisturbed, burned, thinning levels, burned + thinning levels) with this variation attributed mostly to soil moisture, and related canopy cover. This study also found that thinned sites increased soil CO_2 efflux rates significantly more than sites that were burned and thinned, leading to a recommendation that the combination of thinning and burning will reduce soil CO_2 efflux rates (Concilio et al., 2006). In another example, a salvage harvest in a Mediterranean mixed-conifer forest increased soil CO_2 efflux versus untreated sites (Serrano-Ortiz et al., 2011). These results align broadly with other studies that indicate thinning treatments consistently increase soil CO_2 efflux rates over the first few years after treatment. Across all studies one aspect is common, soil CO_2 efflux and site C dynamics are time and resource intensive measurements. Although a solid and representative data foundation exists for California forests, more assessment and monitoring is needed to increase the confidence in data, both spatially and temporally, to support process and LCA modeling efforts. Modelling will be critical to validate and predict the effects of site through landscape scale management of California's forest and wildland ecosystems for resilience and C storage.

D.3 Forest Soil CO2 Efflux Data Synthesis

Management and disturbance factors have been generalized into eight categories (see Table 60) in an effort to constrain the considerable variation that exists across managed forest stands where soil respiration was measured. Site conditions, management objectives, and operator decisions can all significantly affect soil respiration rates, with a wide range of outcomes. In a forest stand, harvest practices and prescribed burning are two important management practices that alter soil respiration. After harvest activities, residual biomass is left on site, either as surface residues, partially mixed into the soil by equipment, or broadcast or pile burned. Both soil incorporation and burning can increase short term soil respiration rates.

This section provides a detailed synthesis of Soil CO2 Efflux data characterizing management and disturbance effects across temperate forest ecosystems. Soil CO2 Efflux is an integrative and dynamic ecosystem property that returns the majority of C fixed annually by photosynthesis back to the atmosphere. The difference between annual productivity and soil CO2 efflux is the quantity of C stored in forest biomass (annual increment) and added to the resident pool of soil organic matter. Characterizing soil CO2 efflux across different stand conditions is an important component of developing site C budgets and predicting the effects of various treatment scenarios. Although this synthesis provides the best available data developed from California specific and comparable temperate forests, the spatial and temporal resolution does not tightly align with C-BREC model inputs for biomass growth and export from forested sites. This difference limits the value of these data to directly support C-BREC, but do provide a robust set of book-end conditions to constrain our understanding about potential effects of forest management on soil C dynamics.

This Soil CO2 Efflux data synthesis was derived from the Soil Respiration Database (SRDB) and a broad array of published and unpublished data. These data covered a range of forest treatment-disturbance conditions and were filtered and condensed into eight key treatment categories most relevant to potential conditions found in California forests: no treatment control stands through thinning, burning, clearcut, and salvage, and other less usual conditions, manipulations of nutrients and water availability.

The SRDB is hosted by Oak Ridge National Laboratory (Oak Ridge National Laboratory, n.d.) and provides data from over 1,487 studies worldwide representing 5,173 measurements of annual soil CO2 efflux across a wide range of landscapes and land use treatments. Along with SRDB and other published data, unpublished data representing California forest soils was obtained, from Dr. Matt Busse of the US Forest Service-Pacific Southwest Research Station and Dr. Si Yan Ma from the UC Berkeley's Biomet Lab, and integrated into this synthesis. In total, this synthesis represents 1,070 unique accounts for total efflux (no distinction between autotrophic and heterotrophic CO2 source), and 187 sites reporting CO2 efflux data partitioned into autotrophic and heterotrophic CO2 sources from warm and well drained Temperate and Mediterranean forest biomes. Table 60 provides summary data reported in megagrams (Mg) per hectare (ha) per year across a range of 8 general treatment-disturbance categories. The %Rh represents a generalized CO2 source relationship calculated from experimental sites which measured both sources of soil efflux (n= 187). This number (0.53) was applied to other study sites where only total CO2 efflux was measured to provide a simple baseline partitioning of soil CO2 flux under varying conditions. Please note the application of this ratio is only to provide a general split between autotrophic and heterotrophic sources for discussion only.

Table 60: Synthesis of Soil Carbon Efflux Values

Treatment	Soil C Respiration ($Mg\ CO_2/ha/yr$) - mean +/- st.dev	Sample Size - n	% Rh - mean +/- st.dev	Heterotrophic C Respiration ($Mg\ CO_2/ha/yr$)	Flux Ratio* - Treatment /Control
Control	34.7 (13.3)	859	0.53 +/- 0.19	18.4	-
Thinned	51.8 (32.2)	100		27.4	1.5
Clearcut	19.7 (4.2)	15		10.4	0.57
Salvaged	17.6 (12.1)	15		9.3	0.51
Irrigated	31 (11.8)	10		16.4	0.89
Fertilized	27.9 (8.3)	41		14.8	0.80
Burned	25.3 (6.5)	10		13.4	0.73
Drought	28.3 (13.2)	10		15.0	0.82

Source: CSU Chico, 2019

These data provide a high-level characterization of annual soil respiration across 8 categories from untreated control through different disturbance/management conditions. These categories provide a gradient of potential conditions based on degree of stand alteration driven by variable harvest intensity, fire, nutrient manipulation, and water availability. Across the 1,070 studies employed, 859 were classified as control or reference producing an average total efflux of 34.7 Mg CO_2/ha/year. This value aligns with other reported values characterizing soil respiration in undisturbed Temperate and Mediterranean forest ecosystems (Concilio et al., 2006) and should be considered the baseline to compare disturbance/management effects on annual total CO_2 efflux.

Two major trends arise from the data: 1) the majority of disturbance/management actions applied to forest stands reduce annual soil CO_2 efflux ranging from ~ 3 to 15 Mg CO_2/ha/yr, and 2) stand thinning increases soil CO_2 efflux (up to 1.5 times baseline conditions). The direction and magnitude of these fluxes are not completely unexpected when the level of stand alteration and associated potential influence on primary productivity (reduced leaf area for photosynthesis) and C inputs to soil/site food web are considered. At one end, clearcutting and salvage logging represent the greatest reduction in potential photosynthesis and C inputs with the removal of live or standing dead trees which produces a reduction of annual CO_2 efflux of up to 15 Mg CO_2/ha/yr.

Although it's difficult to generalize, it's well established that stand conditions and efflux can change dramatically over the first few years post disturbance with an evolution back to a reference or steady state condition as understory plants and trees reoccupy a site. How long it takes a site to return to reference conditions depends on site factors, severity and extent of the disturbance/management, and if management or mitigation actions were taken to replant or recolonize the site with trees or if natural regeneration was allowed to occur.

The next group of conditions represent sites where water or nutrient status was altered through disturbance or active management - irrigated or drought and fertilized or fire. These conditions all have a more modest reduction in total annual efflux of between 3.7 - 9.4 Mg CO_2/ha/yr or an 10-27 % reduction versus the reference. These sites have retained live trees and understory plants which provide C and energy into the soil through roots and litter, supporting autotrophic and heterotrophic respiration, but at a reduced level for various reasons.

Alterations of soil efflux related to water availability is an important issue to consider since much of California and the West are experiencing stand health issues driven by overstocking and drought. These conditions produce water stress across the growing season, at the tree and stand level, which can lower total Soil CO2 Efflux as productivity is restricted leading to a reduction in both plant respiration and the quantity of soil C inputs from roots. Synthesis data show modest reductions in total efflux but from a fairly small sample size (N=10 studies). Considering the impacts of climate change across Western North America more detailed investigations of the relationship between water stressed stands and soil CO2 efflux are needed. The other side of the water availability gradient is the practice of forest irrigation. This was not reviewed at length above since this practice is uncommon in California forests but data indicate a slight reduction in efflux from the reference. This could be due to a few different issues including poor drainage and oversaturated soil and/or nitrogen leaching reducing productivity or enhancing growth and greater C storage in standing biomass.

Forest fertilization is another management practice note extensively used in California, but data show this generally reduces total CO2 efflux. Repeated or high-volume fertilizer applications are known to lower soil pH in many soils which can lead to a suppression of microbial activity and altered site nutrient cycling. It is worth noting the data set only includes N-fertilization, and about a third of the rates were excessive associated with experimental treatments.

A potential explanation for respiration on burn sites being lower than normal is that wildfires can alter the soil microbial population to varying degrees depending on fire intensity and duration. The alteration of surface soil properties like loss of soil organic matter and volatile nutrients along with reduced soil moisture and water holding capacity and impact microbial activity until sites are recolonized by plants which return C inputs to soil through roots and litter decomposition.

Finally, the one disturbance/management action that can be expected to increase total soil efflux in the near term is stand thinning. This change can be substantial with a 1.5 times magnification to 51.8 Mg CO2/ha/yr over the first few years post treatment. The goal of thinning is to reduce stand density (number of trees per unit area) and increase resource availability (light, water, and nutrients) to enhance and maximize stand growth. The removal of living trees can alter soil water and temperature dynamics while providing new C substrates to the soil food web. Roots from harvested trees become an important new resource for microbial decomposition that leads to enhanced soil CO2 efflux and short-term nutrient availability. Depending on the harvest approach (from pre-commercial thins where trees are cut and left in place through commercial thins where biomass is removed from the stand), new surface litters can also be introduced to the forest floor that become decomposed by soil organisms. In all cases, transpiration (water loss to the atmosphere from trees) is reduced increasing soil water content over the first few years after treatment. The combination of new C and ample soil water lead to elevated microbial activity, nutrient turnover, and enhanced CO2 efflux from heterotrophic respiration. Although the resolution of our data does not provide a definitive duration of enhanced soil efflux, stand conditions do return to a steady state as remaining trees occupy resource gaps in the canopy and soil with new growth of aboveground biomass and roots. Like other stand conditions, our understanding of the directionality and magnitude to soil CO_2 efflux is sound but new and more resolved data are needed to support modelling to quantify changes in soil C storage over time.

APPENDIX E
Biomass Mobilization LCI Details

The first section includes the efficiencies and emissions factors for existing and generic biomass power plants in California. The second section includes emissions intensity factors for equipment used on-site at a biomass power plant. Note that these equipment emissions intensity factors ARE NOT currently used in the C-BREC model. They are documented here to facilitate future work, and can easily be added to the net mass emissions results. The third section includes the methodology report developed by CORRIM for this project.

E.1 Plant Efficiency and Stack Emissions Factors

Table 61 includes the efficiency values (η_{pp}) and emissions factors ($Ef_{pp,g}$) used.

Table 61: Biomass Power Plant Efficiency and Stack Emissions Factors

Power Plant Name	Power Plant Type	Efficiency Net Output	Secondary Fuel Use MMBtu/MWhe net	CO	CH4	N2O	VOC	NOx	SOx	PM10	PM2.5
ARP Loyalton Biomass Power	Biomass stoker	0.151	0.000	8.813	0.812	0.109	0.124	1.404	0.568	0.262	0.216
Big Valley Biomass Power	Biomass stoker	0.150	0.000	8.813	0.812	0.109	0.124	1.404	0.568	0.262	0.216
Blue Lake Power	Biomass stoker	0.176	0.000	8.109	0.618	0.081	0.138	1.227	0.203	0.325	0.301
Buena Vista Biomass Power	Fluidized bed combustor	0.195	0.597	0.107	0.527	0.069	0.016	0.987	0.138	0.236	0.141
Burney Forest Power	Biomass stoker	0.186	0.541	4.254	0.565	0.075	0.039	0.844	0.019	0.130	0.117
Chowchilla Biomass Power	Fluidized bed combustor	0.165	0.167	0.107	0.478	0.063	0.008	0.077	0.012	0.038	0.038
Collins Pine Biomass Power	Biomass stoker	0.122	0.000	12.538	0.605	0.080	0.458	3.386	0.362	1.222	1.117
Covanta Burney Mtn. Power	Biomass stoker	0.164	0.000	7.786	0.021	0.006	0.138	1.447	0.131	0.220	0.188
Covanta Delano Power	Fluidized bed combustor	0.219	0.004	0.070	0.457	0.061	0.018	0.503	0.160	0.017	0.016
Covanta Mendota Power	Fluidized bed combustor	0.203	0.007	0.322	0.009	0.018	0.000	0.428	0.163	0.422	0.370
Covanta Pacific Oroville Power	Biomass stoker	0.161	0.000	15.432	0.263	0.015	0.305	1.203	0.238	0.378	0.272
DG Fairhaven	Biomass stoker	0.194	0.360	10.372	0.471	0.062	0.150	1.214	0.219	0.237	0.220
Dinuba Energy	Fluidized bed combustor	0.168	0.048	2.070	0.548	0.073	0.093	0.485	0.324	0.481	0.440
DTE Mt. Poso Cogen	Biomass stoker	0.209	0.000	0.070	0.443	0.058	0.000	0.423	0.033	0.060	0.025
DTE Stockton Biomass Power	Biomass stoker	0.213	0.013	0.311	0.438	0.057	0.037	0.260	0.005	0.028	0.025
DTE Woodland Biomass Power	Fluidized bed combustor	0.196	0.068	0.337	0.445	0.059	0.004	0.475	0.139	0.144	0.129

Power Plant Name	Power Plant Type	Efficiency Net Output	Secondary Fuel Use MMBtu/MWhe net	CO	CH4	N2O	VOC	NOx	SOx	PM10	PM2.5
Greenleaf Desert View Power	Fluidized bed combustor	0.216	0.182	0.070	0.457	0.061	0.018	0.503	0.160	0.017	0.016
Honey Lake Power	Biomass stoker	0.230	0.086	0.006	0.365	0.048	0.007	0.779	0.005	0.191	0.178
Humboldt Redwood Company Scotia Power	Biomass stoker	0.152	0.016	14.273	0.742	0.099	0.398	2.715	0.455	0.597	0.553
Madera Power	Fluidized bed combustor	0.175	0.035	0.637	0.589	0.078	0.007	0.606	0.165	0.169	0.157
Merced Power	Fluidized bed combustor	0.155	0.035	1.017	0.497	0.066	0.022	0.890	0.180	0.202	0.185
Mt. Lassen Power	Biomass stoker	0.168	0.000	0.302	0.099	0.009	0.006	1.307	0.065	0.319	0.297
Pacific Ultrapower Chinese Station Power	Fluidized bed combustor	0.176	0.003	0.128	0.261	0.044	0.012	1.413	0.327	0.425	0.364
Rio Bravo Fresno Biomass Power	Fluidized bed combustor	0.224	0.017	0.007	0.417	0.055	0.004	0.475	0.021	0.185	0.163
Rio Bravo Rocklin Biomass Power	Fluidized bed combustor	0.209	0.029	0.027	0.482	0.064	0.002	0.620	0.129	0.140	0.130
Roseburg Forest Products Biomass Power	Biomass stoker	0.141	0.000	1.928	0.708	0.093	1.136	0.384	0.009	1.332	1.216
SPI Anderson Biomass Power II	Biomass stoker	0.156	0.103	1.132	0.840	0.111	0.056	1.068	0.024	0.165	0.131
SPI Anderson I	Biomass stoker	0.078	0.000	3.555	0.373	0.076	0.086	2.161	0.038	0.351	0.267
SPI Burney Biomass Power	Biomass stoker	0.142	0.005	12.446	0.732	0.097	0.514	1.368	0.009	0.177	0.151
SPI Lincoln Biomass Power	Biomass stoker	0.145	0.052	1.880	0.723	0.096	0.028	1.161	0.035	0.376	0.317
SPI Quincy Biomass Power	Biomass stoker	0.152	0.011	12.507	0.367	0.053	0.294	2.009	0.049	0.201	0.183
SPI Sonora Standard Biomass Power	Biomass stoker	0.090	0.000	9.148	1.447	0.191	0.170	4.297	0.086	2.013	1.856
Tracy Biomass Power	Biomass stoker	0.205	0.204	0.809	0.432	0.057	0.016	0.770	0.120	0.131	0.118

Power Plant Name	Power Plant Type	Efficiency Net Output	Secondary Fuel Use MMBtu/MWhe net	CO	CH4	N2O	VOC	NOx	SOx	PM10	PM2.5
Wadham Biomass Power	Biomass stoker	0.248	0.031	0.617	0.305	0.040	0.003	0.836	0.321	0.110	0.102
Wheelabrator Shasta Energy	Biomass stoker	0.213	0.003	3.865	0.470	0.077	0.049	1.211	0.024	0.262	0.242
Current Gen Combustion Plant Default	Biomass stoker	0.200	NA	1.388	0.509	0.193	0.132	0.509	0.193	0.221	0.196
Current Gen IG/Combustion Plant Default	Integrated gasification and combustion	0.220	NA	0.108	0.104	0.015	0.028	0.104	0.015	0.025	0.022
Next Gen Thermochemical Plant Default	Gasifier	0.280	NA	0.065	0.012	0.003	0.005	0.012	0.003	0.026	0.023
5 MW Plant *	Gasifier	0.280	NA	0.065	0.012	0.003	0.005	0.012	0.003	0.026	0.023
<1 MW Plant *	Gasifier	0.190	NA	0.065	0.012	0.003	0.005	0.012	0.003	0.026	0.023
Dixon Ridge Farms Gasifier Power Pilot **	Gasifier	0.190	NA	0.065	0.012	0.003	0.005	0.012	0.003	0.026	0.023
Ortigalita Power Company **	Gasifier	0.190	NA	0.065	0.012	0.003	0.005	0.012	0.003	0.026	0.023

* Emissions factors set equal to “Next Gen Thermochemical Plant Default”

** Efficiency and emissions factors set equal to “<1 MW Plant”

Carbon monoxide emissions factors were derived from data provided by CARB via special request. The data provided by CARB are shown in Table 62.

Table 62: Carbon Monoxide Data For Existing Biomass Power Plants

ARBID	FACID	CO	AB	DIS	CARB_FACILITY	YEAR	CO_TPY
104450	40	3	MC	AMA	Buena Vista Biomass Power, LLC	2016	6.4
104450	40	3	MC	AMA	Buena Vista Biomass Power, LLC	2015	12.3
104450	40	3	MC	AMA	Buena Vista Biomass Power, LLC	2014	8.8
100041	38	4	SV	BUT	Covanta - Pacific Oroville Power Inc	2012	2128
100041	38	4	SV	BUT	Covanta - Pacific Oroville Power Inc	2011	2128
100041	38	4	SV	BUT	Covanta - Pacific Oroville Power Inc	2010	959
100041	38	4	SV	BUT	Covanta - Pacific Oroville Power Inc	2009	1912.2
100041	38	4	SV	BUT	Covanta - Pacific Oroville Power Inc	2008	1824.6
100058	55	6	SV	COL	Wadham Energy Ltd Partnership	2017	132.9
100058	55	6	SV	COL	Wadham Energy Ltd Partnership	2016	133
100058	55	6	SV	COL	Wadham Energy Ltd Partnership	2015	110.5
100058	55	6	SV	COL	Wadham Energy Ltd Partnership	2014	139.3
100058	55	6	SV	COL	Wadham Energy Ltd Partnership	2013	81.7
100058	55	6	SV	COL	Wadham Energy Ltd Partnership	2012	129.5
100058	55	6	SV	COL	Wadham Energy Ltd Partnership	2011	135.1
100058	55	6	SV	COL	Wadham Energy Ltd Partnership	2010	99.5
100058	55	6	SV	COL	Wadham Energy Ltd Partnership	2009	99.5
100058	55	6	SV	COL	Wadham Energy Ltd Partnership	2008	151.3
100035	825	10	SJV	SJU	Covanta - Mendota	2017	0
100035	825	10	SJV	SJU	Covanta - Mendota	2016	0
100035	825	10	SJV	SJU	Covanta - Mendota	2015	2.1
100035	825	10	SJV	SJU	Covanta - Mendota	2014	60.6
100035	825	10	SJV	SJU	Covanta - Mendota	2013	60.5
100035	825	10	SJV	SJU	Covanta - Mendota	2012	60.3
100035	825	10	SJV	SJU	Covanta - Mendota	2011	57.6
100035	825	10	SJV	SJU	Covanta - Mendota	2010	66.7
100035	825	10	SJV	SJU	Covanta - Mendota	2009	66.7

ARBID	FACID	CO	AB	DIS	CARB_FACILITY	YEAR	CO_TPY
100035	825	10	SJV	SJU	Covanta - Mendota	2008	60.9
100265	1820	10	SJV	SJU	Rio Bravo Fresno	2017	2.6
100265	1820	10	SJV	SJU	Rio Bravo Fresno	2016	1.7
100265	1820	10	SJV	SJU	Rio Bravo Fresno	2015	1.5
100265	1820	10	SJV	SJU	Rio Bravo Fresno	2014	0.7
100265	1820	10	SJV	SJU	Rio Bravo Fresno	2013	0.5
100265	1820	10	SJV	SJU	Rio Bravo Fresno	2012	0.4
100265	1820	10	SJV	SJU	Rio Bravo Fresno	2011	0.4
100265	1820	10	SJV	SJU	Rio Bravo Fresno	2010	1.4
100265	1820	10	SJV	SJU	Rio Bravo Fresno	2009	1.8
100265	1820	10	SJV	SJU	Rio Bravo Fresno	2008	3.8
100040	60	12	NC	NCU	Scotia Sawmill Cogen	2017	890.5
100040	60	12	NC	NCU	Scotia Sawmill Cogen	2016	1421
100040	60	12	NC	NCU	Scotia Sawmill Cogen	2015	637.3
100040	60	12	NC	NCU	Scotia Sawmill Cogen	2014	683.2
100026	96	12	NC	NCU	DG Fairhaven Power LLC	2017	10.9
100026	96	12	NC	NCU	DG Fairhaven Power LLC	2016	616.8
100026	96	12	NC	NCU	DG Fairhaven Power LLC	2015	1341.1
100026	96	12	NC	NCU	DG Fairhaven Power LLC	2014	1466.1
100026	96	12	NC	NCU	DG Fairhaven Power LLC	2013	1359.2
100026	96	12	NC	NCU	DG Fairhaven Power LLC	2012	1368.9
100026	96	12	NC	NCU	DG Fairhaven Power LLC	2011	1239.5
100026	96	12	NC	NCU	DG Fairhaven Power LLC	2010	1056.7
100026	96	12	NC	NCU	DG Fairhaven Power LLC	2009	1246.1
100026	96	12	NC	NCU	DG Fairhaven Power LLC	2008	1682.8
100053	97	12	NC	NCU	Blue Lake Power	2017	0
100053	97	12	NC	NCU	Blue Lake Power	2016	0.4
100053	97	12	NC	NCU	Blue Lake Power	2015	26.7
100053	97	12	NC	NCU	Blue Lake Power	2014	659.2

ARBID	FACID	CO	AB	DIS	CARB_FACILITY	YEAR	CO_TPY
100053	97	12	NC	NCU	Blue Lake Power	2013	729.2
100053	97	12	NC	NCU	Blue Lake Power	2012	501.6
100053	97	12	NC	NCU	Blue Lake Power	2011	118.7
100053	97	12	NC	NCU	Blue Lake Power	2010	289
101737	68	13	SS	IMP	Imperial Valley Resource Recovery, LLC	2017	0
101737	68	13	SS	IMP	Imperial Valley Resource Recovery, LLC	2016	0
101737	68	13	SS	IMP	Imperial Valley Resource Recovery, LLC	2015	0
101737	68	13	SS	IMP	Imperial Valley Resource Recovery, LLC	2014	0
101737	68	13	SS	IMP	Imperial Valley Resource Recovery, LLC	2013	0
101737	68	13	SS	IMP	Imperial Valley Resource Recovery, LLC	2012	0
101737	68	13	SS	IMP	Imperial Valley Resource Recovery, LLC	2011	12.5
101737	68	13	SS	IMP	Imperial Valley Resource Recovery, LLC	2010	98.8
101737	68	13	SS	IMP	Imperial Valley Resource Recovery, LLC	2009	0
101737	68	13	SS	IMP	Imperial Valley Resource Recovery, LLC	2008	0
101228	91	15	SJV	SJU	Mt. Poso Cogeneration Company	2017	8.4
101228	91	15	SJV	SJU	Mt. Poso Cogeneration Company	2016	3.7
101228	91	15	SJV	SJU	Mt. Poso Cogeneration Company	2015	7.8
101228	91	15	SJV	SJU	Mt. Poso Cogeneration Company	2014	13.4
101228	91	15	SJV	SJU	Mt. Poso Cogeneration Company	2013	0
101228	91	15	SJV	SJU	Mt. Poso Cogeneration Company	2012	34.2
101228	91	15	SJV	SJU	Mt. Poso Cogeneration Company	2011	34.2
101228	91	15	SJV	SJU	Mt. Poso Cogeneration Company	2010	73.3
101228	91	15	SJV	SJU	Mt. Poso Cogeneration Company	2009	73.3
101228	91	15	SJV	SJU	Mt. Poso Cogeneration Company	2008	83.6
100029	15	18	NEP	LAS	HL Power Company	2017	1.2
100029	15	18	NEP	LAS	HL Power Company	2016	1.2
100029	15	18	NEP	LAS	HL Power Company	2015	1.2
100029	15	18	NEP	LAS	HL Power Company	2014	1.2
100029	15	18	NEP	LAS	HL Power Company	2013	1.2

ARBID	FACID	CO	AB	DIS	CARB_FACILITY	YEAR	CO_TPY
100029	15	18	NEP	LAS	HL Power Company	2012	1.2
100029	15	18	NEP	LAS	HL Power Company	2011	1.2
100029	15	18	NEP	LAS	HL Power Company	2010	1.2
100029	15	18	NEP	LAS	HL Power Company	2009	1.2
100029	15	18	NEP	LAS	HL Power Company	2008	1.2
100038	16	18	NEP	LAS	Shutdown - Covanta - Mt. Lassen Power	2011	19.4
100038	16	18	NEP	LAS	Shutdown - Covanta - Mt. Lassen Power	2010	19.4
100038	16	18	NEP	LAS	Shutdown - Covanta - Mt. Lassen Power	2009	19.4
100038	16	18	NEP	LAS	Shutdown - Covanta - Mt. Lassen Power	2008	19.4
101278	799	20	SJV	SJU	Madera Power LLC	2017	0
101278	799	20	SJV	SJU	Madera Power LLC	2016	0
101278	799	20	SJV	SJU	Madera Power LLC	2015	0
101278	799	20	SJV	SJU	Madera Power LLC	2014	0
101278	799	20	SJV	SJU	Madera Power LLC	2013	0
101278	799	20	SJV	SJU	Madera Power LLC	2012	7.1
101278	799	20	SJV	SJU	Madera Power LLC	2011	106.3
101278	799	20	SJV	SJU	Madera Power LLC	2010	100.5
101278	799	20	SJV	SJU	Madera Power LLC	2009	96.8
101278	799	20	SJV	SJU	Madera Power LLC	2008	12.8
101666	3775	20	SJV	SJU	Ampersand Chowchilla Biomass, LLC, 93610	2017	3
101666	3775	20	SJV	SJU	Ampersand Chowchilla Biomass, LLC, 93610	2016	3
101666	3775	20	SJV	SJU	Ampersand Chowchilla Biomass, LLC, 93610	2015	9.2
101666	3775	20	SJV	SJU	Ampersand Chowchilla Biomass, LLC, 93610	2014	6.2
101666	3775	20	SJV	SJU	Ampersand Chowchilla Biomass, LLC, 93610	2013	6.2
101666	3775	20	SJV	SJU	Ampersand Chowchilla Biomass, LLC, 93610	2012	6.1
101666	3775	20	SJV	SJU	Ampersand Chowchilla Biomass, LLC, 93610	2011	6.1
101666	3775	20	SJV	SJU	Ampersand Chowchilla Biomass, LLC, 93610	2010	5.8
101666	3775	20	SJV	SJU	Ampersand Chowchilla Biomass, LLC, 93610	2009	5.5
101666	3775	20	SJV	SJU	Ampersand Chowchilla Biomass, LLC, 93610	2008	5.6

ARBID	FACID	CO	AB	DIS	CARB_FACILITY	YEAR	CO_TPY
101665	4607	24	SJV	SJU	Merced Power, LLC, 95340	2017	52.8
101665	4607	24	SJV	SJU	Merced Power, LLC, 95340	2016	68.1
101665	4607	24	SJV	SJU	Merced Power, LLC, 95340	2015	70.9
101665	4607	24	SJV	SJU	Merced Power, LLC, 95340	2014	81.2
101665	4607	24	SJV	SJU	Merced Power, LLC, 95340	2013	35.6
101665	4607	24	SJV	SJU	Merced Power, LLC, 95340	2012	119.5
101665	4607	24	SJV	SJU	Merced Power, LLC, 95340	2011	79.8
101665	4607	24	SJV	SJU	Merced Power, LLC, 95340	2010	4.9
101665	4607	24	SJV	SJU	Merced Power, LLC, 95340	2009	0
101680	188	31	SV	PLA	Sierra Pacific Industries (SPI) - Lincoln	2017	194
101680	188	31	SV	PLA	Sierra Pacific Industries (SPI) - Lincoln	2016	375.3
101680	188	31	SV	PLA	Sierra Pacific Industries (SPI) - Lincoln	2015	194
101680	188	31	SV	PLA	Sierra Pacific Industries (SPI) - Lincoln	2014	194
101680	188	31	SV	PLA	Sierra Pacific Industries (SPI) - Lincoln	2013	194
101680	188	31	SV	PLA	Sierra Pacific Industries (SPI) - Lincoln	2012	194
101680	188	31	SV	PLA	Sierra Pacific Industries (SPI) - Lincoln	2011	192.1
101680	188	31	SV	PLA	Sierra Pacific Industries (SPI) - Lincoln	2010	192.1
101680	188	31	SV	PLA	Sierra Pacific Industries (SPI) - Lincoln	2009	241.6
101680	188	31	SV	PLA	Sierra Pacific Industries (SPI) - Lincoln	2008	190
100055	212	31	SV	PLA	Rio Bravo Rocklin	2017	12.1
100055	212	31	SV	PLA	Rio Bravo Rocklin	2016	10.7
100055	212	31	SV	PLA	Rio Bravo Rocklin	2015	5.4
100055	212	31	SV	PLA	Rio Bravo Rocklin	2014	3.8
100055	212	31	SV	PLA	Rio Bravo Rocklin	2013	5.8
100055	212	31	SV	PLA	Rio Bravo Rocklin	2012	4
100055	212	31	SV	PLA	Rio Bravo Rocklin	2011	4
100055	212	31	SV	PLA	Rio Bravo Rocklin	2010	5.4
100055	212	31	SV	PLA	Rio Bravo Rocklin	2009	5.8
100055	212	31	SV	PLA	Rio Bravo Rocklin	2008	2.9

ARBID	FACID	CO	AB	DIS	CARB_FACILITY	YEAR	CO_TPY
101378	3	32	MC	NSI	Sierra Pacific Industries (SPI) - Quincy Division	2017	1664
101378	3	32	MC	NSI	Sierra Pacific Industries (SPI) - Quincy Division	2016	1856.9
101378	3	32	MC	NSI	Sierra Pacific Industries (SPI) - Quincy Division	2015	1932.3
101378	3	32	MC	NSI	Sierra Pacific Industries (SPI) - Quincy Division	2014	2122.9
101378	3	32	MC	NSI	Sierra Pacific Industries (SPI) - Quincy Division	2013	2102.4
101378	3	32	MC	NSI	Sierra Pacific Industries (SPI) - Quincy Division	2012	2261.7
101378	3	32	MC	NSI	Sierra Pacific Industries (SPI) - Quincy Division	2011	2305
101378	3	32	MC	NSI	Sierra Pacific Industries (SPI) - Quincy Division	2010	2145.7
101378	3	32	MC	NSI	Sierra Pacific Industries (SPI) - Quincy Division	2009	2196.5
101378	3	32	MC	NSI	Sierra Pacific Industries (SPI) - Quincy Division	2008	2223.6
101250	15	32	MC	NSI	Collins Pine Co.	2017	461.3
101250	15	32	MC	NSI	Collins Pine Co.	2016	481.9
101250	15	32	MC	NSI	Collins Pine Co.	2015	502.3
101250	15	32	MC	NSI	Collins Pine Co.	2014	570.3
101250	15	32	MC	NSI	Collins Pine Co.	2013	605.8
101250	15	32	MC	NSI	Collins Pine Co.	2012	550.3
101250	15	32	MC	NSI	Collins Pine Co.	2011	526.8
101250	15	32	MC	NSI	Collins Pine Co.	2010	489.2
101250	15	32	MC	NSI	Collins Pine Co.	2009	483.8
101250	15	32	MC	NSI	Collins Pine Co.	2008	504.2
100022	100154	33	SC	SC	Colmac Energy, Inc. 92254	2013	32.5
100022	100154	33	SC	SC	Colmac Energy, Inc. 92254	2012	31.9
100022	100154	33	SC	SC	Colmac Energy, Inc. 92254	2011	31.1
100022	100154	33	SC	SC	Colmac Energy, Inc. 92254	2010	31
100022	100154	33	SC	SC	Colmac Energy, Inc. 92254	2009	29.8
100022	100154	33	SC	SC	Colmac Energy, Inc. 92254	2008	6
104455	645	39	SJV	SJU	DTE Stockton, LLC	2017	91
104455	645	39	SJV	SJU	DTE Stockton, LLC	2016	113.5
104455	645	39	SJV	SJU	DTE Stockton, LLC	2015	113.6

ARBID	FACID	CO	AB	DIS	CARB_FACILITY	YEAR	CO_TPY
104455	645	39	SJV	SJU	DTE Stockton, LLC	2014	113.7
104455	645	39	SJV	SJU	DTE Stockton, LLC	2013	17.8
104455	645	39	SJV	SJU	DTE Stockton, LLC	2012	0.1
104455	645	39	SJV	SJU	DTE Stockton, LLC	2011	0
104455	645	39	SJV	SJU	DTE Stockton, LLC	2010	0
104455	645	39	SJV	SJU	DTE Stockton, LLC	2009	335.5
104455	645	39	SJV	SJU	DTE Stockton, LLC	2008	331.3
100052	1026	39	SJV	SJU	Thermal Energy Development Partnership, L.P.	2017	0
100052	1026	39	SJV	SJU	Thermal Energy Development Partnership, L.P.	2016	0
100052	1026	39	SJV	SJU	Thermal Energy Development Partnership, L.P.	2015	0
100052	1026	39	SJV	SJU	Thermal Energy Development Partnership, L.P.	2014	97.3
100052	1026	39	SJV	SJU	Thermal Energy Development Partnership, L.P.	2013	109.3
100052	1026	39	SJV	SJU	Thermal Energy Development Partnership, L.P.	2012	113.9
100052	1026	39	SJV	SJU	Thermal Energy Development Partnership, L.P.	2011	227.8
100052	1026	39	SJV	SJU	Thermal Energy Development Partnership, L.P.	2010	95.3
100052	1026	39	SJV	SJU	Thermal Energy Development Partnership, L.P.	2009	95.3
100052	1026	39	SJV	SJU	Thermal Energy Development Partnership, L.P.	2008	95.3
100043	18	45	SV	SHA	Sierra Pacific Industries (SPI) - Burney	2017	1547.5
100043	18	45	SV	SHA	Sierra Pacific Industries (SPI) - Burney	2016	1304.8
100043	18	45	SV	SHA	Sierra Pacific Industries (SPI) - Burney	2015	1168.8
100043	18	45	SV	SHA	Sierra Pacific Industries (SPI) - Burney	2014	1518.5
100043	18	45	SV	SHA	Sierra Pacific Industries (SPI) - Burney	2013	1403
100043	18	45	SV	SHA	Sierra Pacific Industries (SPI) - Burney	2012	1594.6
100043	18	45	SV	SHA	Sierra Pacific Industries (SPI) - Burney	2011	1639.9
100043	18	45	SV	SHA	Sierra Pacific Industries (SPI) - Burney	2010	1624.6
100043	18	45	SV	SHA	Sierra Pacific Industries (SPI) - Burney	2009	1564.7
100043	18	45	SV	SHA	Sierra Pacific Industries (SPI) - Burney	2008	1562.5
100019	42	45	SV	SHA	Covanta - Burney Mountain Power	2011	0
100019	42	45	SV	SHA	Covanta - Burney Mountain Power	2010	598.9

ARBID	FACID	CO	AB	DIS	CARB_FACILITY	YEAR	CO_TPY
100019	42	45	SV	SHA	Covanta - Burney Mountain Power	2009	474.3
100019	42	45	SV	SHA	Covanta - Burney Mountain Power	2008	682.2
100282	43	45	SV	SHA	Wheelabrator Shasta Energy Company	2017	1421.5
100282	43	45	SV	SHA	Wheelabrator Shasta Energy Company	2016	1157.1
100282	43	45	SV	SHA	Wheelabrator Shasta Energy Company	2015	2191
100282	43	45	SV	SHA	Wheelabrator Shasta Energy Company	2014	2098.3
100282	43	45	SV	SHA	Wheelabrator Shasta Energy Company	2013	2112.3
100282	43	45	SV	SHA	Wheelabrator Shasta Energy Company	2012	2112.3
100282	43	45	SV	SHA	Wheelabrator Shasta Energy Company	2011	549.6
100282	43	45	SV	SHA	Wheelabrator Shasta Energy Company	2010	1994.3
100282	43	45	SV	SHA	Wheelabrator Shasta Energy Company	2009	472.3
100282	43	45	SV	SHA	Wheelabrator Shasta Energy Company	2008	2230
100090	48	45	SV	SHA	Sierra Pacific Industries (SPI) - Anderson, 96007	2017	124.2
100090	48	45	SV	SHA	Sierra Pacific Industries (SPI) - Anderson, 96007	2016	106.1
100090	48	45	SV	SHA	Sierra Pacific Industries (SPI) - Anderson, 96007	2015	90
100090	48	45	SV	SHA	Sierra Pacific Industries (SPI) - Anderson, 96007	2014	74.7
100090	48	45	SV	SHA	Sierra Pacific Industries (SPI) - Anderson, 96007	2013	70.9
100090	48	45	SV	SHA	Sierra Pacific Industries (SPI) - Anderson, 96007	2012	96.4
100090	48	45	SV	SHA	Sierra Pacific Industries (SPI) - Anderson, 96007	2011	115.1
100090	48	45	SV	SHA	Sierra Pacific Industries (SPI) - Anderson, 96007	2010	123.4
100090	48	45	SV	SHA	Sierra Pacific Industries (SPI) - Anderson, 96007	2009	130.5
100090	48	45	SV	SHA	Sierra Pacific Industries (SPI) - Anderson, 96007	2008	129.7
100018	51	45	SV	SHA	Burney Forest Products	2017	1065.8
100018	51	45	SV	SHA	Burney Forest Products	2016	1050.1
100018	51	45	SV	SHA	Burney Forest Products	2015	927.1
100018	51	45	SV	SHA	Burney Forest Products	2014	1064.3
100018	51	45	SV	SHA	Burney Forest Products	2013	984.3
100018	51	45	SV	SHA	Burney Forest Products	2012	1314.7
100018	51	45	SV	SHA	Burney Forest Products	2011	1060.3

ARBID	FACID	CO	AB	DIS	CARB_FACILITY	YEAR	CO_TPY
100018	51	45	SV	SHA	Burney Forest Products	2010	1024.3
100018	51	45	SV	SHA	Burney Forest Products	2009	939.2
100018	51	45	SV	SHA	Burney Forest Products	2008	1042.5
101328	1	46	MC	NSI	Sierra Pacific Industries (SPI) - Loyalton	2010	536.4
101328	1	46	MC	NSI	Sierra Pacific Industries (SPI) - Loyalton	2009	609.2
101328	1	46	MC	NSI	Sierra Pacific Industries (SPI) - Loyalton	2008	625.7
101702	29	47	NEP	SIS	Roseburg Forest Products	2017	387
101702	29	47	NEP	SIS	Roseburg Forest Products	2016	122.6
101702	29	47	NEP	SIS	Roseburg Forest Products	2015	122.6
101702	29	47	NEP	SIS	Roseburg Forest Products	2014	122.6
101702	29	47	NEP	SIS	Roseburg Forest Products	2013	122.6
101702	29	47	NEP	SIS	Roseburg Forest Products	2012	122.6
101702	29	47	NEP	SIS	Roseburg Forest Products	2011	122.6
101702	29	47	NEP	SIS	Roseburg Forest Products	2010	122.6
101702	29	47	NEP	SIS	Roseburg Forest Products	2009	122.6
101702	29	47	NEP	SIS	Roseburg Forest Products	2008	122.6
100025	285	54	SJV	SJU	Dinuba Energy	2017	0
100025	285	54	SJV	SJU	Dinuba Energy	2016	0
100025	285	54	SJV	SJU	Dinuba Energy	2015	109
100025	285	54	SJV	SJU	Dinuba Energy	2014	192.5
100025	285	54	SJV	SJU	Dinuba Energy	2013	187
100025	285	54	SJV	SJU	Dinuba Energy	2012	212.1
100025	285	54	SJV	SJU	Dinuba Energy	2011	187.4
100025	285	54	SJV	SJU	Dinuba Energy	2010	11.3
100025	285	54	SJV	SJU	Dinuba Energy	2009	177.3
101682	1	55	MC	TUO	Sierra Pacific Industries (SPI) - Sonora	2017	173.8
101682	1	55	MC	TUO	Sierra Pacific Industries (SPI) - Sonora	2016	173.8
101682	1	55	MC	TUO	Sierra Pacific Industries (SPI) - Sonora	2015	221
101682	1	55	MC	TUO	Sierra Pacific Industries (SPI) - Sonora	2014	221

ARBID	FACID	CO	AB	DIS	CARB_FACILITY	YEAR	CO_TPY
101682	1	55	MC	TUO	Sierra Pacific Industries (SPI) - Sonora	2013	221
101682	1	55	MC	TUO	Sierra Pacific Industries (SPI) - Sonora	2012	135.8
101682	1	55	MC	TUO	Sierra Pacific Industries (SPI) - Sonora	2011	252.2
101682	1	55	MC	TUO	Sierra Pacific Industries (SPI) - Sonora	2010	606.3
101682	1	55	MC	TUO	Sierra Pacific Industries (SPI) - Sonora	2009	606.3
101682	1	55	MC	TUO	Sierra Pacific Industries (SPI) - Sonora	2008	606.3
101298	12	55	MC	TUO	Pacific Ultrapower Chinese	2017	13.2
101298	12	55	MC	TUO	Pacific Ultrapower Chinese	2016	13.2
101298	12	55	MC	TUO	Pacific Ultrapower Chinese	2015	11.6
101298	12	55	MC	TUO	Pacific Ultrapower Chinese	2014	11.6
101298	12	55	MC	TUO	Pacific Ultrapower Chinese	2013	11.6
101298	12	55	MC	TUO	Pacific Ultrapower Chinese	2012	11.6
101298	12	55	MC	TUO	Pacific Ultrapower Chinese	2011	25.6
101298	12	55	MC	TUO	Pacific Ultrapower Chinese	2010	25.6
101298	12	55	MC	TUO	Pacific Ultrapower Chinese	2009	25.6
101298	12	55	MC	TUO	Pacific Ultrapower Chinese	2008	25.6
101493	257	57	SV	YS	Woodland Biomass Power, Ltd	2017	61.5
101493	257	57	SV	YS	Woodland Biomass Power, Ltd	2016	27.2
101493	257	57	SV	YS	Woodland Biomass Power, Ltd	2015	54.2
101493	257	57	SV	YS	Woodland Biomass Power, Ltd	2014	36.5
101493	257	57	SV	YS	Woodland Biomass Power, Ltd	2013	45.9
101493	257	57	SV	YS	Woodland Biomass Power, Ltd	2012	71
101493	257	57	SV	YS	Woodland Biomass Power, Ltd	2011	103.9
101493	257	57	SV	YS	Woodland Biomass Power, Ltd	2010	101.8
101493	257	57	SV	YS	Woodland Biomass Power, Ltd	2009	101.1
101493	257	57	SV	YS	Woodland Biomass Power, Ltd	2008	59.3

E.2 Power Plant On-Site Equipment and Waste Product Emissions Factors

The following table lists recommended emissions factors to use for on-site equipment at the power plant used to manage biomass. These emissions factors ARE NOT used in this version of the C-BREC framework. These emissions can be easily added to net mass emissions results from the C-BREC model.

Table 63: Power Plant On-Site Equipment and Waste Product Emissions Factors

Equipment	CO	N2O	CH4	NOx	PM10	PM2.5	SOx	VOC
On-site equipment, 2 loaders, 1 dozer, 1 bobcat	6.60E-02	0.00E+00	6.94E-04	1.03E-01	4.80E-03	4.41E-03	1.19E-04	1.02E-02
Lubricating Oil, at plant	1.83E-05	4.98E-07	1.52E-04	7.63E-05	6.93E-09	5.33E-06	2.20E-04	8.53E-04
Ammonia, liquid, at regional storehouse	3.58E-08	2.42E-09	9.24E-07	1.67E-07	8.77E-11	4.14E-08	4.02E-07	5.78E-06
Chemicals organic, at plant	1.43E-04	8.07E-07	7.90E-04	1.66E-04	2.08E-08	9.98E-06	2.25E-04	1.47E-03
Chlorine, liquid, production mix, at plant, kg-emission/MWh-elec	1.81E-06	1.18E-07	1.42E-05	6.49E-06	1.12E-09	1.92E-07	1.33E-05	7.39E-05
Sodium chloride, powder, at plant	5.20E-06	1.72E-07	1.87E-05	9.46E-06	1.40E-09	3.23E-07	1.83E-05	9.25E-05
Water, decarbonized, at plant	1.06E-08	3.12E-10	2.40E-08	1.43E-08	1.87E-12	4.17E-10	1.99E-08	1.24E-07
Disposal, used mineral oil, 10% water, to hazardous waste incineration	8.40E-07	8.88E-09	4.73E-06	7.24E-06	4.35E-10	1.42E-06	1.28E-06	2.86E-05
Disposal, municipal solid waste, 22.9% water, to municipal incineration	8.40E-06	4.70E-07	3.00E-06	1.62E-05	2.31E-10	2.86E-07	1.54E-06	1.75E-05
Treatment, sewage, to wastewater treatment, class 2	2.05E-06	9.06E-07	9.02E-06	8.57E-06	3.87E-10	7.81E-08	1.18E-05	2.56E-05
Disposal, wood ash mixture, pure, 0% water, to sanitary landfill	4.05E-05	5.24E-07	6.70E-04	1.51E-04	1.57E-09	1.31E-05	2.00E-04	1.24E-04
Disposal, wood ash mixture, pure, 0% water, to municipal incineration	3.37E-04	2.41E-07	6.52E-05	5.60E-04	4.61E-09	1.44E-05	1.92E-05	4.02E-04
Disposal, wood ash mixture, pure, 0% water, to land farming	2.30E-06	3.83E-08	1.15E-06	1.36E-05	5.44E-12	1.24E-06	1.19E-06	1.88E-06

All data produced by CORRIM using SimaPro, method TRACI 2.1 V1.0.1 / U.S. 2008.
All values are in units of kg / MWh_e

E.3 Forest Residue Mobilization Equipment Systems Matrix

A graphic representation of a selection matrix for forest residue mobilization equipment is shown on the following page. Note that equipment IDs colored red represent the default options used in the C-BREC model. However, all options are available in the C-BREC model.

calculated	user option	user option	assumption	4 user options	user option	assumption	determined by slope raster	--	All equipment and transportation are user options									
Plot Level							Raster Cell Level											
									Where there is more than one option, static equipment choices for internal statewide analysis are show in red. Additional options that CORRIM provided, shown in black, will be allowed in the website tool. The appropriate emissions factor for 20%/40%/60%/80% BA removal will be applied.									
Residue Volume	Moisture / Dirt Content	Comminution	Assumed Processing Location for choosing a CORRIM equipment pathway	Residue Disposition (4 user options: p70%/s30%, p50%/s50%, p30%/s70%, p0%/s100%)	Residue Collection Type	Assumed Residue Collection Location for choosing a CORRIM equipment pathway	Cell slope (slope of each individual 30m x 30m raster cell, cells >80% = no activity)	Comminution	Equipment 1	Equipment 2	Equipment 3	Equipment 4	Equipment 5	Equipment 6	Equipment 7	Transportation 1 (from road to transfer point or facility	Transportation 2 (distance from transfer point to facility)
High Residue Volume (> 1,000 BDT)	Clean and Green	Chip	Chip Aggregation Point (assumed in field)	Any of the 4 user options	Collect Piles	At landing	<10%	chip	C.1 C.2	L.1						H.5	H.5
							10%<x<35%	chip	C.1 C.2	L.1						L.1+H.5 H.6	L.1+H.5
							35% < x < 80%	chip	C.1 C.2	L.1						H.3 H.9	L.1+H.5
				Any of the 4 user options	Collect Piles and Scattered	In Field	<10%	chip	T.1 + L.3	L.1	C.1 C.2					H.5	H.5
							10%<x<35%	chip	T.1 + L.3	L.1	C.1 C.2					L.1+H.5 H.6	L.1+H.5
							35% < x < 80%	chip	CY.1 CY.2 CY.3	T.1 + L.3	L.1	C.1 C.2				H.3 H.9	L.1+H.5
		Grind	Grind Aggregation Point (assumed in field)	Any of the 4 user options	Collect Piles	At landing	<10%	grind	L.1	G.1 G.2						H.5	H.5
							10%<x<35%	grind	L.1	G.1 G.2						L.1+H.5 H.6	L.1+H.5
							35% < x < 80%	grind	L.1	G.1 G.2						H.3 H.9	L.1+H.5
				Any of the 4 user options	Collect Piles and Scattered	In Field	<10%	grind	T.1 + L.3	L.1	G.1 G.2					H.5	H.5
							10%<x<35%	grind	T.1 + L.3	L.1	G.1 G.2					L.1+H.5 H.6	L.1+H.5
							35% < x < 80%	grind	CY.1 CY.2 CY.3	T.1 + L.3	G.1 G.2	L.1				H.3 H.9	L.1+H.5
	Dirty and/or Dry	Grind	Grind Aggregation Point (assumed in field)	Any of the 4 user options	Collect Piles	At landing	<10%	grind	G.1 G.2	L.1						H.5	H.5
							10%<x<35%	grind	G.1 G.2	L.1						H.1 H.4 L.1+H.5	L.1+H.5
							35% < x < 80%	grind	G.1 G.2	L.1						H.8 H.10 H.11	L.1+H.5
				Any of the 4 user options	Collect Piles and Scattered	In Field	<10%	grind	T.1 + L.3	L.1	G.1 G.2					H.5	H.5
							10%<x<35%	grind	T.1 + L.3	L.1	G.1 G.2					H.1 H.4 L.1+H.5	L.1+H.5
							35% < x < 80%	grind	CY.1 CY.2 CY.3	T.1 + L.3	L.1	G.1 G.2				H.8 H.10 H.11	L.1+H.5
Small scale operation	All	Grind (chipping not available for small-scale)	Grind Aggregation Point (assumed in field)	Any of the 4 user options	Collect Piles	At landing	<10%	grind	L.1	G.1 G.2	L.1					H.5	H.5
							10%<x<35%	grind	L.1	G.1 G.2	L.1					H.1 H.4 L.1+H.5 H.6	L.1+H.5
							35% < x < 80%	grind	L.3	L.1	G.1 G.2	L.1				H.3 H.8 H.9 H.10 H.11	L.1+H.5
				Any of the 4 user options	Collect Piles and Scattered	In Field	<10%	grind	SS.2.WT	L.3	L.1	G.1 G.2	CS.1	L.1		H.5	H.5
							10%<x<35%	grind	SS.2.WT	L.3	L.1	G.1 G.2	CS.1	L.1		H.1 H.4 L.1+H.5 H.6	L.1+H.5
							35% < x < 80%	grind	CY.1 CY.2 CY.3	T.1	L.3	G.1 G.2	L.1	CS.1	L.1	H.3 H.8 H.9 H.10 H.11	L.1+H.5

E.4 Methods Report by CORRIM

The following is the methods report developed by CORRIM who developed the mobilization LCI equipment systems and emissions factors.

California Biopower Impacts Project

EPC-16-047

CORRIM Final Report

Submitted in support of
Task 4: RESIDUAL BIOMASS-TO-ENERGY LIFE CYCLE EMISSIONS ACCOUNTING FRAMEWORK.

Elaine E. Oneil, PhD

CORRIM
Consortium for Research on Renewable Industrial Materials

www.corrim.org
The Go-To Place for Wood LCA

Contents

List of Figures and Tables

Project Deliverables and Outcomes

CORRIM was commissioned to assist Humboldt State University's Schatz Energy Research Center (hereafter SERC) with the development of an attributional life cycle inventory (LCI) framework for a range of forest biomass-to-energy supply chain and end-use scenarios that were likely to occur in California for a given range of forest residue conditions. Data were drawn from existing sources in order to summarize the likely attributional LCI outputs per bone dry metric ton (BDT) of biomass at the landing or roadside loaded on the truck and ready for transport to a facility. The outputs were categorized across a range of harvest, feedstock handling, and management pathways. These outputs reflect the different types of management inputs and harvest equipment that are most likely to be used for each combination of scenarios. Transportation LCI data were generated by metric ton kilometer (tkm) for a range of hauling options that consider terrain, accessibility, and biomass characteristics. These data will allow SERC to integrate the LCI data into a network analysis and comparative LCA that was developed under separate tasks within the California Biopower Impacts Project.

Analysis of the common forest residue outcomes by forest type was summarized using representative stands generated from the forest inventory spatial analysis. This analysis of 177 representative stands was used to characterize the likely types of equipment by stand type, and the potential for biomass recovery. Based on this analysis, an equipment decision tree was developed to assist SERC in developing an online LCA tool that could incorporate estimates of greenhouse gas emissions from residue recovery systems that would be most appropriate for the conditions and feedstock characteristics of any given site.

Life cycle inventory data for eleven trucking alternatives, 11 roadside recovery equipment alternatives and 12 in-woods recovery equipment choices were developed. Analysis conducted to estimate the efficiency impact of partial harvest operations on in-woods recovery resulted in an additional 39 data points for in-woods recovery. LCI data on incidental emissions associated with biomass recovery, including transport of crew and equipment were also generated. Overall, a total of 77 LCI datasets were developed to quantify emission estimates from forest residue recovery.

Life Cycle Inventory of Biomass Recovery Alternatives

Life cycle assessments that meet ISO standards require four main steps: 1) goal and scope definition; 2) life cycle inventory analysis; 3) life cycle impact assessment and 4) interpretation. For this report only steps 1) and 2) were completed as the life cycle impact assessment and interpretation were included in tasks that are outside the project scope for CORRIM. The goal and scope definition characterizes the process to be followed, including details on the functional and/or reference unit, the boundary condition, excluded processes, data granularity, cutoff rules, impact indicators, characterization factors, and assumptions. No impact indicators or characterization factors are included in this report as an LCA was not conducted. Instead, data were extracted for use in a larger consequential analysis of the greenhouse gas outcome of collecting and using forest residues for biomass as an alternative to burning them in situ or burning them during wildfires.

Reference unit and boundary

In developing the California Residual Biomass-To-Energy Carbon Accounting Tool (CARBCAT), the focus is solely on the greenhouse gas emissions as measured in carbon dioxide equivalent that are directly related to recovery of forest biomass for energy. The functional unit for analysis and reporting of biomass volume and emissions associated with it is a bone dry metric ton (BDT) of residues. The system boundary (Figure 1) was set based on the assumption that the forest residues from commercial harvest would otherwise be considered waste if they were not collected and utilized for energy. Therefore, any activities related to growing, managing and harvesting the commercial trees are excluded from consideration. Likewise, for fire risk reduction treatments, all activities related to thinning, yarding, and piling are excluded from the boundary under the assumption that the primary treatment objective is fire risk reduction. This constrained boundary condition means that recovery begins at the roadside or landing within the treatment unit, unless effort is made to recover dispersed slash or slash piled in the setting (green insert - Figure 1) that would otherwise be left to decay or be burned to reduce fire risk and create plantable spots. For ground-based operations these additional recovery options are included as alternative systems for whole tree operations. For cable-based systems, they are excluded as operationally infeasible for cut to length systems, and unlikely for whole tree systems. These two assumptions regarding treatment and recovery are based on the overall assumption that collecting forest residues is a waste recovery operation since the biomass does not come from a dedicated energy crop. The only condition under which the boundary constraint is expanded is related to salvage harvest of dead and dying trees over regeneration. In such cases there is no onus to collect the materials as waste or reduce fire risk, so the entire burden is allocable to the biomass recovery.

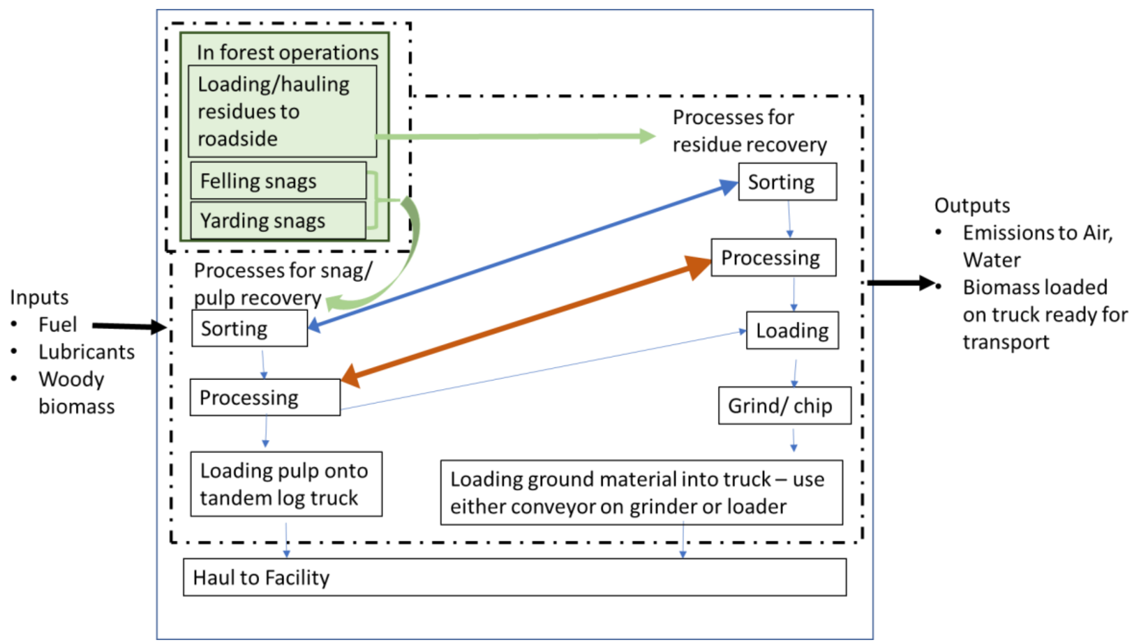


Figure 1: System Boundary for biomass recovery with insert for in-woods recovery

Excluded Processes, Data Quality, Granularity

Emissions associated with equipment manufacturing are excluded from the LCI given the choice to exclude operations upstream of the residue (i.e. no allocation to the forest harvest) which is where the majority of the equipment gets most of its use. Furthermore, there is no clear information on how much of the equipment time would be allocable to biomass recovery from forest residues as that is an industry in its nascent stage, so if it were to be included, the data quality would be highly uncertain. All emission data were developed using SimaPro 8.5.2.0 software (Pre 2018). Input data for the LCI analysis was aggregated from secondary data sources, including CORRIM equipment utilization factors and fuel data generated for Johnson et al 2012, Han et al 2014, and Oneil and Puettmann 2017. Additional data from the published literature was used to supplement these data, including primary data collected for the Humboldt State University Waste to Wisdom project (Bisson and Han 2016, Kizha and Han 2016, Waste to Wisdom 2017). Data used to derive partial harvest emission factors was generated through interpolation of relative efficiency reductions for partial harvests as reported in Handler et al 2014. Data on small scale operations were developed from similar data in Delasaux et al 2009. Efficiency differential data for turbo and naturally aspirated diesel engines were calculated for select equipment using relationships between horsepower and fuel usage from the Barrington Diesel Club (barringtondieselclub.co.za). Fuel usage and associated emissions per BDT are highly variable as they are a function of the interaction between equipment type, size, and operator skill combined with biomass characteristics such as size, moisture content, how much dirt and rocks are in the residues, and other operational constraints. As such, these representative emissions per BDT of material represent point estimates of a wide range of potentials. Uncertainty analysis regarding the range of potential emissions per BDT per system were not completed as part of this project.

Harvest System and Harvest Intensity Alternatives

Life cycle inventory data were aggregated for recovery systems for four harvest system alternatives and four harvest intensity alternatives. The harvest system alternatives are 1) ground-based, whole tree harvest; 2) ground-based, cut to length harvest; 3) cable-based, whole tree harvest; and 4) Cable-based, cut to length harvest. Harvest intensity alternatives include 100% harvest (clearcut); 80% removal, 60% removal, 40% removal and 20% removal where percentages are based on initial stand basal area and operations preferentially remove the smaller diameter trees first. Recovery systems reflect the different equipment types that are most likely to be used for the range of conditions found in the stand inventories consistent with operational feasibility. In practice what this means is that very large efficient machinery combinations are limited to where there is enough biomass to warrant their deployment. Smaller scale machinery is utilized where limited biomass is available. Some combinations of recovery systems and harvest alternatives produce so little biomass that they were excluded from the analysis due to techno-economic constraints.

For whole tree harvesting, residues are collected from the landing/roadside only under the assumption that most residues make it to the landing/roadside as part of the primary harvest activity. No in-woods recovery is modeled. For cut-to-length harvesting, life cycle inventory data are provided for an alternative where additional residues may be collected from the field for ground-based systems. Additional recovery of residues for cable-based systems was deemed operationally infeasible.

Operations at the roadside or landing include processing, grinding or chipping, and loading. Different biomass types can have different pathways for densification based on piece size and quality. Alternatives were provided for integration into CARBCAT. Regardless of harvest system or harvest intensity alternatives, roadside operations will have a similar carbon footprint per BDT under the assumption that equipment will not come on site unless it can be fully utilized. As such equipment with very high throughput (e.g. 30-40 BDT per hour processing speed), will only come onsite, if there is a sufficiently large supply of biomass to process.

Forest Stand Condition Analysis

Forest stand characteristics drive equipment choice and efficiency; therefore, it was necessary to analyze 'binned' forestry representative stand data to assign equipment and generate representative LCI data by silvicultural operation. Stands across California were analyzed (Comnick and Rogers, 2018) and binned into 177 categories that reflect differences in stand characteristics using the following 3 step protocol. First, all GNN stands were classified into species groups by basal area. Stands with greater than 80% basal area in a single species were classified by that species (i.e. "DF" for Douglas fir). Stands with less than 80% were classified as mixed (prepended with an "M"), followed by the species with the majority or plurality of basal area, followed by other species with at least 20% basal area in descending order (i.e. "MDF" for mixed Douglas fir with minor species, "MDFBO" for mixed Douglas fir with a significant black oak component (> 20% by basal area)). All species groups that made up at least 1% of forest area in California were identified. The remaining species groups were generalized by first keeping the majority/plurality species but lumping minor species into hardwoods or softwoods (i.e. "MDFOS" for mixed Douglas fir with other softwoods or "MDFOH" for mixed Douglas fir with other hardwoods). Finally, species groups that still didn't make up at least 1% of forest area were further generalized into "MOSOH" (mixed other softwoods with other hardwoods) or "MOHOS" (mixed other hardwoods with other softwoods). Second, for each species group, k-means clustering was used to group stands with similar structural attributes. Centering and scaling were used to normalize TPA, QMD, stand height, snag tons per acre, and downed woody debris tons per acre. "Elbow" plots of within groups sums-of-squares were produced using 1 to 15 clusters, and the "optimal" number of clusters was identified for each species group. Third, for each species-structure group, a representative stand was identified. This was the stand with the minimum Euclidean distance from the mean values in normalized space. A total of 177 groups/ representative stands were identified.

Figure 2 shows three stand metrics of import in making equipment choices: density in trees per acre (TPA); pre-harvest volume in board feet per acre (bf/ac): and the total stand basal area per acre (BA) for each of the 177 representative stands. Stand metrics show that these representative stands range from newly regenerated forests with no recoverable biomass (bottom left of chart) to extremely high volume stands (>50 MMBF/acre) that include massive specimens (>40" dbh) (diameter at breast) which likely means they would be considered old growth forests in the region. These stand metrics along with data on residues remaining at the roadside/landing and in the woods were used to assess the types of equipment that could be utilized for the volume that remains on site after harvest entries. A single stand had no standing live or dead trees but did have down dead wood (DWD) in the inventory. It was included in the analysis for potential residue recovery without treatment under the assumption that the inventory reflects an immediate past harvest. All remaining representative stands had standing inventory with metrics as displayed in Figure 2.

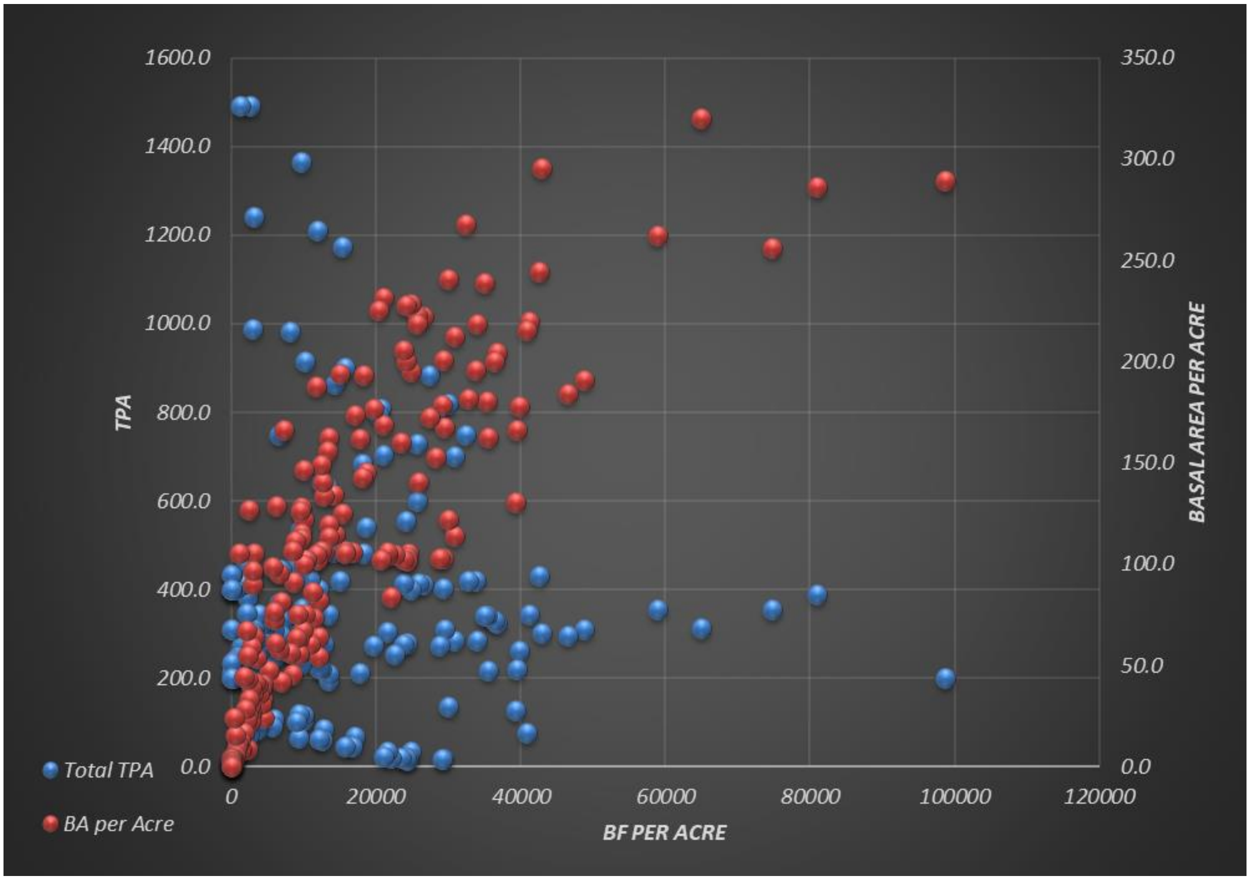


Figure 2: Stand Metrics for 177 Representative Stands

The 177 representative stands were organized into 5 major treatment options based on stand characteristics, with sub-categories based on characteristics that drive operational efficiencies. Spatial analysis to assess the number of acres represented by each treatment type generated the values shown in Table 1. Detailed summaries of the stand characteristics are provided in Appendix 1.

Treatment Option	Treatment Sub-Category	# Representative Stands	Estimated Acres	Percent of Area
Post-harvest recovery	biomass recovery opportunity	1	1,169,106	3.1%
Commercial Operation	commercial harvest	45	9,366,230	25.1%
	commercial harvest - low volume	21	4,921,251	13.2%
	commercial harvest plus Fire Risk Reduction	20	3,457,761	9.3%
	commercial harvest plus salvage	2	74,124	0.2%
Do Not Treat	do not treat - old growth	5	159,293	0.4%
	do not treat - pre-commercial	22	6,816,724	18.3%
	do not treat - pre-commercial - low density	5	3,635,982	9.7%
	do not treat - regen under small diameter snags	2	205,427	0.6%
	do not treat - regeneration	28	5,122,998	13.7%
Fire Risk Reduction Only	Fire Risk Reduction	4	538,228	1.4%
Salvage	salvage - regen under snags	14	1,639,522	4.4%
	salvage - regen under snags - low density	5	224,029	0.6%
	salvage - snags plus PCT	3	19,038	0.1%
Grand Total		177	37,349,714	100%

Table 1: Stand Category and Treatment Acres

Stands without opportunity for biomass recovery

The analysis boundary assumed that collecting forest residues is a waste recovery operation since the biomass does not come from a dedicated energy crop. That waste would only be generated during a commercial harvest operation, a stand management activity, or a fire risk reduction treatment. Given these assumptions on the system boundary, 62 of the 177 representative stands were deemed to have no opportunity for biomass recovery within the analysis timeframe. The rationale for excluding these 62 representative stand types varies depending on stand characteristics identified in the sub-categories of Table 1 as follows.

Five of 177 representative stands with volume greater than 50,000 bf/ac and more than 250 square feet per acre of basal area were classified as likely old growth forests (right hand side of Figure 1). They are excluded from biomass recovery as they are likely excluded from harvest operations. On the opposite end of the spectrum, 30 of 177 stands with less than 30 square feet of basal area and a quadratic mean diameter (QMD) less than 5 inches were classified as regenerating stands which would not have a harvest entry for at least 35 - 50 years (bottom left panel of Figure 1). Another 22 representative stands had adequate stocking and a QMD between 5-10 inches, representing those immature stands that are the future harvestable inventory in 15-35 years. A further 5 representative stands were considered both pre-commercial and not sufficiently restocked (NSR) with a mean inventory of less than 60 square feet of basal area and less than 120 trees per acre; they would benefit from activities to increase stocking, which are unlikely to result in recoverable biomass residues. As the representative stand metrics were derived based on stand structural attributes and not total area covered by each representative stand, the overall impact on biomass availability is dependent on where the stands that are represented by these average values and treatment opportunities occur across the landscape.

Fire Risk Reduction Treatments

While any stand can have fire risk reduction activities to reduce stocking and raise the height to live crown, for operational efficiency stands that are more likely to have a marked benefit from fuels reduction activities were called out for fire risk reduction treatments. Of our 177 representative stands, four meet criteria for fire risk reduction without options for commercial harvest in that they contain high stand densities (> 900 TPA to upwards of 1500 TPA), low average diameter (3-6"), and low heights. An additional 20 representative stands have enough volume to warrant a commercial entry and would benefit from simultaneous fire risk reduction treatments due to high stocking density. If fire risk reduction activities were conducted as part of a harvest operation, the boundary condition would exclude activities that occurred on the treated area except for recovery of otherwise distributed slash

Salvage

Twenty-two representative stands had more than 50% of their standing basal area as hard snags. Of these stands, only 1 of them had any appreciable green tree volume; most were characterized by a sea of snags over very small regeneration (less than 5 years old). Salvage operations under the conditions characterized by these data (i.e. having no green volume) would be non-commercial. Under such conditions it is necessary to expand the boundary to include emissions related to the entire harvesting process as the assumption that the activity would have occurred anyway no longer has merit. The option to salvage would impact the regenerating forest to a greater or lesser degree so equipment options were chosen to minimize this impact. For recovery of small diameter snags (5-7" diameter) and for small scale operations on relatively flat terrain, a modified skid steer equipment that can be hauled using a heavy-duty pick-up was modeled based on productivity and fuel usage as provided in Delasaux et al (2009). This alternative would be suitable around homes with small diameter trees only. The option to forgo harvest, especially where snag density is low, is also a reasonable alternative pathway.

Harvestable Stands

The remaining 68 representative stands contain enough green volume and a large enough piece size, to warrant commercial entries. In cases where there are also a large number of snags, they would be recovered along with merchantable green volume consistent with the boundary conditions used in our primary assumptions. Limitations to operations on these stands will be driven primarily by harvest system and harvest intensity alternatives.

Equipment Emission Profiles

All emissions were generated using SimaPro version 8.5.2.0 (Pre Consultants 2018) and include upstream emissions associated with fuels, lubricants, and transport, but do not include emissions associated with equipment manufacturing as that is outside the LCI boundary. Fuel and lubricant use on a per BDT biomass basis are calculated and emissions associated with their manufacturing and use are included in the LCI emissions data. Upstream emissions of consumables (fuel, lubricants) are based on national averages for what it takes to produce diesel as far back as its recovery at the well through refining, what it takes to transport that diesel to its point of eventual use (US average data) and emissions associated with combustion.

Emission profiles were generated for a wide range of biomass recovery and harvest equipment based on efficiency and utilization data for commercial operations (Johnson et al 2012, Han et al 2014, Bisson and Han 2016, Kizha and Han 2016, Waste to Wisdom 2017). Most of those operations involved high volume stands and nearly 100% removal of all merchantable stems. As such these data represent the most efficient harvest systems and harvest intensities for the region with concomitant lower emissions per BDT of biomass produced. Table 2 shows modeled biomass recovery equipment used at the roadside or landing for comminution and loading. Table 3 shows modeled biomass recovery equipment used at the roadside or landing for comminution and loading.

Operations that require retention of standing trees and/or treatment of lower volume stands will always be less efficient as the distance and time travelled per piece of material is higher and therefore energy usage is higher. Data were developed from Handler et al 2014 to scale the 100% removal data for partial harvest entries. Linearities observed in recovery productivity based on thinning percent (30%, 70%, 100%) from Handler et al 2014 were used to predict productivity and hence fuel usage for 20, 40, 60, and 80% removal treatments. These productivity assumptions do not negate the fact that there are highly variable production rates in almost all aspects of biomass recovery due to variability in site (slope, terrain uniformity etc.) and stand (diameter, stem distribution, etc.) conditions.

For operations at the landing or roadside, including chipping, grinding, loading and processing, operational efficiency can be maximized by aggregating material prior to bringing in equipment. Traditionally this is done during harvest activities, with biomass recovery occurring either immediately after harvest or after some period of drying. One assumption used for equipment use at the roadside or landing is that if there is enough material to warrant bringing in the equipment for a minimum of 3 days of processing, then efficiency during operations is the same regardless of harvest intensity. This 3-day minimum is approximately equal to 1000 BDT of material based on equipment operating efficiencies from 30-40 BDT/machine hour. This efficiency assumption should hold true for actual operating time, but additional utilization constraints are required to account for either having to move aggregated piles, or move the equipment, or both, on sites with limited biomass supply.

Reduced efficiency estimates are incorporated to account for the loading operations at roadside and landing when volumes per acre are constrained by available biomass. Stand characteristics will preclude or suggest specific equipment types for the main harvest operation. Those choices will then drive the outcome of residue recovery. For example, seven of the merchantable representative stands had an average diameter larger than 29 inches which is essentially the upper limit for mechanized harvests using a feller-buncher (FB), thus hand falling was the only alternative for harvest operations in these representative stands. The weight limits on moving these large trees would result in falling and bucking operations occurring in the woods, with no recovery of tops and limbs thus constraining recovery. At the opposite end of the size spectrum cut to length (CTL) systems are often used for thinning operations in smaller diameter stands as the harvesting and processing steps can occur at once leaving logs that are shorter thus causing less damage as they are hauled from the woods. Using these systems constrains biomass recovery as well as the limbs are felled and used to support the machine thus reducing ground disturbance and root impacts on residual trees. Recovering tops and limbs in this instance would be very challenging and result in a very dirty product.

Equipment Code	Equipment Type	Equipment Model/HP	Scale
S.1	sawdust machine	Beaver Korea Sawdust Machine (400 HP)	high volume
S.2	sawdust machine	Morbark Beever M20R (400 HP)	high volume
B.1	large wood baler	Forest Concepts	small scale
B.2	small wood baler	Forest Concepts	small scale
C.1	Chipper	Large Morbark Chipper (875 HP)	high volume
C.2	Chipper	Peterson Micro-Chipper model 4300 (765 HP)	high volume
G.1	Grinder	Small Grinder- Peterson Pacific Horizontal Grinder (475 HP)	high volume
G.2	Grinder	Large Grinder- Peterson Pacific Horizontal Grinder (1050 HP)	high volume
L.1	Loader	feeding grinder or chipper (250HP)	high volume
L.2	Loader	for loading pulp logs	high volume
L.3	Loader	for sorting logs and pulp at landing	high volume
T.2	In Woods Truck	AWD modified Dump Truck to staging site	high volume

Table 2: Roadside Biomass Recovery Equipment.

Equipment Code	Equipment Type	Equipment Model/HP/Comments	Scale
T.1	In Woods Truck	AWD modified Dump Truck in Unit High utilization	high vol
T.3	Forwarder	Self-loading small diameter log recovery 10 ton	small scale
T.4	Forwarder	Self-loading small diameter log recovery 12 ton	small scale
SS.1	Skid Steer	120 HP diesel model for fuel reduction and mastication	small scale
SS.2	Skid Steer	120 HP turbo diesel model for fuel reduction and mastication	small scale
P.1	Processor in Unit	no sorting	high vol
Y.1	Shovel Yarder	no sorting	high vol
L.3	Loader in unit	Loading in-woods dump truck	high vol
CY.1	cable yarding	cable yarding of residues, large skyline, clearcut	high vol
CY.2	cable yarding	cable yarding of residues, large skyline, thinning 80%	high vol
CY.3	cable yarding	cable yarding of residues, medium skyline, thinning	high vol
CS.1	Chainsaw	average productivity	small scale

Table 3: In-woods Biomass Recovery Equipment.

Fixed vs Variable Emission Profiles

LCI data for each piece of equipment reflect emission profiles from operations on a per dry ton of biomass basis assuming a range of equipment utilization factors (usually 75-95% efficiency). These emissions are analogous to the variable costs in an economic model. There are also LCI emissions associated with getting the equipment to the site, and to travel between sites. The transportation emissions are independent of the tons of biomass produced at a given site, and therefore are analogous to fixed costs in an economic model. Each piece of equipment has a productivity rating based on manufacturing specifications and/or utilization studies and that rating was used to define the minimum amount of biomass that would need to be available to move a given piece of equipment to a site. For example, a Peterson Pacific Horizontal Grinder (1050 HP) can process 38 BDT of wood residues per machine hour. Effectively this means that in a 10-hour work day, the machine with process 380 BDT of material. The assumption we used for fixed emissions in this analysis is that equipment would be moved to a site if there were a minimum of 3 days' worth of biomass for it to process, so in our example above the fixed emissions would be allocated over a minimum of 1140 BDT or larger. The total fixed emissions attributable to moving to and from the site would be added to variable emissions per BDT of biomass. Thus, for sites with a low density of material, or few acres, there is a fixed emission cost that is higher per BDT of biomass than for larger areas with more available biomass. If there are too few residues on site to utilize that machine for at least 3 days, then it would not be used.

Transportation LCI Data

Biomass characteristics including density and moisture content as generated from the Waste to Wisdom project (SERC 2016), combined with average wood properties for dominant California species (Briggs 1994), were used to estimate the volume and weight characteristics of ground biomass across a range of moisture contents. These data were then used to assess the range of conditions under which trucks hauling biomass would be expected to be weight limited or volume limited. The trucking analysis was developed using standard LCI methodologies for hauling freight that include a reference unit of tkm (tonne-kilometer). The emissions per tkm represent the emissions associated with each metric ton of material moved (converted to bone dry mass) per km of travel. Moisture included in the wood reduces the amount of bone-dry mass carried. All hauling from the in-woods location to the facilities assumes a 5.1 mpg average fuel use consistent with log trucking survey data (Mason et al 2008) for the PNW region. Using this methodology allows the CARBCAT user to input distance to facility, trucking option, and biomass characteristics (moisture content and densification if any) to determine the life cycle inventory emissions associated with moving 1 BDT of biomass. Conversions from green moisture content to BDT are included in the calculations.

There are two limits associated with moving biomass to market. The less common alternative for moving low density biomass is weight limited hauling where the truck reaches its maximum allowable weight as permitted on the roads in California. More commonly, particularly during the drier season, trucks are volume limited, unless they put very large sideboards above the main truck box to extend their available hauling space. Eleven total hauling alternatives were developed based on combinations of weight or volume limits, whether logs or chipped/ground material was hauled, moisture content, site conditions, and trucking configuration Table 4.

Limit	Material	Explanation of Alternatives
weight	Pulp logs hauled whole	two alternatives: pulp hauling assumes average 57,183 lb. payload for mule train weighted avg 5, 6, 7 axles hauling 12.99 OD metric tonnes (50% mc on green basis) or 9.62 ODT (63% MC on green basis); both weight limited (i.e. max weight is reached before max volume is reached)
weight	Chipped material, flat with easy access	chip hauling for chip van. Assume weight limited at 63% MC
weight	Chipped – steep terrain	two alternatives: chip hauling for truck only used (end) dump trucks with hoist weight limited at 30,000 lb. payload at 50% MC wet basis (equal to 6.81 OD metric Tonnes) and at 63% MC (wet basis) equal to 5.05 OD metric tonnes
weight	Chipped – flat terrain	two alternatives: chip hauling for truck plus trailer used (end) dump trucks with hoist weight limited at 30,000 lb. payload plus trailer with 32,000 lb. payload for total ODT payload of 6.81 ODT plus 7.27 ODT at 50% MC (wet basis) and 5.05 ODT plus 5.38 ODT at 63% MC (wet basis).
volume	Chipped – steep terrain	three alternatives: chip hauling for truck only used (end) dump trucks with hoist weight limited at 30,000 lb. payload but added height (sides on box) in order to haul 17 yd (4.13 ODT), 20 yd (4.86 ODT), and 25 yds (6.08 ODT) of material (does not exceed weight max).
volume	Chipped – flat terrain	chip hauling for truck plus trailer used (end) dump trucks with hoist weight limited at 30,000 lb. payload plus trailer with 32,000 lb. payload with sides added to attain 25 yd in truck and trailer both. Total of 6.08 + 6.08 ODT

Table 4 Trucking Configurations by limit, type, terrain, moisture content, and payload.

Each trucking configuration has a maximum payload and maximum volume limit. The moisture content of the wood is the primary factor determining weight or volume limits with the split occurring between 50 and 63% moisture content (wet basis). In practical terms, unless the material is removed at the same time as the primary harvest activity, it will almost always result in a volume limit on the trucking configuration.

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Appendix 1

Representative Stand #	Green trees BdFt	Green trees Avg DBH	Green Trees Avg Ht	Green Tree TPA	Green Trees BA	Pct live BA	Hard Snags TPA	Hard Snags BA	Hard snags height	Hard snags avg DBH	Total Standing BA	Hard DWD <6 in	Hard DWD > 6	Soft DWD <6	Soft DWD >6	Category
102141281	-	0	0	-	0	0	0	0	0	0	0	151	77	75	23	biomass recovery opportunity
363591313	48,778	9.3	40	357	190.9	93%	116.0	13.7	69	19.2	204.7	292	356	51	50	commercial harvest
409342613	46,529	5.7	25	310	184.0	72%	194.7	71.8	77	22.1	255.8	550	363	81	50	commercial harvest
520272697	42,962	19.9	74	295	295.9	85%	55.0	51.7	80	22.2	347.6	591	79	180	23	commercial harvest
436682601	42,606	11.6	39	302	244.5	58%	179.2	175.4	68	22.9	419.8	326	267	57	46	commercial harvest
356472573	41,128	20.0	76	433	219.9	59%	130.4	155.6	78	22.1	375.5	628	384	205	112	commercial harvest
373150005	40,846	16.9	76	344	215.8	91%	22.7	21.8	73	19.1	237.6	284	146	251	102	commercial harvest
580140001	39,839	26.6	94	77	177.9	99%	1.1	1.1	80	23.1	179.0	218	136	231	132	commercial harvest
485702697	39,436	22.4	94	263	166.7	62%	51.6	103.7	97	24.9	270.4	469	75	152	22	commercial harvest
521982565	36,676	23.1	88	127	204.7	86%	22.0	33.3	80	23.1	238.0	602	314	209	92	commercial harvest
514852609	36,267	5.4	21	325	200.5	89%	117.3	25.6	71	22.3	226.1	284	282	47	42	commercial harvest
481112617	35,509	4.4	21	331	162.5	58%	441.9	116.1	78	21.2	278.6	588	290	90	51	commercial harvest
508390005	35,359	22.9	83	217	180.4	87%	23.4	26.2	78	23.2	206.6	266	144	332	172	commercial harvest
483860005	34,954	17.1	70	342	239.2	91%	25.1	24.2	65	18.9	263.4	340	159	386	199	commercial harvest
378232569	34,004	16.5	66	343	218.9	72%	127.0	84.8	70	21.1	303.7	568	212	154	42	commercial harvest
541820005	33,828	18.3	71	285	196.1	88%	24.3	28.0	77	22.0	224.1	275	157	252	113	commercial harvest
489362569	32,705	17.0	55	419	181.6	69%	55.7	81.3	77	25.1	262.9	655	410	232	121	commercial harvest

Representative Stand #	Green trees BdFt	Green trees Avg DBH	Green Trees Avg Ht	Green Tree TPA	Green Trees BA	Pct live BA	Hard Snags TPA	Hard Snags BA	Hard snags height	Hard snags avg DBH	Total Standing BA	Hard DWD <6 in	Hard DWD > 6	Soft DWD <6	Soft DWD >6	Category
610542589	32,415	9.3	36	419	267.7	60%	180.6	182.0	66	23.3	449.7	351	330	61	57	commercial harvest
610192693	30,803	18.3	71	285	212.5	89%	21.8	27.5	84	22.5	240.0	450	65	151	18	commercial harvest
506461921	29,491	21.1	82	135	167.9	95%	15.7	9.7	80	22.1	177.6	366	206	236	57	commercial harvest
486152573	29,291	19.8	68	310	200.6	67%	117.2	100.8	72	23.0	301.3	453	194	156	57	commercial harvest
468391473	29,242	32.4	123	19	103.1	100%	0.1	0.2	112	27.3	103.3	740	45	254	12	commercial harvest
346480005	29,098	19.0	72	404	178.8	90%	26.1	19.0	74	22.0	197.8	269	171	297	190	commercial harvest
449901473	28,700	33.9	131	17	103.2	100%	0.1	0.3	115	29.0	103.5	658	49	228	13	commercial harvest
612800017	28,314	8.3	32	274	153.0	85%	21.2	27.1	62	19.6	180.0	123	427	65	182	commercial harvest
370080017	25,788	4.4	20	413	140.5	71%	210.9	57.6	59	16.2	198.1	390	879	173	325	commercial harvest
331151281	25,748	12.1	54	414	222.8	96%	29.8	8.2	44	11.9	230.9	773	222	190	59	commercial harvest
350251285	24,864	12.3	61	600	228.7	93%	39.8	17.1	69	17.0	245.7	487	268	170	78	commercial harvest
468291285	24,745	12.2	74	399	195.1	91%	44.2	18.3	72	13.5	213.4	405	231	160	67	commercial harvest
567592788	24,380	27.7	108	34	105.5	99%	0.3	0.7	100	31.9	106.2	528	124	160	24	commercial harvest
499692753	24,334	31.4	109	20	103.7	99%	0.2	0.9	94	27.5	104.6	556	48	195	14	commercial harvest
325430193	24,214	34.2	131	16	101.9	100%	0.1	0.3	102	27.3	102.3	427	32	397	24	commercial harvest
508112693	24,062	16.1	69	281	200.0	92%	22.5	18.3	71	18.2	218.2	408	67	134	20	commercial harvest
596582565	24,061	17.8	55	554	228.2	92%	38.5	18.6	61	20.4	246.9	795	395	250	117	commercial harvest
518130212	23,853	31.3	126	20	102.6	99%	0.2	0.8	107	31.3	103.4	400	58	309	21	commercial harvest
498172569	23,714	17.4	63	278	206.0	81%	59.0	48.1	63	22.1	254.1	414	120	129	35	commercial harvest

Representative Stand #	Green trees BdFt	Green trees Avg DBH	Green Trees Avg Ht	Green Tree TPA	Green Trees BA	Pct live BA	Hard Snags TPA	Hard Snags BA	Hard snags height	Hard snags avg DBH	Total Standing BA	Hard DWD <6 in	Hard DWD > 6	Soft DWD <6	Soft DWD >6	Category
329491329	23,403	6.5	33	414	160.2	89%	112.1	19.3	65	16.4	179.5	429	357	61	48	commercial harvest
529092788	22,588	30.6	107	19	104.7	99%	0.3	0.9	89	27.7	105.7	512	80	157	16	commercial harvest
465752788	21,453	31.8	109	20	104.1	99%	0.3	1.0	89	29.3	105.1	474	60	143	12	commercial harvest
351182753	21,444	26.5	95	34	106.2	100%	0.2	0.5	89	23.4	106.7	551	71	181	21	commercial harvest
465052565	21,064	15.0	63	304	168.6	89%	24.8	20.7	65	16.5	189.3	454	201	156	59	commercial harvest
509160193	20,745	28.6	109	24	102.5	99%	0.3	1.0	84	24.4	103.5	382	31	433	32	commercial harvest
486732617	18,521	9.0	33	275	145.5	52%	179.0	136.1	59	19.9	281.6	219	354	40	60	commercial harvest
382691313	18,323	4.1	26	542	193.4	86%	214.1	30.9	53	11.4	224.3	816	1115	112	131	commercial harvest
517321313	18,073	4.4	21	483	143.1	82%	144.1	31.3	70	21.5	174.4	577	726	76	79	commercial harvest
480472565	17,047	17.0	58	211	173.9	89%	25.3	20.4	59	18.8	194.3	337	55	111	16	commercial harvest
517321473	16,665	20.1	79	67	106.1	100%	0.2	0.2	82	24.0	106.3	554	26	183	7	commercial harvest - low volume
465742772	15,754	20.8	79	47	106.8	99%	0.5	1.0	71	20.6	107.9	416	106	123	19	commercial harvest - low volume
548542753	15,647	24.5	82	45	105.7	100%	0.3	0.4	77	25.9	106.2	385	36	129	11	commercial harvest - low volume
148391297	14,318	5.8	26	421	114.8	78%	139.9	33.0	62	17.5	147.8	613	713	78	74	commercial harvest - low volume
328631285	13,493	9.0	45	486	162.8	94%	45.9	11.3	51	14.4	174.1	386	112	131	32	commercial harvest - low volume
451671285	13,422	12.7	55	194	119.8	90%	21.0	12.7	60	14.1	132.5	490	130	142	38	commercial harvest - low volume
596150049	13,385	2.9	10	345	113.4	86%	48.4	19.1	35	12.0	132.5	193	190	81	58	commercial harvest - low volume
491551925	13,205	13.3	56	209	156.2	89%	26.7	18.8	65	18.8	175.1	322	142	250	64	commercial harvest - low volume
179411473	12,679	16.1	76	87	106.1	100%	0.0	0.0	85	18.3	106.1	957	64	309	18	commercial harvest - low volume

Representative Stand #	Green trees BdFt	Green trees Avg DBH	Green Trees Avg Ht	Green Tree TPA	Green Trees BA	Pct live BA	Hard Snags TPA	Hard Snags BA	Hard snags height	Hard snags avg DBH	Total Standing BA	Hard DWD <6 in	Hard DWD > 6	Soft DWD <6	Soft DWD >6	Category
579951285	12,649	10.8	53	277	140.4	93%	24.2	10.8	50	17.6	151.2	421	190	135	55	commercial harvest - low volume
500282788	12,455	19.2	73	60	106.8	99%	0.5	0.7	66	20.8	107.5	416	104	126	22	commercial harvest - low volume
440410049	12,089	5.4	17	220	64.5	73%	110.2	24.2	43	16.9	88.6	89	157	60	92	commercial harvest - low volume
505910001	12,060	19.2	45	64	81.9	99%	1.1	0.9	46	20.6	82.7	59	10	89	10	commercial harvest - low volume
594722593	11,982	4.3	19	223	54.2	87%	12.2	8.1	79	26.5	62.3	77	179	16	28	commercial harvest - low volume
350482581	11,879	3.1	13	400	102.6	67%	191.0	51.4	57	19.0	153.9	763	464	103	57	commercial harvest - low volume
509581969	11,655	6.6	24	246	104.6	80%	149.2	25.7	59	22.5	130.3	180	231	97	65	commercial harvest - low volume
105631297	11,318	4.0	17	370	73.5	88%	190.8	9.7	51	15.6	83.2	188	185	39	33	commercial harvest - low volume
358841313	11,260	2.7	17	464	86.3	86%	105.4	13.9	61	15.4	100.3	374	343	60	51	commercial harvest - low volume
373840242	10,818	3.4	14	274	60.3	84%	26.2	11.6	74	22.5	71.9	98	123	36	42	commercial harvest - low volume
490392593	10,282	4.9	22	424	102.7	87%	182.2	15.7	44	13.2	118.4	266	273	51	58	commercial harvest - low volume
523152593	10,230	3.0	10	264	75.2	87%	31.8	11.7	57	23.3	86.9	110	227	26	34	commercial harvest - low volume
507932676	30,854	2.9	13	748	113.9	93%	108.2	8.3	61	18.9	122.3	391	277	107	65	commercial harvest plus Fire Risk Reduction
598660116	29,946	3.3	14	702	122.3	93%	126.5	8.6	66	21.5	130.9	360	220	276	173	commercial harvest plus Fire Risk Reduction
481760005	29,914	10.8	44	821	241.2	94%	65.0	15.2	60	16.4	256.3	435	185	424	216	commercial harvest plus Fire Risk Reduction
367690116	27,336	2.6	15	793	172.3	92%	27.5	14.7	63	16.7	187.0	229	374	139	218	commercial harvest plus Fire Risk Reduction

Representative Stand #	Green trees BdFt	Green trees Avg DBH	Green Trees Avg Ht	Green Tree TPA	Green Trees BA	Pct live BA	Hard Snags TPA	Hard Snags BA	Hard snags height	Hard snags avg DBH	Total Standing BA	Hard DWD <6 in	Hard DWD > 6	Soft DWD <6	Soft DWD >6	Category
507110005	26,500	10.5	46	885	222.3	94%	47.1	14.6	60	15.5	237.0	333	177	349	175	commercial harvest plus Fire Risk Reduction
581052569	25,704	15.0	54	730	218.6	88%	87.0	30.3	69	22.4	248.9	494	317	180	93	commercial harvest plus Fire Risk Reduction
407330005	20,986	10.0	50	706	231.9	94%	40.7	14.7	55	12.2	246.7	381	175	416	222	commercial harvest plus Fire Risk Reduction
369390009	20,399	10.2	46	807	225.5	91%	78.0	22.7	52	13.2	248.3	326	185	349	178	commercial harvest plus Fire Risk Reduction
599740005	19,607	9.6	56	794	177.0	91%	29.0	16.7	54	10.6	193.7	281	164	287	136	commercial harvest plus Fire Risk Reduction
350600005	17,742	9.0	47	684	162.2	93%	26.2	12.9	49	11.4	175.1	233	112	241	109	commercial harvest plus Fire Risk Reduction
384671396	15,284	2.1	14	900	125.3	94%	50.6	7.9	60	17.3	133.3	527	259	122	57	commercial harvest plus Fire Risk Reduction
371241281	15,022	7.9	51	1,174	194.2	98%	81.6	4.0	45	8.1	198.2	464	257	164	75	commercial harvest plus Fire Risk Reduction
432650065	14,192	3.1	18	865	134.6	99%	6.2	1.1	37	7.8	135.7	179	146	257	183	commercial harvest plus Fire Risk Reduction
584261297	12,699	4.0	21	630	133.6	83%	342.7	27.3	49	11.2	160.9	868	617	124	84	commercial harvest plus Fire Risk Reduction
483580009	12,376	7.7	41	643	149.3	88%	56.1	20.6	53	10.4	169.9	271	189	266	163	commercial harvest plus Fire Risk Reduction
538931281	11,753	8.2	47	1,210	187.7	98%	77.6	4.3	46	10.5	192.0	473	293	164	86	commercial harvest plus Fire Risk Reduction

Representative Stand #	Green trees BdFt	Green trees Avg DBH	Green Trees Avg Ht	Green Tree TPA	Green Trees BA	Pct live BA	Hard Snags TPA	Hard Snags BA	Hard snags height	Hard snags avg DBH	Total Standing BA	Hard DWD <6 in	Hard DWD > 6	Soft DWD <6	Soft DWD >6	Category
434240005	9,973	9.3	44	915	147.0	95%	30.5	7.0	49	14.1	154.0	261	171	275	162	commercial harvest plus Fire Risk Reduction
370060005	9,652	6.8	31	1,365	128.1	95%	40.1	6.5	39	10.3	134.6	132	69	173	87	commercial harvest plus Fire Risk Reduction
392601281	7,256	7.9	45	983	166.7	98%	45.3	3.2	42	7.4	169.9	454	193	162	57	commercial harvest plus Fire Risk Reduction
502692565	6,165	6.0	31	748	128.7	95%	47.9	7.2	47	10.4	135.9	320	94	119	27	commercial harvest plus Fire Risk Reduction
487980049	39,260	10.3	44	219	130.5	48%	151.3	140.4	88	23.3	270.9	334	343	123	148	commercial harvest plus salvage
523292609	22,112	7.6	33	253	84.1	40%	193.2	125.3	70	20.8	209.4	366	568	51	67	commercial harvest plus salvage
595442561	98,630	41.0	137	37	289.5	99%	0.8	3.5	86	24.6	293.0	452	237	176	69	do not treat - old growth
500400009	80,936	32.6	105	201	286.6	63%	53.4	167.9	99	30.5	454.5	286	165	336	182	do not treat - old growth
148641297	74,753	9.9	40	389	256.2	85%	117.1	44.6	77	22.5	300.8	611	548	89	73	do not treat - old growth
502182589	64,953	11.2	47	355	320.1	51%	189.0	307.3	80	21.6	627.4	488	451	82	78	do not treat - old growth
539602585	58,823	12.0	46	312	262.6	61%	89.6	165.4	93	28.9	428.0	250	239	56	56	do not treat - old growth
562981925	9,920	13.6	50	106	99.9	83%	23.6	20.5	55	16.1	120.4	145	271	152	108	do not treat - pre-commercial
505952569	9,914	18.6	44	117	122.2	66%	51.2	62.4	42	19.6	184.6	195	3	33	0	do not treat - pre-commercial
595221285	9,616	11.4	46	232	112.9	89%	23.2	14.5	46	18.5	127.4	285	71	101	20	do not treat - pre-commercial
375262565	9,456	9.3	35	258	126.1	91%	31.0	12.5	47	13.4	138.6	412	256	150	74	do not treat - pre-commercial
348880005	9,090	10.2	36	118	75.6	85%	21.9	13.1	42	12.8	88.7	47	3	79	3	do not treat - pre-commercial
596710049	8,995	3.7	17	328	63.6	65%	96.3	33.9	41	13.6	97.4	449	698	161	232	do not treat - pre-commercial

Representative Stand #	Green trees BdFt	Green trees Avg DBH	Green Trees Avg Ht	Green Tree TPA	Green Trees BA	Pct live BA	Hard Snags TPA	Hard Snags BA	Hard snags height	Hard snags avg DBH	Total Standing BA	Hard DWD <6 in	Hard DWD > 6	Soft DWD <6	Soft DWD >6	Category
508212757	8,844	14.1	54	103	111.7	84%	20.2	21.8	59	17.8	133.5	381	83	139	24	do not treat - pre-commercial
500392581	8,517	3.7	16	452	106.9	69%	166.2	47.4	46	16.7	154.3	850	932	101	92	do not treat - pre-commercial
486320017	8,087	5.1	19	259	56.5	72%	63.0	21.8	40	14.9	78.3	124	156	38	40	do not treat - pre-commercial
479732697	6,865	10.7	40	298	81.5	77%	52.2	24.4	56	17.6	105.9	248	57	97	17	do not treat - pre-commercial
512881953	6,495	4.1	19	445	95.8	79%	227.0	25.9	41	10.7	121.6	197	225	102	74	do not treat - pre-commercial
509721937	5,907	6.1	18	249	72.7	77%	16.9	21.4	45	17.6	94.2	115	217	87	62	do not treat - pre-commercial
365761285	5,861	12.0	42	109	76.3	84%	21.1	14.0	40	15.5	90.3	189	7	78	2	do not treat - pre-commercial
429242565	5,758	8.2	37	307	98.9	92%	22.6	8.3	34	9.8	107.2	425	310	157	91	do not treat - pre-commercial
472882573	3,078	9.9	27	220	64.2	56%	111.6	49.5	26	13.6	113.7	160	16	71	5	do not treat - pre-commercial
535572569	3,007	8.7	32	311	90.0	78%	51.3	25.2	33	12.2	115.3	293	90	79	27	do not treat - pre-commercial
431021929	2,816	6.7	36	435	59.2	85%	53.4	10.7	25	5.3	69.9	154	14	174	5	do not treat - pre-commercial
147471941	2,454	4.4	18	267	33.4	62%	111.0	20.8	43	12.0	54.2	104	195	86	66	do not treat - pre-commercial
579512565	2,042	10.6	30	102	67.3	84%	20.4	13.2	26	14.2	80.5	126	42	39	12	do not treat - pre-commercial
523422792	1,993	4.9	25	255	23.3	54%	21.6	19.8	35	7.1	43.1	246	95	75	22	do not treat - pre-commercial
598072561	1,868	9.7	31	346	28.7	100%	2.5	0.1	45	19.3	28.8	147	70	64	21	do not treat - pre-commercial
509311297	353	2.2	15	401	24.4	70%	175.5	10.5	16	2.9	34.9	370	87	71	22	do not treat - pre-commercial
346160001	9,261	13.0	48	67	55.5	99%	1.0	0.4	55	17.6	55.9	46	2	59	2	do not treat - pre-commercial - low density
546600005	5,096	9.6	32	90	47.8	82%	21.5	10.8	32	10.5	58.7	39	3	67	2	do not treat - pre-commercial - low density

Representative Stand #	Green trees BdFt	Green trees Avg DBH	Green Trees Avg Ht	Green Tree TPA	Green Trees BA	Pct live BA	Hard Snags TPA	Hard Snags BA	Hard snags height	Hard snags avg DBH	Total Standing BA	Hard DWD <6 in	Hard DWD > 6	Soft DWD <6	Soft DWD >6	Category
377702565	3,384	11.0	34	84	53.8	81%	20.8	12.5	36	14.7	66.2	129	5	62	1	do not treat - pre-commercial - low density
427942049	2,284	10.8	25	71	55.0	99%	0.7	0.3	24	12.5	55.2	24	0	18	0	do not treat - pre-commercial - low density
375512753	568	9.5	28	30	15.4	100%	0.1	0.0	22	9.4	15.4	27	1	12	0	do not treat - pre-commercial - low density
485882589	1,718	2.1	12	450	44.3	42%	389.9	62.1	28	5.8	106.4	1610	1177	200	143	do not treat - regen under small diameter snags
352311329	324	0.7	5	241	3.9	18%	370.5	18.0	23	5.9	21.9	294	86	50	15	do not treat - regen under small diameter snags
523192609	9,756	3.2	10	262	67.3	87%	20.0	9.8	52	22.0	77.0	110	232	27	39	do not treat - regeneration
370802593	9,677	2.6	11	359	115.5	89%	23.7	14.9	37	13.7	130.4	114	243	27	50	do not treat - regeneration
600021345	9,293	1.8	9	536	63.1	100%	0.0	0.0	40	14.2	63.1	323	179	149	53	do not treat - regeneration
363062593	8,600	2.8	11	338	91.3	85%	45.3	16.0	34	12.4	107.3	169	225	40	43	do not treat - regeneration
518140033	8,438	3.6	14	259	45.8	81%	123.5	11.1	45	16.7	56.8	124	186	68	105	do not treat - regeneration
356560021	6,880	2.5	12	333	42.0	59%	112.2	29.1	50	14.4	71.0	247	294	95	97	do not treat - regeneration
483572597	6,461	2.8	13	370	58.4	60%	186.1	39.6	61	18.4	98.0	825	967	110	115	do not treat - regeneration
583521329	4,522	1.3	7	266	24.2	62%	332.2	14.7	39	13.8	38.9	320	121	59	17	do not treat - regeneration
360350017	4,386	3.0	12	311	40.7	62%	129.0	24.7	29	10.8	65.4	219	289	94	106	do not treat - regeneration
349060049	4,342	2.1	8	283	33.2	62%	59.6	20.7	38	14.9	53.9	159	235	61	75	do not treat - regeneration
579772609	4,144	1.7	8	322	31.2	79%	134.3	8.4	52	15.6	39.6	123	182	27	18	do not treat - regeneration

Representative Stand #	Green trees BdFt	Green trees Avg DBH	Green Trees Avg Ht	Green Tree TPA	Green Trees BA	Pct live BA	Hard Snags TPA	Hard Snags BA	Hard snags height	Hard snags avg DBH	Total Standing BA	Hard DWD <6 in	Hard DWD > 6	Soft DWD <6	Soft DWD >6	Category
600190017	4,129	2.5	10	265	38.5	84%	29.3	7.3	30	14.3	45.8	124	135	54	64	do not treat - regeneration
465772609	3,739	1.0	5	273	36.0	68%	33.0	16.9	44	16.9	52.9	182	165	31	16	do not treat - regeneration
466480033	3,667	1.7	7	343	40.4	70%	135.4	17.6	32	14.5	58.0	317	253	136	111	do not treat - regeneration
472321297	3,334	1.6	7	287	41.2	67%	37.7	19.9	32	13.3	61.0	226	276	36	28	do not treat - regeneration
328750033	2,917	3.1	11	306	35.8	68%	44.2	16.6	29	12.3	52.4	173	281	67	97	do not treat - regeneration
369890049	2,799	3.0	10	239	26.6	60%	32.7	17.4	27	14.7	44.0	122	245	48	74	do not treat - regeneration
352762609	2,735	1.6	6	304	39.2	76%	82.8	12.3	28	12.9	51.5	245	142	41	14	do not treat - regeneration
529140049	2,661	2.5	10	240	25.2	63%	76.9	14.6	28	11.7	39.8	131	237	49	74	do not treat - regeneration
348942609	2,573	2.4	7	215	30.0	91%	2.6	2.9	36	20.8	32.9	50	61	5	7	do not treat - regeneration
579460033	2,517	1.9	8	231	22.4	68%	16.2	10.5	25	9.8	32.8	66	117	39	67	do not treat - regeneration
595952609	2,270	2.2	8	295	43.4	76%	34.9	13.4	29	12.0	56.8	195	265	34	33	do not treat - regeneration
351820033	2,259	1.9	7	381	25.6	60%	314.0	17.3	20	15.4	42.9	144	46	64	15	do not treat - regeneration
538100065	1,681	1.8	8	413	17.0	99%	0.2	0.1	26	16.2	17.1	17	0	28	0	do not treat - regeneration
369480033	1,238	0.8	4	274	13.2	54%	115.5	11.4	25	9.7	24.6	94	58	39	17	do not treat - regeneration
347800017	931	1.3	6	218	10.8	67%	10.0	5.2	24	10.7	16.0	34	96	13	29	do not treat - regeneration
522232577	894	0.8	4	250	11.2	59%	12.8	7.7	37	11.8	18.9	71	151	13	15	do not treat - regeneration
578892577	670	0.5	3	243	8.8	62%	6.8	5.4	32	12.3	14.2	83	162	36	30	do not treat - regeneration
417901921	3,022	5.8	23	1,240	105.5	96%	106.2	4.1	28	12.5	109.6	299	141	243	64	Fire Risk Reduction
478941285	2,939	4.0	28	989	96.7	96%	21.2	4.4	41	7.4	101.1	360	309	149	91	Fire Risk Reduction

Representative Stand #	Green trees BdFt	Green trees Avg DBH	Green Trees Avg Ht	Green Tree TPA	Green Trees BA	Pct live BA	Hard Snags TPA	Hard Snags BA	Hard snags height	Hard snags avg DBH	Total Standing BA	Hard DWD <6 in	Hard DWD > 6	Soft DWD <6	Soft DWD >6	Category
505082565	2,471	3.8	17	1,492	127.0	91%	270.4	12.9	25	7.9	139.9	473	273	155	80	Fire Risk Reduction
464852565	998	3.3	26	1,494	105.2	95%	91.0	5.6	25	3.5	110.8	241	6	83	2	Fire Risk Reduction
479830049	2,184	1.3	7	238	9.0	26%	50.6	26.2	47	15.3	35.2	118	153	47	42	salvage - regen under snags
560092803	1,375	2.0	10	239	9.1	18%	85.6	41.8	41	11.3	50.9	169	372	26	40	salvage - regen under snags
359690017	587	1.4	5	214	5.9	20%	97.6	24.1	13	11.8	30.1	127	300	31	59	salvage - regen under snags
366461937	207	1.9	7	209	4.6	16%	63.1	24.7	21	9.9	29.3	32	19	2	1	salvage - regen under snags
359940049	60	1.0	5	236	0.6	1%	358.2	50.0	25	20.0	50.7	1047	275	224	59	salvage - regen under snags
276031729	-	0.4	5	435	1.2	15%	75.1	6.4	50	10.7	7.6	1616	262	537	76	salvage - regen under snags
470262621	-	0.1	2	235	0.1	0%	128.8	236.5	79	23.2	236.6	308	598	48	81	salvage - regen under snags
484313060	-	0.5	5	435	2.7	14%	69.5	17.2	58	19.4	19.9	894	360	271	77	salvage - regen under snags
501872585	-	0.3	4	213	0.6	1%	96.9	67.2	44	19.2	67.8	318	617	56	84	salvage - regen under snags
506523060	-	0.9	6	400	2.7	5%	105.6	57.3	46	12.6	60.0	651	872	158	181	salvage - regen under snags
507222597	-	1.1	7	309	4.6	30%	224.1	10.7	14	3.2	15.3	271	6	47	1	salvage - regen under snags
518560500	-	0.6	6	400	1.1	1%	112.5	92.9	57	16.0	94.0	425	782	278	493	salvage - regen under snags
541372585	-	0.4	5	310	2.4	15%	240.6	13.4	17	3.5	15.8	164	163	33	16	salvage - regen under snags
542062609	-	0.1	3	200	0.0	0%	90.3	89.3	19	15.3	89.4	220	338	27	40	salvage - regen under snags
348520468	-	0.6	5	435	3.8	48%	30.3	4.2	59	22.8	7.9	305	167	250	114	salvage - regen under snags - low density
360032369	-	0.5	6	400	0.8	6%	25.5	11.9	64	20.3	12.7	720	242	442	65	salvage - regen under snags - low density
360083044	-	0.6	5	435	3.9	19%	20.5	16.7	29	9.7	20.5	681	823	186	154	salvage - regen under snags - low density

Representative Stand #	Green trees BdFt	Green trees Avg DBH	Green Trees Avg Ht	Green Tree TPA	Green Trees BA	Pct live BA	Hard Snags TPA	Hard Snags BA	Hard snags height	Hard snags avg DBH	Total Standing BA	Hard DWD <6 in	Hard DWD > 6	Soft DWD <6	Soft DWD >6	Category
492830657	-	2.5	7	202	2.3	20%	18.4	9.3	22	11.3	11.6	27	58	2	1	salvage - regen under snags - low density
595493028	-	1.1	6	400	3.8	36%	23.2	6.7	16	6.4	10.6	346	605	105	127	salvage - regen under snags - low density
362652585	6,047	4.3	17	257	61.3	44%	83.7	78.0	46	20.1	139.3	251	458	37	45	salvage - snags plus PCT
504542609	1,145	6.2	20	203	7.8	5%	149.8	140.7	50	19.7	148.6	200	410	36	66	salvage - snags plus PCT
357952609	228	9.1	32	201	1.4	1%	285.1	184.3	60	24.8	185.7	452	551	55	64	salvage - snags plus PCT

Appendix 2

Trucking data derived from weight limits on trucking configurations based on moisture content of biomass

Equipment Code	Terrain Limits	Biomass Characteristics/ limits	Equipment Configuration	Haul Limit
H.1	10-35% slope with adequate turnaround	Comminuted material, moisture content > 50%	truck/trailer combo 50% mc	weight
H.2	none	Logs > 4" diameter	pulp logs 50% MC	weight
H.3	none	Comminuted material, moisture content > 50%	dump truck only 50% MC	weight
H.4	10-35% slope with adequate turnaround	Comminuted material, moisture content < 50%	hauling chipped/ground material using truck/trailer assume 25 yd each	volume
H.5	<10% slope with adequate turnaround	Comminuted material, moisture content > 50%	Chip van (63% MC)	weight
H.6	10-35% slope with adequate turnaround	Comminuted material, moisture content > 50%	hauling chipped/ground material using truck trailer combo with 63% MC	weight
H.7	Not available on steeper terrain without turnarounds	Logs > 4" diameter	haul pulp using mule train (5, 6, 7 axle combos) 63% MC	weight
H.8	Potential Height limitation (oversize load restrictions)	Comminuted material, moisture content < 50%	haul chipped/ground material using 4 axle dump truck) 25 yd	volume
H.9	none	Comminuted material, moisture content > 50%	haul chipped/ground material using 4 axle dump truck) 63% MC	weight
H.10	none	Comminuted material, moisture content < 50%	haul chipped/ground material using 4 axle dump truck) 20 yd	volume
H.11	none	Comminuted material, moisture content < 50%	haul chipped/ground material using 4 axle dump truck) 17 yd	volume

APPENDIX F
Calculation of the Carbon Fraction of Volatile Organic Compounds (VOCs)

Volatile organic compounds (VOCs) is a catch-all grouping of a large number of chemicals that are involved in a variety of important chemical interactions which impact human and environmental health. VOCs are commonly regulated as criteria pollutants. Biomass burning can be a significant source of VOCs. However, there is a lack of literature that sufficiently calculates an average carbon fraction for this group of chemicals. Determining the carbon fraction of VOCs is important for carbon balance calculation methods as used for the C-BREC model.

To address this, we calculate a carbon fraction for a representative group of VOCs that can be reasonably assumed to represent the composition of reported VOC emissions factors for biomass burning of woody fuels found in California's forested lands. We use data from (Gilman et al., 2015), using data for biomass species from the Northern United States data set which is represented by three woody fuels: Englemann spruce, grand fir, and ponderosa pine needles from Montana. Data used for calculating the carbon fraction are shown in the following table. The overall calculated carbon fraction is 0.68 mass carbon per mass VOC. This is arrived at by taking the sum of the "Mass Carbon Emitted. N Avg" column divided by the "Mass emitted (assuming constant ppmv CO emitted) ug/m^3. N Avg." column. Input data used to calculate a VOC emissions factor are shown in Table 64.

Table 64: Carbon Fraction of VOC Compounds

Group	VOC constituent	Chemical Formula	MW	Carbon Atoms	Compound Carbon Fraction	Emissions Ratio from Gilman et al., 2015. Northern (N) U.S. Avg	Mass emitted (assuming constant ppmv CO emitted) ug/m^3. N Avg.	Mass Carbon Emitted. N Avg
Alkanes	Ethane	C2H6	30	2	0.8007	6.8510	8.4061	6.7305
	Propane	C3H8	44	3	0.8189	1.4633	2.6333	2.1563
	Butane_iso	C4H10	58	4	0.8283	0.0982	0.2329	0.1929
	Butane_n	C4H10	58	4	0.8283	0.4005	0.9501	0.7869
	Propane_22dimethyl	C5H12	72	5	0.8340	0.0006	0.0018	0.0015
	Pentane_iso	C5H12	72	5	0.8340	0.0322	0.0948	0.0791
	Pentane_n	C5H12	72	5	0.8340	0.1400	0.4123	0.3438
	Butane_22dimethyl	C6H14	86	6	0.8379		0.0000	0.0000
	Pentane_3methyl	C6H14	86	6	0.8379	0.0045	0.0158	0.0133
	Hexane_n	C6H14	86	6	0.8379	0.0814	0.2863	0.2399
	Heptane_n	C7H16	100	7	0.8407	0.0836	0.3419	0.2875
	Octane_n	C8H18	114	8	0.8428	0.0536	0.2499	0.2106
	Nonane_n	C9H20	128	9	0.8445	0.0369	0.1932	0.1631
	Decane_n	C10H22	142	10	0.8458	0.0330	0.1917	0.1621
	Undecane_n	C11H24	156	11	0.8469	0.0425	0.2712	0.2296
Alkenes	Ethene	C2H4	28	2	0.8579	18.3160	20.9754	17.9939
	Propene	C3H6	42	3	0.8579	8.5115	14.6210	12.5427
	Propene_2methyl	C4H8	56	4	0.8579	0.3162	0.7242	0.6213
	Butene_1	C4H8	56	4	0.8579	1.5227	3.4876	2.9918
	Butene_cis2	C4H8	56	4	0.8579	0.2397	0.5490	0.4710
	Butene_trans2	C4H8	56	4	0.8579	0.2732	0.6257	0.5368
	Butene_1_2methyl	C5H10	70	5	0.8579	0.0881	0.2522	0.2164
	Butene_1_3methyl	C5H10	70	5	0.8579	0.0183	0.0524	0.0449
	Butene_2_2methyl	C5H10	70	5	0.8579	0.1881	0.5385	0.4620
	Cyclopentane	C5H10	70	5	0.8579	0.0108	0.0309	0.0265
	Pentene_1	C5H10	70	5	0.8579	0.2311	0.6616	0.5676
	Pentene_cis2	C5H10	70	5	0.8579	0.2905	0.8317	0.7135
	Pentene_trans2	C5H10	70	5	0.8579	0.1180	0.3378	0.2898

Group	VOC constituent	Chemical Formula	MW	Carbon Atoms	Compound Carbon Fraction	Emissions Ratio from Gilman et al., 2015. Northern (N) U.S. Avg	Mass emitted (assuming constant ppmv CO emitted) ug/m^3. N Avg.	Mass Carbon Emitted. N Avg
	Cyclopentane_1methyl	C6H12	84	6	0.8579	0.0159	0.0546	0.0469
	Pentene_1_2methyl	C6H12	84	6	0.8579	0.4980	1.7109	1.4677
	Cyclohexane	C6H12	84	6	0.8579	0.0052	0.0179	0.0153
	Hexene_1	C6H12	84	6	0.8579	0.4904	1.6848	1.4453
	Hexene_cis2	C6H12	84	6	0.8579	0.1552	0.5332	0.4574
	Hexenes (sum of 3 isomers)	C6H12	84	6	0.8579	0.5432	1.8662	1.6009
	Cyclohexane_methyl	C7H14	98	7	0.8579	0.0111	0.0445	0.0382
	Heptene_1	C7H14	98	7	0.8579	0.2868	1.1495	0.9861
	Octene_1	C8H16	112	8	0.8579	0.1651	0.7563	0.6488
	Nonene_1	C9H18	126	9	0.8579	0.0474	0.2443	0.2095
	Decene_1	C10H20	140	10	0.8579	0.0812	0.4649	0.3989
	Undecene_1	C11H22	154	11	0.8579	0.0647	0.4075	0.3496
Alkynes and Alkenes, polyunsaturated	Ethyne	C2H2	26	2	0.9238	5.0910	5.4137	5.0015
	Propyne	C3H4	40	3	0.9008	0.7876	1.2885	1.1606
	Butadiyne_13 (Diacetylene)	C4H2	50	4	0.9608	0.0427	0.0873	0.0839
	Butenyne (Vinylacetylene)	C4H4	52	4	0.9238	0.0824	0.1752	0.1619
	Butadiene_12	C4H6	54	4	0.8896	0.0441	0.0974	0.0866
	Butadiene_13	C4H6	54	4	0.8896	1.8781	4.1480	3.6901
	Butyne (1- or 2-)	C4H6	54	4	0.8896	0.0693	0.1531	0.1362
	Cyclopentadiene_13	C5H6	66	5	0.9098	0.5836	1.5754	1.4333
	Pentenyne isomer (e.g., propenylacetylene)	C5H6	66	5	0.9098	0.0651	0.1757	0.1599
	Butyne_3methyl	C5H8	68	5	0.8831	0.0426	0.1185	0.1046
	Cyclopentene	C5H8	68	5	0.8831	0.2815	0.7829	0.6914
	Pentadiene_cis13	C5H8	68	5	0.8831	0.1733	0.4820	0.4256
	Pentadiene_trans13	C5H8	68	5	0.8831	0.2504	0.6964	0.6150
	Hexadienyne (e.g., divinylacetylene)	C6H6	78	6	0.9238	0.0569	0.1815	0.1677
	Cyclopentadiene_methyl (sum of 2 isomers)	C6H8	80	6	0.9008	0.1831	0.5991	0.5396
	Hexenyne (e.g., 2-methyl-1-penten-3-yne)	C6H8	80	6	0.9008	0.0674	0.2205	0.1986
	Cyclohexene	C6H10	82	6	0.8788	0.0927	0.3109	0.2732
	Cyclopentene_1methyl	C6H10	82	6	0.8788	0.1109	0.3719	0.3268
	Hexadiene_cis13	C6H10	82	6	0.8788	0.0097	0.0325	0.0286
	Hexadiene_trans13	C6H10	82	6	0.8788	0.0266	0.0892	0.0784

Group	VOC constituent	Chemical Formula	MW	Carbon Atoms	Compound Carbon Fraction	Emissions Ratio from Gilman et al., 2015. Northern (N) U.S. Avg	Mass emitted (assuming constant ppmv CO emitted) ug/m^3. N Avg.	Mass Carbon Emitted. N Avg
	Other C6H10 (sum of 5 isomers)	C6H10	82	6	0.8788	0.1954	0.6553	0.5759
	Heptadiyne (sum of 2 isomers)	C7H8	92	7	0.9138	0.0464	0.1746	0.1595
	Cyclohexene_1methyl	C7H12	96	7	0.8757	0.0437	0.1716	0.1503
	Octadiene	C8H14	110	8	0.8735	0.1387	0.6240	0.5450
	Nonadiene	C9H16	124	9	0.8717	0.0171	0.0867	0.0756
	C10H14 non-aromatic (e.g., hexahydronaphthalene)	C10H14	134	10	0.8963	0.0155	0.0849	0.0761
Terpenes (Polyunsaturated)	Isoprene	C5H8	68	5	0.8831	0.6942	1.9307	1.7050
	Camphene	C10H16	136	10	0.8831	0.1193	0.6636	0.5860
	Carene_3	C10H16	136	10	0.8831	0.1578	0.8777	0.7751
	Limonene_D	C10H16	136	10	0.8831	0.8384	4.6635	4.1183
	Limonene_iso	C10H16	136	10	0.8831	0.0237	0.1318	0.1164
	Myrcene	C10H16	136	10	0.8831	0.1313	0.7303	0.6450
	Pinene_alpha	C10H16	136	10	0.8831	0.8105	4.5083	3.9812
	Pinene_beta	C10H16	136	10	0.8831	0.1638	0.9111	0.8046
	Terpinene_gamma	C10H16	136	10	0.8831	0.0310	0.1724	0.1523
	Terpinolene	C10H16	136	10	0.8831	0.0339	0.1886	0.1665
	Sesquiterpenes (sum of all isomers)	C15H24	204	15	0.8831	0.0915	0.7634	0.6742
Aromatics with saturated subsituents	Benzene	C6H6	78	6	0.9238	2.1381	6.8209	6.3015
	Toluene	C7H8	92	7	0.9138	1.3375	5.0327	4.5989
	Benzene_ethyl	C8H10	106	8	0.9064	0.1766	0.7656	0.6940
	Xylene_o	C8H10	106	8	0.9064	0.1429	0.6195	0.5615
	Xylenes_m&p (sum of 2 isomers)	C8H10	106	8	0.9064	0.5088	2.2058	1.9994
	Benzene_123trimethyl	C9H12	120	9	0.9008	0.0906	0.4447	0.4005
	Benzene_124trimethyl	C9H12	120	9	0.9008	0.0828	0.4064	0.3660
	Benzene_135trimethyl	C9H12	120	9	0.9008	0.0401	0.1968	0.1773
	Benzene_1ethyl_2methyl	C9H12	120	9	0.9008	0.0374	0.1836	0.1653
	Benzene_1ethyl_3&4_methyl (sum of 2 isomers)	C9H12	120	9	0.9008	0.1265	0.6209	0.5592
	Benzene_isoPropyl	C9H12	120	9	0.9008	0.0290	0.1423	0.1282
	Benzene_nPropyl	C9H12	120	9	0.9008	0.0331	0.1625	0.1463
	Benzene_isoButyl	C10H14	134	10	0.8963	0.0248	0.1359	0.1218
	Benzene_nButyl	C10H14	134	10	0.8963	0.0329	0.1803	0.1616
	Benzene_1methyl_4isopropyl (p-Cymene)	C10H14	134	10	0.8963	0.1726	0.9459	0.8478

Group	VOC constituent	Chemical Formula	MW	Carbon Atoms	Compound Carbon Fraction	Emissions Ratio from Gilman et al., 2015. Northern (N) U.S. Avg	Mass emitted (assuming constant ppmv CO emitted) ug/m^3. N Avg.	Mass Carbon Emitted. N Avg
	Benzene_nPropyl_methyl (sum of 2 isomers)	C10H14	134	10	0.8963	0.0420	0.2302	0.2063
	Benzene_14diethyl	C10H14	134	10	0.8963	0.0165	0.0904	0.0810
	Xylene_ethyl (sum of 2 isomers)	C10H14	134	10	0.8963	0.0379	0.2077	0.1862
Aromatics with unsaturated substituents	Benzene_ethynyl (Phenylethyne)	C8H6	102	8	0.9420	0.0686	0.2862	0.2696
	Styrene (Phenylethyne)	C8H8	104	8	0.9238	0.3361	1.4296	1.3208
	Indene	C9H8	116	9	0.9318	0.1311	0.6220	0.5796
	Benzene_1propenyl	C9H10	118	9	0.9160	0.0135	0.0652	0.0597
	Benzene_2propenyl	C9H10	118	9	0.9160	0.0236	0.1139	0.1043
	Benzene_isoPropenyl	C9H10	118	9	0.9160	0.0232	0.1120	0.1026
	Styrene_2methyl	C9H10	118	9	0.9160	0.0414	0.1998	0.1830
	Styrene_3methyl	C9H10	118	9	0.9160	0.0865	0.4175	0.3824
	Styrene_4methyl	C9H10	118	9	0.9160	0.0314	0.1515	0.1388
	Indane	C9H10	118	9	0.9160	0.0261	0.1260	0.1154
	Naphthalene	C10H8	128	10	0.9383	0.0215	0.1126	0.1056
	Indene_1or3methyl	C10H10	130	10	0.9238	0.0079	0.0420	0.0388
	Naphthalene_12dihydro	C10H10	130	10	0.9238	0.0277	0.1473	0.1361
	Naphthalene_13dihydro	C10H10	130	10	0.9238	0.0339	0.1802	0.1665
	Benzene_1butenyl	C10H12	132	10	0.9098	0.0140	0.0756	0.0688
	Benzene_methylpropenyl (2-phenyl-2-butene)	C10H12	132	10	0.9098	0.0436	0.2354	0.2142
	Styrene_ethyl	C10H12	132	10	0.9098	0.0196	0.1058	0.0963
Nitrogen-containing organics	Acid_Hydrocyanic (Hydrogen cyanide)	HCN	27	1	0.4448	3.0223	3.3375	1.4846
	Acid_Isocyanic	HNCO	43	1	0.2793	1.3360	2.3496	0.6563
	Methylnitrite (Nitrous acid, methyl ester)	CH3NO2	61	1	0.1969	0.7641	1.9063	0.3753
	Nitromethane	CH3NO2	61	1	0.1969	0.0713	0.1779	0.0350
	Acetonitrile	C2H3N	41	2	0.5859	1.6524	2.7709	1.6233
	Hydrazine_11dimethyl	C2H8N2	60	2	0.4003	0.1976	0.4849	0.1941
	Propenenitrile_2 (Acrylonitrile)	C3H3N	53	3	0.6798	0.3217	0.6973	0.4741
	Propanenitrile (Cyanoethane)	C3H5N	55	3	0.6551	0.0981	0.2207	0.1446
	Pyrrole	C4H5N	67	4	0.7170	0.1066	0.2921	0.2095
	Pyrazole_1methyl	C4H6N2	82	4	0.5859	0.0359	0.1204	0.0705
	Diazine_methyl (sum of 3 isomers)	C5H6N2	94	5	0.6388	0.1125	0.4325	0.2763
	Pyrrole_1methyl	C5H7N	81	5	0.7414	0.0217	0.0719	0.0533

Group	VOC constituent	Chemical Formula	MW	Carbon Atoms	Compound Carbon Fraction	Emissions Ratio from Gilman et al., 2015. Northern (N) U.S. Avg	Mass emitted (assuming constant ppmv CO emitted) ug/m^3. N Avg.	Mass Carbon Emitted. N Avg
	Pyrazine_2ethyl	C6H8N2	108	6	0.6672	0.0296	0.1307	0.0872
	Benzonitrile (Cyanobenzene)	C7H5N	103	7	0.8162	0.1380	0.5813	0.4745
OVOCs with low degrees of unsaturation	Formaldehyde	CH2O	30	1	0.4003	17.9180	21.9853	8.8014
	Acid_Formic	CH2O2	46	1	0.2611	1.7538	3.2996	0.8615
	Methanol	CH4O	32	1	0.3753	13.6981	17.9280	6.7286
	Acetaldehyde	C2H4O	44	2	0.5459	5.4742	9.8513	5.3779
	Acid_Acetic	C2H4O2	60	2	0.4003	9.6068	23.5750	9.4378
	Formate_methyl (Formic Acid, methyl ester)	C2H4O2	60	2	0.4003	0.2096	0.5144	0.2059
	Acid_Glycolic	C2H4O3	76	2	0.3161	0.0114	0.0354	0.0112
	Ethanol	C2H6O	46	2	0.5222	0.2673	0.5029	0.2626
	Acetone	C3H6O	58	3	0.6212	2.6208	6.2170	3.8621
	Propanal	C3H6O	58	3	0.6212	0.9246	2.1933	1.3625
	Acetate_methyl	C3H6O2	74	3	0.4869	0.6537	1.9785	0.9633
	Formate_ethyl	C3H6O2	74	3	0.4869	0.0472	0.1429	0.0696
	Butanal_n	C4H8O	72	4	0.6672	0.1971	0.5804	0.3873
	Butanone_2 (MEK)	C4H8O	72	4	0.6672	0.8027	2.3638	1.5772
	Propanal_2methyl	C4H8O	72	4	0.6672	0.1657	0.4880	0.3256
	Propanoate_methyl (Prop- anoic Acid, methyl ester)	C4H8O2	88	4	0.5459	0.0186	0.0669	0.0365
	Butanol_1	C4H10O	74	4	0.6492	0.1434	0.4340	0.2818
	Butanal_2methyl	C5H10O	86	5	0.6983	0.1323	0.4653	0.3249
	Butanone_2_3methyl	C5H10O	86	5	0.6983	0.1092	0.3841	0.2682
	Pentanone_2	C5H10O	86	5	0.6983	0.1791	0.6300	0.4399
	Pentanone_3	C5H10O	86	5	0.6983	0.1330	0.4678	0.3267
	Butanoate_methyl (Butryic Acid, methyl ester)	C5H10O2	102	5	0.5887	0.0097	0.0405	0.0238
	Hexanal_n	C6H12O	100	6	0.7206	0.0635	0.2597	0.1871
	Hexanone_2	C6H12O	100	6	0.7206	0.0462	0.1890	0.1362
	Hexanone_3	C6H12O	100	6	0.7206	0.1646	0.6732	0.4851
OVOCs with high degrees of unsaturation	Propenal_2 (Acrolein)	C3H4O	56	3	0.6434	3.5441	8.1174	5.2227
	Acid_Acrylic	C3H4O2	72	3	0.5004	0.3672	1.0813	0.5411
	Acid_Pyruvic	C3H4O3	88	3	0.4094	0.0562	0.2023	0.0828
	Butenal_2 (Crotonaldehyde)	C4H6O	70	4	0.6863	0.5275	1.5102	1.0364
	Methacrolein (MACR)	C4H6O	70	4	0.6863	0.5501	1.5749	1.0809

Group	VOC constituent	Chemical Formula	MW	Carbon Atoms	Compound Carbon Fraction	Emissions Ratio from Gilman et al., 2015. Northern (N) U.S. Avg	Mass emitted (assuming constant ppmv CO emitted) ug/m^3. N Avg.	Mass Carbon Emitted. N Avg
	Methylvinylketone (MVK)	C4H6O	70	4	0.6863	2.1216	6.0741	4.1686
	Butadione_23	C4H6O2	86	4	0.5586	1.2062	4.2427	2.3700
	Acrylate_methyl (2-Propenoic Acid, methyl ester)	C4H6O2	86	4	0.5586	0.0470	0.1653	0.0923
	Acetate_vinyl (Acetic Acid, vinyl ester)	C4H6O2	86	4	0.5586	0.0048	0.0169	0.0094
	Dioxin_14_23dihydro	C4H6O2	86	4	0.5586	0.0179	0.0630	0.0352
	Cyclopentenedione	C5H4O2	96	5	0.6255	0.0401	0.1574	0.0985
	Cyclopentenone	C5H6O	82	5	0.7323	0.9221	3.0925	2.2647
	Pentenone (e.g., Ethyl vinyl ketone)	C5H8O	84	5	0.7149	1.4135	4.8562	3.4716
	Pentanone_cyclo	C5H8O	84	5	0.7149	0.7012	2.4090	1.7222
	Butenal_2_2methyl	C5H8O	84	5	0.7149	0.0384	0.1319	0.0943
	Methacrylate_methyl (Methacrylic Acid, methyl ester)	C5H8O2	100	5	0.6005	0.1287	0.5264	0.3161
	Phenol	C6H6O	94	6	0.7666	2.4947	9.5911	7.3525
	Benzene_12&13diol (sum of 2 isomers)	C6H6O2	110	6	0.6551	3.9631	17.8299	11.6802
	Benzaldehyde	C7H6O	106	7	0.7931	0.6995	3.0326	2.4052
	Phenol_methyl (sum of cresol isomers)	C7H8O	108	7	0.7784	2.0703	9.1449	7.1186
Furans (heterocyclic OVOCs)	Furan	C4H4O	68	4	0.7065	1.1090	3.0843	2.1790
	Furan_25dihydro	C4H6O	70	4	0.6863	0.0071	0.0203	0.0140
	Furan_tetrahydro	C4H8O	72	4	0.6672	0.0101	0.0297	0.0198
	Furaldehyde_2 (Furfural)	C5H4O2	96	5	0.6255	1.2999	5.1039	3.1926
	Furaldehyde_3	C5H4O2	96	5	0.6255	0.0687	0.2697	0.1687
	Furan_2methyl	C5H6O	82	5	0.7323	1.2105	4.0598	2.9730
	Furan_3methyl	C5H6O	82	5	0.7323	0.1758	0.5896	0.4318
	Furan_25dimethyl	C6H8O	96	6	0.7506	0.1808	0.7099	0.5329
	Furan_2ethyl	C6H8O	96	6	0.7506	0.0821	0.3224	0.2420
	Benzofuran	C8H6O	118	8	0.8142	0.2504	1.2085	0.9840
	Benzofuran_methyl (sum of 4 isomers)	C9H8O	132	9	0.8189	0.1980	1.0690	0.8753

APPENDIX G
Climate Metric Methodology Details

The following sections provide additional detail regarding the calculation of the Absolute Global Warming Potential (AGWP) and the Absolute Global Temperature Potential (AGTP), and the derivation of the "emissions scenario" versions of these metrics. The first two sections detail the derivation of the definite forms of the AGWP and the AGTP for a pulse emission, respectively. These derivations are applied in the third section which details the derivation of the "emissions scenario" versions of these metrics.

G.1 Definition of the Absolute Global Warming Potential (AGWP) for a Pulse Emission of Anthropogenic GHGs

The Absolute Global Warming Potential (AGWP) is the time-integrated radiative forcing due to a pulse emission of gas (Myhre et al., 2013). This is defined as

$$AGWP_i^{Pulse}(TH) = \int_0^{TH} RF_i(t)dt$$

where i represents a particular gas species, TH represents the time horizon, and $RF_i(t)$ is the per unit mass radiative efficiency for each gas species. (Myhre et al., 2013) suggest that the name "cumulative forcing index" is more appropriate since the AGWP does not actually link emissions to temperature or any other climate variable. However, because the term "Global Warming Potential" is so widely known and used, this name is retained here.

G.1.1 $AGWP_i^{Pulse}$ for CO_2, CH_4, and N_2O

For CO_2, CH_4, and N_2O the following are used to define $RF_i(t) = R_i \cdot IRF_i(t)$ (Giuntoli et al., 2015; Myhre et al., 2013):

Table 65: AGWP Functions for CO2, CH4, and N2O

	R_i	$IRF_i(t)$
CO_2	A_{CO_2}	$a_0 + \sum_{j=1}^{N} a_j \cdot exp\left(-\frac{t}{\tau_j}\right)$
CH_4	$(1 + f_1 + f_2) \cdot A_{CH_4}$	$exp\left(-\frac{t}{\tau_{CH_4}}\right)$
N_2O	$\left(1 - 0.36 \cdot (1 + f_1 + f_2) \cdot \frac{RE_{CH_4}}{RE_{N_2O}}\right) \cdot A_{N_2O}$	$exp\left(-\frac{t}{\tau_{N_2O}}\right)$

Equations from (Giuntoli et al., 2015; Myhre et al., 2013).

R_i is radiative efficiency, and IRF_i is impulse response function represented by exponential terms. Note that the IRF_i functions used in the definitions of $RF_i(t)$ above are only applicable to anthropogenic sources where vegetation regrowth that acts as a sink is not considered. Hence, these IRF_i functions asymptotically approach a non-zero atmospheric concentration associated with a pulse perturbation to the atmosphere without any biogenic sink to remove the gas from the atmosphere within a relevant time frame. This is consistent with the boundaries of C-BREC in that changes in landscape carbon stock are not assigned to residues used for electricity or heat production.

$IRF_{CO_2}(t)$ is limited to the first three terms which is the approach proposed by (Joos et al., 2013) and followed by (Giuntoli et al., 2015). $RF_{CH_4}(t)$ and $RF_{N_2O}(t)$ use the updated expressions detailed in (Myhre et al., 2013) and followed by (Giuntoli et al., 2015) which scale the RF by the effects on ozone and stratospheric water. The parameters detailed in Table 66 are used in the above equations to obtain numerical solutions (Giuntoli et al., 2015; Joos et al., 2013; Myhre et al., 2013). Note that A_i and RE_i represent radiative efficiency of gas i on a mass basis and volume basis respectively. The method for converting between the two is described in (Aamaas et al., 2013). For CO_2, CH_4, and N_2O the following are the discrete solutions to their respective AGWP (Myhre et al., 2013):

$$AGWP_{CO_2}^{Pulse}(t) = A_{CO_2}\left\{a_0 t + \sum_{j=1}^{3} a_j \tau_j \left(1 - exp\left(-\frac{t}{\tau_j}\right)\right)\right\}$$

$$AGWP_{CH_4}^{Pulse}(t) = (1 + f1 + f2) \cdot A_{CH_4} \cdot \tau_{CH_4} \cdot \left(1 - exp\left(-\frac{t}{\tau_{CH_4}}\right)\right)$$

$$AGWP_{N_2O}^{Pulse}(t) = \left(1 - 0.36 \cdot (1 + f1 + f2) \cdot \frac{RE_{CH_4}}{RE_{N_2O}}\right) \cdot A_{N_2O} \cdot \tau_{N_2O} \cdot \left(1 - exp\left(-\frac{t}{\tau_{N_2O}}\right)\right)$$

Table 66: AGWP Function Parameters

Species	Parameter, Value, and Units
CO_2	$A_{CO_2} = 1.75 \times 10^{-15} \frac{W}{m^2 \cdot kg}$ $a_0 = 0.2173 \quad a_1 = 0.2240 \quad a_2 = 0.2824 \quad a_3 = 0.2763$ $\tau_1 = 394.4\ years \quad \tau_2 = 36.54\ years \quad \tau_3 = 4.304\ years$
CH_4	$A_{CH_4} = 1.28 \times 10^{-13} \frac{W}{m^2 \cdot kg}$ $RE_{CH_4} = 3.63 \times 10^{-4} \frac{W}{m^2 \cdot ppb}$ $\tau_{CH_4} = 12.4\ years$ $f_1 = 0.5 \quad f_2 = 0.15$
N_2O	$A_{N_2O} = 3.85 \times 10^{-13} \frac{W}{m^2 \cdot kg}$ $RE_{N_2O} = 3.00 \times 10^{-3} \frac{W}{m^2 \cdot ppb}$ $\tau_{N_2O} = 121\ years$ $f_1 = 0.5 \quad f_2 = 0.15$

Values from (Giuntoli et al., 2015; Joos et al., 2013; Myhre et al., 2013).

G.1.2 AGWP for Near-Term Climate Forcers

Regarding with NTCFs to consider, work by (Unger et al., 2010) shows that ozone precursors, black carbon (BC), organic carbon (OC), are key species to consider for biomass combustion, and aerosol indirect effects must also be taken into consideration (AIE). Discrete AGWP and AGTP solutions for ozone precursors are provided by (Aamaas et al., 2013). BC and OC need more investigation to verify, but it appears discrete solutions could be pulled from (Bond et al., 2013; Fuglestvedt et al., 2010) or others. It is not clear if AIE can be addressed. This needs to be investigated, and is left to future work.

G.2 Definition of the Absolute Global Temperature Potential (AGTP) for a Pulse Emission of Anthropogenic GHGs

The Absolute Global Temperature Potential (AGTP) presents a way of “physically discounting” (Aamaas et al., 2013) the AGWP of a gas species. This is accomplished by introducing an impulse response function that links emissions to temperature (Aamaas et al., 2012) into the AGWP using convolution. This results in the following definition:

$$AGTP_i^{Pulse}(t) = (RF_i * R_T)(t) = \int_0^t RF_i(t')R_T(t-t')dt'$$

where $R_T(t)$ represents the climate response to a unit forcing $RF_i(t)$. It is defined as the following (Myhre et al., 2013):

$$R_T(t) = \sum_{j=1}^{M} \frac{c_j}{d_j} exp\left(-\frac{t}{d_j}\right)$$

c_j represents "the components of the climate sensitivity", and d_j "represents the response times". "The first term in the summation can crudely be associated with the response of the ocean mixed layer to a forcing and the higher order terms the response of the deep ocean." (Myhre et al., 2013).

$AGTP_i^{Pulse}(t)$ does not apply physical discounting "memory" of times other than the evaluation point t. The integrated absolute global temperature potential ($iAGTP_i(t)$) can be used to retain full "memory" for times greater than the time horizon t. However, as recommended by (Levasseur et al., 2016), AGTP is used to quantify long term climate impacts.

G.2.1 AGTP for CO_2, CH_4, and N_2O

For CO_2, CH_4, and N_2O the following are the discrete solutions to their respective AGTP using the definitions for $RF_i(t)$ in Table 65, truncating IRF_{CO_2} to the first three terms, and truncating $R_T(t)$ to the first two terms (Myhre et al., 2013):

$$AGTP_{CO_2}^{Pulse}(t) = A_{CO_2}\sum_{j=1}^{2}\left\{a_0 c_j\left[1 - exp\left(-\frac{t}{d_j}\right)\right] + \sum_{k=1}^{3}\frac{a_k\tau_k c_j}{\tau_k - d_j}\left[exp\left(-\frac{t}{\tau_k}\right) - exp\left(-\frac{t}{d_j}\right)\right]\right\}$$

$$AGTP_{CH_4}^{Pulse}(t) = (1 + f_1 + f_2)\cdot A_{CH_4}\sum_{j=1}^{2}\frac{\tau_{CH_4}c_j}{\tau_{CH_4} - d_j}\left\{exp\left(-\frac{t}{\tau_{CH_4}}\right) - exp\left(-\frac{t}{d_j}\right)\right\}$$

$$AGTP_{N_2O}^{Pulse}(t) = \left(1 - 0.36\cdot(1 + f_1 + f_2)\cdot\frac{RE_{CH_4}}{RE_{N_2O}}\right)A_{N_2O}\sum_{j=1}^{2}\frac{\tau_{N_2O}c_j}{\tau_{N_2O} - d_j}\left\{exp\left(-\frac{t}{\tau_{N_2O}}\right) - exp\left(-\frac{t}{d_j}\right)\right\}$$

The parameters in Table 66 are used in the AGTP equations (Myhre et al., 2013), along with those detailed in Table 67 to obtain numerical solutions.

Table 67: AGTP Function Parameters

	1^{st} Term	2^{nd} Term
$c_j\left(\frac{K\cdot m^2}{W}\right)$	0.631	0.429
d_j (years)	8.4	409.5

Values from (Giuntoli et al., 2015).

G.2.2 AGTP for Near-Term Climate Forcers

Consideration of near term climate forcers is left to future work.

G.3 Discrete-Time Convolution Method

The convolution required to implement the "Emissions Scenario" approach to the climate metrics is implemented using a "Discrete-Time Convolution" approach. We implement the following definitions:

$$AGWP_i^{Scenario}(t) = \int_0^t E_i(t')AGWP_i^{Pulse}(t-t')dt' = \sum_{s=0}^{t-1} E_{i,s} \int_s^{s+1} AGWP_i^{Pulse}(t-t')dt' = \sum_{s=0}^{t-1} AGWP_{i,ts}^{Pulse} E_{i,s}$$

$$AGTP_i^{Scenario}(t) = \int_0^t E_i(t')AGTP_i^{Pulse}(t-t')dt' = \sum_{s=0}^{t-1} E_{i,s} \int_s^{s+1} AGTP_i^{Pulse}(t-t')dt' = \sum_{s=0}^{t-1} AGTP_{i,ts}^{Pulse} E_{i,s}$$

where

$$AGWP_{i,ts}^{Pulse} = \begin{cases} \int_s^{s+1} AGWP_i^{Pulse}(t-t')dt' & 0 \le s \le t-1 \\ 0 & s \ge t \end{cases}$$

$$AGTP_{i,ts}^{Pulse} = \begin{cases} \int_s^{s+1} AGTP_i^{Pulse}(t-t')dt' & 0 \le s \le t-1 \\ 0 & s \ge t \end{cases}$$

The definite solutions used to create the lower triangular matrices $AGWP_{i,ts}^{Pulse}$ and $AGTP_{i,ts}^{Pulse}$ are as follows for each gas species CO_2, CH_4 and N_2O using the definitions for $RF_i(t)$ in Table 65, truncating IRF_{CO_2} to the first three terms, and truncating $R_T(t)$ to the first two terms:

$$AGWP_{CO_2,ts}^{Pulse} = A_{CO_2}\left\{a_0\left(t-s-\frac{1}{2}\right) + \sum_{j=1}^{3} a_j\tau_j(1-\tau_j)exp\left(-\frac{t-s}{\tau_j}\right)\left[exp\left(\frac{1}{\tau_j}\right)-1\right]\right\}$$

$$AGWP_{CH_4,ts}^{Pulse} = (1+f1+f2)A_{CH_4}\tau_{CH_4}\left\{1-\tau_{CH_4}exp\left(-\frac{t-s}{\tau_{CH_4}}\right)\left[exp\left(\frac{1}{\tau_{CH_4}}\right)-1\right]\right\}$$

$$AGWP_{N_2O,ts}^{Pulse} = \left(1-0.36(1+f1+f2)\frac{RE_{CH_4}}{RE_{N_2O}}\right)A_{N_2O}\tau_{N_2O}\left\{1-\tau_{N_2O}exp\left(-\frac{t-s}{\tau_{N_2O}}\right)\left[exp\left(\frac{1}{\tau_{N_2O}}\right)-1\right]\right\}$$

and

$$AGTP_{CO_2,ts}^{Pulse} = A_{CO_2}\sum_{j=1}^{2}\left\{\begin{array}{c} a_0c_j\left[d_jexp\left(-\frac{s+1}{d_j}\right)\left(exp\left(\frac{1}{d_j}\right)-1\right)-exp\left(-\frac{t}{d_j}\right)\right]+ \\ \sum_{k=1}^{3}\frac{a_k\tau_kc_j}{d_j-\tau_k}\left[exp\left(-\frac{t}{d_j}\right)+\frac{d_j\tau_k}{d_j-\tau_k}\left(exp\left(-\frac{d_j(t-s)+\tau_k(s+1)}{d_j\tau_k}\right)\cdot\left(exp\left(\frac{1}{d_j}\right)-exp\left(\frac{1}{\tau_k}\right)\right)\right)\right]\end{array}\right\}$$

$$AGTP_{CH_4,ts}^{Pulse} = (1+f_1+f_2)A_{CH_4}\sum_{j=1}^{2}\frac{\tau_{CH_4}c_j}{d_j-\tau_{CH_4}}\left[\begin{array}{c} exp\left(-\frac{t}{d_j}\right)+ \\ \frac{d_j\tau_{CH_4}}{d_j-\tau_{CH_4}}\left[exp\left(-\frac{d_j(t-s)+\tau_{CH_4}(s+1)}{d_j\tau_{CH_4}}\right)\cdot\left(exp\left(\frac{1}{d_j}\right)-exp\left(\frac{1}{\tau_{CH_4}}\right)\right)\right]\end{array}\right]$$

$$AGTP_{N_2O,ts}^{Pulse} = \left(1-0.36(1+f_1+f_2)\frac{RE_{CH_4}}{RE_{N_2O}}\right)A_{N_2O}\sum_{j=1}^{2}\frac{\tau_{N_2O}c_j}{\tau_{N_2O}-d_j}\left[\begin{array}{c} exp\left(-\frac{t}{d_j}\right)+ \\ \frac{d_j\tau_{N_2O}}{d_j-\tau_{N_2O}}\left[\begin{array}{c} exp\left(-\frac{d_j(t-s)+\tau_{N_2O}(s+1)}{d_j\tau_{N_2O}}\right)\cdot \\ \left(exp\left(\frac{1}{d_j}\right)-exp\left(\frac{1}{\tau_{N_2O}}\right)\right)\end{array}\right]\end{array}\right]$$

Matrix multiplication is then used to multiply these lower triangular matrices with $E_{i,s}$. The result is a function of time t. A numerical value for each climate metric can then be obtained by evaluating the resulting function at any desired time horizon within $0 \le t \le 100$ years.