Report

Criteria Air Pollutant Emissions of Biopower Generation from Forest Residues in California

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Prepared by:
Kevin Fingerman and Jerome Carman
Schatz Energy Research Center and Humboldt State University Department of Environmental Science and Management
Humboldt State University
Arcata, CA 95521
(707) 826-4345

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Contact: kevin.fingerman@humboldt.edu

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EXECUTIVE SUMMARY

California's forests are diverse and representative of many temperate forest ecosystem types found across Western North America and the world. California forests are currently responding to a variety of environmental stressors, including overstocking, drought, pests, disease, and wildfire, producing concerns of declining forest productivity and extensive mortality. These conditions make the need for forest management critical, with increasing interest in utilizing non-timber biomass for biopower production. Removal of residue for biopower can have a range of environmental impacts, both positive and negative. Supported by the California Energy Commission under Grant Funding Opportunity 16-306, the California Biopower Impacts Project seeks to understand a broad range of these impacts. This report is a component of that effort, and provides insights into a key impact of woody residue removal for biopower: namely net emissions of health-harming air pollutants - particularly Volatile Organic Compounds (VOCs), Oxides of Nitrogen and Sulphur (NO_X and SO_X), Carbon monoxide (CO) and Particulates at both 2.5 and 10-micron scales ($PM_{2.5}$ and PM_{10}).

Key findings with respect to the criteria air pollutant impact of mobilizing post-treatment forest residues for bioelectricity generation are as follows:

- In almost all cases, a significant reduction in net emissions of health-harming air pollutants is achieved when woody biomass that would otherwise be burned is removed from the field to be used in electric power generation. By removing this material to an engineered combustion chamber, and one where emissions are tightly controlled, criteria pollutant emissions are significantly reduced from a ton of biomass vs burning that same ton in the field.
- Where residue would have been left to decay in the forest, mobilization for biopower generation yields generally slightly greater emissions of criteria pollutants, but the results are mixed depending on the scenario and the emission species of concern. Moreover, while the infrequency of wildfire means the expected emissions from a given mass of forest residue are generally lower in one year if left in situ vs being used for biopower, they could be exposed to wildfire in future years as they decay.
- While mobilization of this woody biomass typically reduces the total mass of criteria pollutants emitted per ton of residue, it is worth noting that it also aggregates this emission to a point source, and one that may be closer to human populations. This work does not evaluate exposure to these pollutants, nor the distribution of that health burden across human populations. This is an important area for future research that is supported by the modeling tools and datasets developed under this project.
- There is also significant spatial variation in the emissions dynamics associated with leaving or burning residues in the field. There are two key drivers for this:
    - The forest treatments differ in residue base characteristics such as species and size class distribution, which affects the behavior of a prescribed burn or wildfire.
    - Across California's forested landscapes there is significant variation in climate, influencing both the probability of wildfire occurrence as well as the combustion and emission dynamics of fires when they occur.

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1. Introduction

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. These conditions are creating a need to treat forest stands and broader landscapes for multiple benefits including resilient forest ecosystems while reducing wildfire risk. 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 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.

Residues generated by forest thinning and fuels treatment as well as commercial forestry and agricultural activities have the potential to be transformed from a waste stream into a renewable energy resource. If managed properly, bioenergy from woody residues can support sustainable forest management and agricultural activities while also advancing California's Renewable Portfolio Standard goals. However, there are legitimate concerns surrounding climate, air quality, and ecosystem health implications of improperly managed bioenergy systems.

The California Biopower Impacts (CBI) Project, supported by the California Energy Commission under Grant Funding Opportunity 16-306, has sought to rigorously and transparently establish the variable environmental performance of bioenergy from forest residues. Elements of the CBI Project have focused on different considerations surrounding the mobilization of woody residues in California to generate biopower. These include an assessment of the technically recoverable biomass residue resource base, modeling the life-cycle climate impact of its utilization, and evaluation of mechanisms to improve the economics of residue mobilization.

One additional consideration investigated through the CBI Project is the air quality impact of bioenergy from forestry residues. While climate impact is often central to bioenergy policy development – and is a key element of our work – other air pollution effects can have significant implications for human health and environmental quality, and should be carefully evaluated. This report focuses on the effect of residue mobilization and biopower generation on gross and net emissions of the following Criteria Air Pollutants: Volatile Organic Compounds (VOCs), NO_X, SO_2, $PM_{2.5}$, PM_{10}, and Black Carbon. It also discusses black carbon's role as a short-lived climate pollutant and our approach to considering its climate forcing effect.

2. Methods

The core of the CBI Project effort has been development and implementation of the California Biomass Residue Emissions Characterization (C-BREC) Model, a life-cycle assessment (LCA) framework specific to the use of California forest and agricultural residues for electricity generation and heating applications. This model, and the webtool version that can be found at schatzcenter.org/cbrec/, enables robust, transparent accounting for the emissions associated with residual woody biomass energy systems in the state. This includes comprehensive accounting of the avoided emissions from decay and/or combustion that would have occurred had the residue not been removed from the field.

In order to run the C-BREC model users specify the following key project characteristics:

1. Location of residue generation
2. Type and intensity of forest treatment or harvest activity being conducted
3. Baseline residue disposition (fraction piled after primary treatment)
4. Location of residue utilization
5. Reference fate of unremoved biomass (prescribed burn, left in place)
6. Key supply-chain characteristics such as biomass removal level, any post-harvest treatment, end-use technology, etc.

For a given project profile, the C-BREC model reports emissions of the air pollutant species listed above. It quantifies the emissions associated directly with a "use" case in which biomass residuals are mobilized from the field for use in a biomass energy supply chain and a "reference" case in which they are not mobilized. The net emissions of the biopower system is the difference between these two fates for the same material. The use case includes emissions from mobilization, transportation, and end-use. The reference emissions are made up of three distinct processes, applied in probabilistic fashion to any given ton of biomass:

- Pile or broadcast burning of residuals in year 1
- Decay extending for 100 years of material piled/scattered on the forest floor
- Ongoing exposure to wildfire over a 100-year period

Residue from a given forest treatment in C-BREC is modeled at 0%, 30%, 50%, and 70% piled disposition to account for the variability in forest harvest and residue management practices. A forest manager then faces three options: remove the residue for bioelectricity generation, burn it, or leave it on site. In the use case, both removal of piles only and removal of all technically recoverable biomass are modeled. These pile fraction and removal types also influence the type of burn that occurs in the reference case as the residue removal and the counterfactual prescribed burn are intended to target the same material. Where only piles are removed in the use case, C-BREC assigns a pile burn the as prescribed burn option. Where all technically recoverable material is removed in the use case, C-BREC models pile (if piles are present) and broadcast burn prescription as the reference case. Land managers typically either collect residue or conduct a prescribed burn, and therefore prescribed burns are not modeled following collection in the use cases.

This approach allows C-BREC to rigorously and transparently account for the net air pollutant emissions associated with power generation from forest residue bioelectricity. The emissions of greenhouse gases and resultant climate impact of these activities is the subject of our report titled *Climate Impacts of Biopower Generation from Forest Residues in California*, which is available at schatzcenter.org/cbrec/. Greenhouse gases are not the only air pollutants that arise from biopower generation and from the alternative fate of woody biomass in the field. Other air pollutants, particularly those regulated under the Clean Air Act—commonly referred to as "criteria air pollutants"—have important human health and environmental impacts and can also be exacerbated, or mitigated, by the systems under consideration. This report lays out findings for the following air pollutant species tracked and reported by the C-BREC model:

- VOCs - 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 (as SO_2)
- 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 $PM_{2.5}$

Emissions by Source

The modeling methods and implementation are described in detail in the model framework document (Carman et al., 2021) available at www.schatzcenter.org/cbrec/. Methods for deriving criteria pollutants from different sources are described briefly here.

Prescribed Burns and Wildfire

Wildfire and prescribed burns of forest residues are modeled using the "activity" fuels equations from the Consume software, version 4.2, created by the US Forest Service (Prichard et al., 2006). These 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 emission factors compiled from both the Consume model (Prichard et al., 2006) and the Bluesky modeling framework (Larkin et al., 2010), and supplemented with black carbon speciation values from CARB (California Air Resources Board, 2016b). Variability by combustion phase (flaming, smoldering, residual) and residue disposition (piled or scattered) is captured. For piles, dirt content impacts emissions factors; piled residues are considered “very dirty”.

Both emissions and fire behavior models require inputs for fuel moisture and mid-flame wind speed. To estimate these inputs, the 4 km resolution GRIDMET gridded surface meteorological data set is used (Abatzoglou, 2013; Abatzoglou & Brown, 2012) augmented with additional fuel moisture parameters (Cohen & Deeming, 1985) and treatment-specific wind adjustment factors (Andrews, 2012). For wildfire simulations, 97th percentile conditions are used for all climate variables constrained to the months of June through September for all years from 2000 to 2017. For prescribed fire simulations, 37.5th percentile conditions are used for all climate variables constrained to September and October (the typical fall prescribed fire season) from the same time period.

The C-BREC model averages expected emissions from wildfire in each of the next 100 years on a given landscape, both with and without forest residues left in the field. However, it is of course not possible to predict when a fire will occur at a given site. C-BREC therefore annualizes emissions from wildfire at each location in each year by taking the product of the expected emissions from the residue's exposure to wildfire in that year and the probability of such a fire occurring. Current and projected wildfire probability in California is derived from the Cal-Adapt dataset (Westerling, 2018). For the future wildfire probability projections, C-BREC uses the representative concentration pathway (RCP) 4.5 emissions trajectory and business as usual population growth assumptions.

Fossil Fuel Sources

Combustion of fossil fuels are associated with residue mobilization equipment, and with drip torch fuel used for prescribed burns. Emissions factors for mobilization equipment were developed by the Consortium for Research on Renewable Industrial Materials (CORRIM). A variety of equipment systems were developed that depend on project area, volume of residue collected, moisture content, residue disposition, project terrain, and comminution type. Hauling distances to existing power plants are calculated using the existing road network, including forest service access roads. Emissions factors were created using SimaPro, method TRACI 2.1 v1.0.1 / U.S. 2008, and supplemented with black carbon speciation values from CARB (California Air Resources Board, 2016b). Drip torch fuel quantities vary by burn type and project area, and associated emissions factors were derived from EPA literature (United States Environmental Protection Agency, 2021).

Power Plant Sources

Emissions resulting from energy conversion of biomass into heat and electricity are calculated based on the biomass fuel properties weighted by species composition, power plant specifications, and pollutant emissions factors. C-BREC allows mobilization of residues to existing power plants or to five different generic power plants:

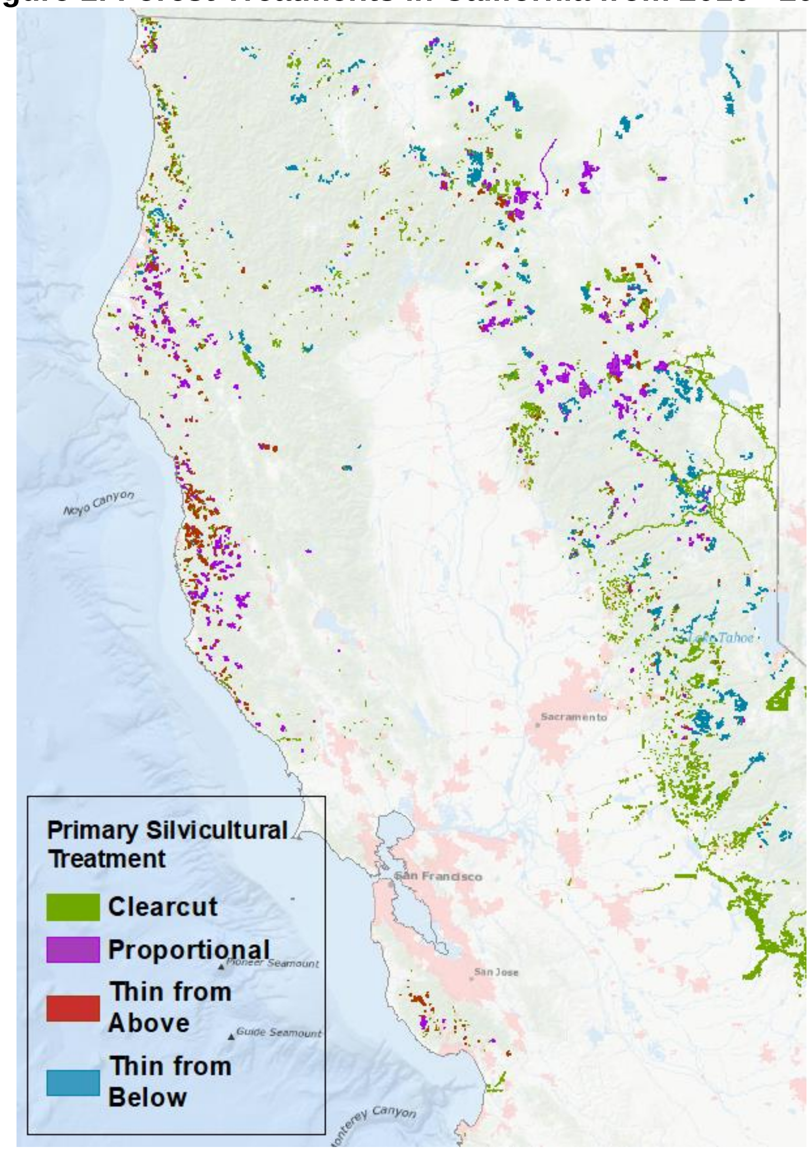
- Current generation biomass combustion
- Current generation integrated gasification / combustion
- Next generation thermochemical conversion gasifier
- 5MW gasifier
- <1 MW gasifier

For existing power plants, conversion rates of fuel to heat and electricity are obtained from the California Energy Commission (California Energy Commission, 2018), and emissions factors for existing power plants are obtained from the California Air Resources Board (California Air Resources Board, 2016a). For generic current power plants performance and emissions factors are obtained from a variety of sources. Emissions factors are supplemented with black carbon speciation values from CARB (California Air Resources Board, 2016b).

Case Study Approach

This report offers a detailed look at the results generated by the C-BREC model, applied across a range of forestry treatment activities on California landscapes. While the model is able to evaluate the impact of residue removal from any forestry activity type on any forested landscape in the state, this report is focused on a case study of the actual treatment activities conducted in California in the years 2016-2019, characterized by data from Timber Harvest Plans and Non-commercial Timber Management Plans (Figure 1) filed with the California Department of Forestry and Fire Protection (CALFIRE). The results of that analysis shed light on the variable environmental performance of biomass electricity systems in California, and also the drivers of that variation.

Figure 1: Forest Treatments in California from 2016 - 2019



The 11,035 individual forest treatment activities that make up the case study detailed in this report. This map focuses on the northern region of California as it contains the majority of the working forests in the state and therefore almost all of the treatments evaluated for this study.

3. Air Pollutant Impact Results

Results vary across system characteristics such as forest treatment type and residue disposition as well as geographic characteristics such as residue species, decay rate, and wildfire behavior and probability. As such, considering the distribution of net emission profiles across the treatments conducted in California over the four year case study period allows a better understanding of the sources of this variation and the sensitivity of biopower criteria pollutant emissions to various system characteristics and model assumptions. This will provide useful insight in shaping forest and bioelectricity policy and industry going forward.

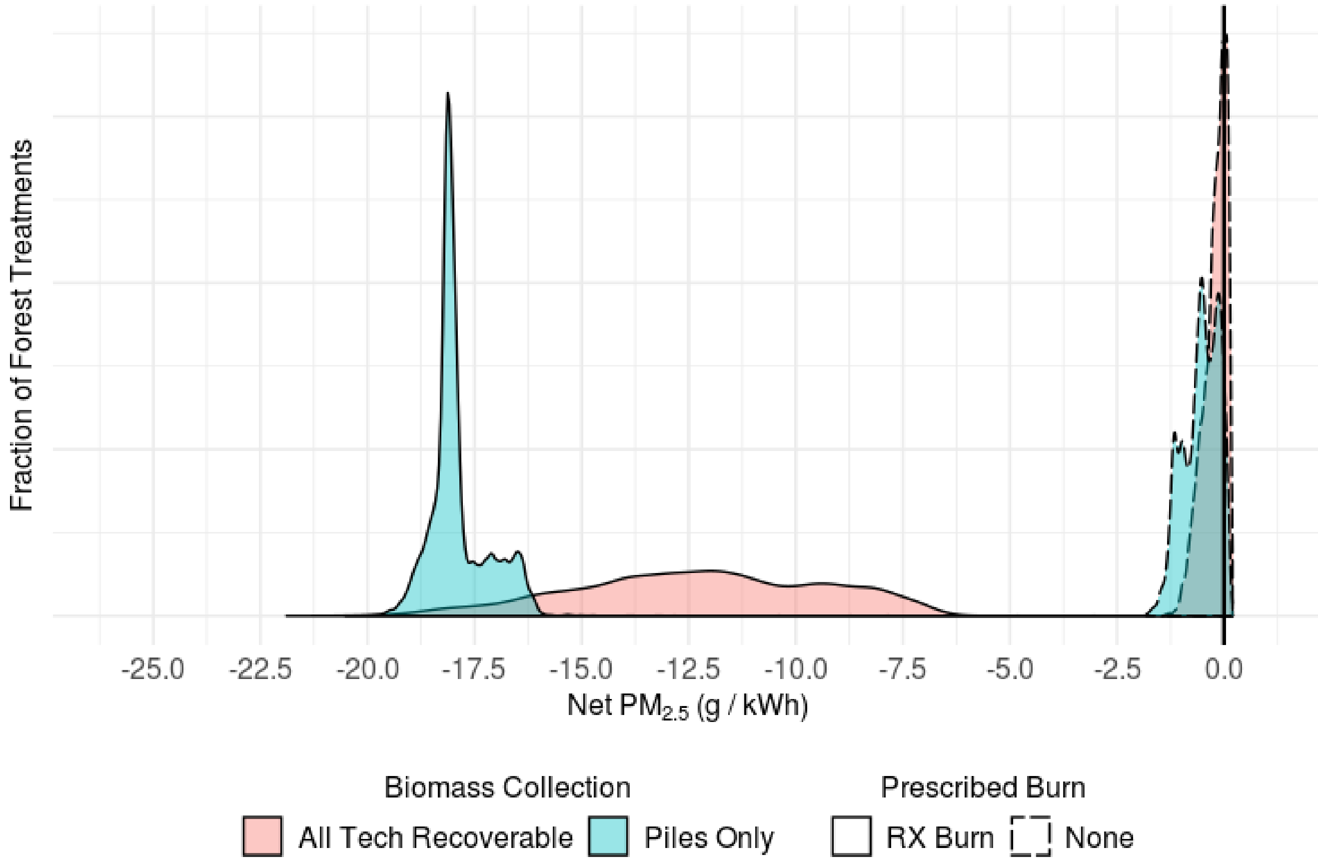
In order to evaluate trends, most of the figures in this results section isolate many of the system configuration variables in C-BREC in order to explore the impact of others. For the purposes of this report, except where otherwise noted, the following base case parameters are assumed for all of the systems under consideration:

- Biopower is generated using a current-generation combustion plant of 20% efficiency and emission characteristics and without combined heat and power (CHP) capability
- Biomass collection is carried out using a modeled "large harvest" equipment system and comminution is conducted on dry wood using a grinder
- Residue is hauled 50 km to the power generation facility
- Results are filtered to remove unrepresentative outliers, such as treatments in which <1T of total residue is present and which are therefore unlikely to be mobilized for bioelectricity generation.

In addition, most of the distributions presented here report aggregate criteria pollutant emissions over the 10-year period following residue generation. In accounting for greenhouse gas emissions, it is possible to normalize an emission time series to year-1 CO2 equivalent (CO_2e) as described in the C-BREC framework and LCA results report available at schatzcenter.org/cbrec/. For criteria pollutant emissions, actual emission mass is reported as there is no equivalency basis for normalizing different emissions species or emissions at different times. Results therefore report 10-year aggregate criteria pollutant emissions as a compromise between reporting first-year or full 100-year emissions, which underestimate or overestimate the impact of wildfire emissions respectively.

Results indicate that mobilizing forestry residues for biopower generation typically leads to reduction in emissions of health-harming criteria air pollutants. Figure 2 shows this effect for the case of $PM_{2.5}$, a particularly harmful atmospheric pollutant.

Figure 2: Net 10-Year Cumulative $PM_{2.5}$ Impacts



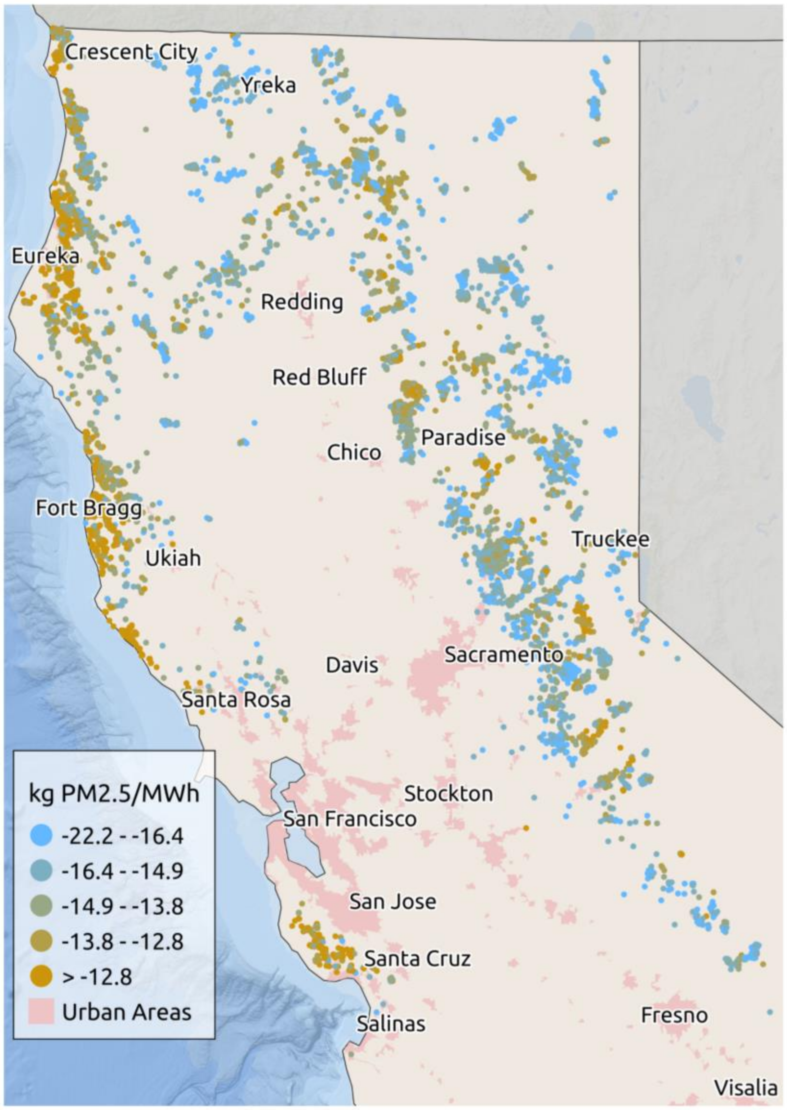
Distribution of 10-year aggregate $PM_{2.5}$ emissions from different residue mobilization and counterfactual scenarios across the California recent treatments dataset. The average $PM_{2.5}$ emission factor for existing biomass power plants in California is 0.299 g/kWh.

Because these figures display the net emissions, higher emissions in the reference case lead to lower (or more negative) values here because these are the net emissions associated with residue mobilization and use. The reduction in emissions from biomass utilization is unsurprisingly strongest where biomass would otherwise have been burned in the field. By removing this material to an engineered combustion chamber, and one where emissions are tightly controlled, the particulate emissions from a ton of biomass are significantly reduced vs burning that same ton in the field. Where residue would have been left in the field rather than subjected to a prescribed burn, mobilization for biopower generation yields generally slightly lower $PM_{2.5}$ emissions over a 10-year period, though the results are mixed.

It is worth noting here that while mobilization of this woody biomass may reduce the total mass of particulates emitted per ton of residue, it also aggregates this emission to a point source, and one that may be closer to human populations. This report does not evaluate the exposure of humans to these pollutants, nor the equity of distribution of that health burden across human populations. This is an important area for future research that will be enabled by the modeling tools and datasets developed under this project.

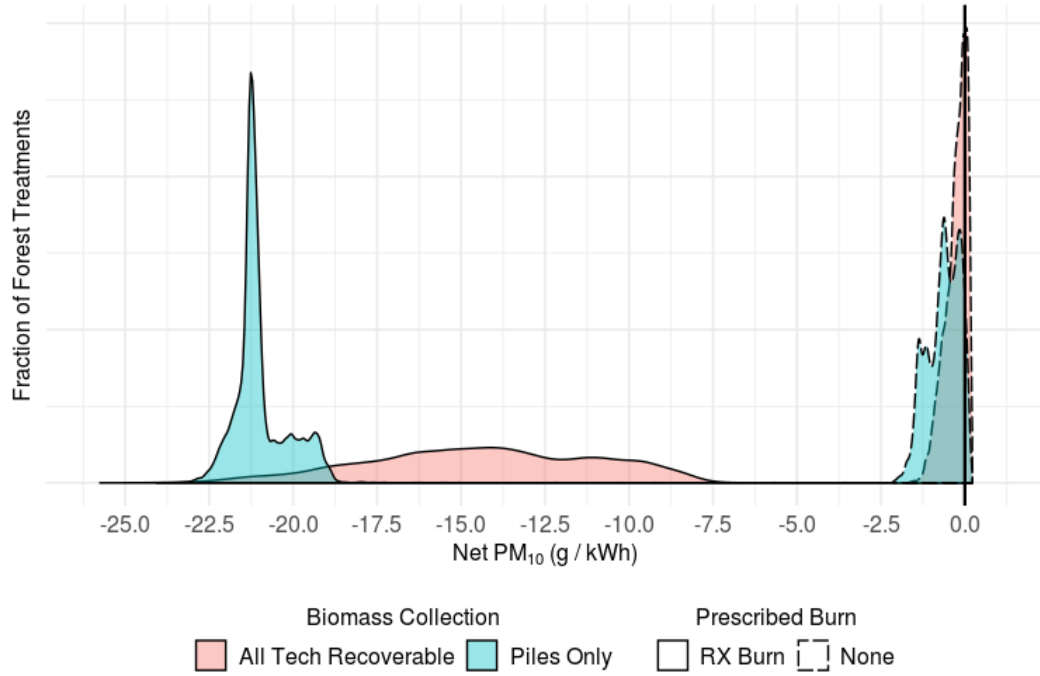
A great deal of the variation seen within each of the distribution curves in Figure 2 above is attributable to spatially-variable emissions dynamics associated with leaving or burning residues in the field. This is because the many forest treatments being evaluated differ in their residue base characteristics as well as in their climatic drivers of both the probability of wildfire occurrence as well as the dynamics of a fire when it occurs. For example, larger, wetter material will tend to smolder. This has a significant effect on the emissions associated with that burning. Mapping the net emissions from biomass utilization allows an assessment of these geographic discrepancies and thereby lending insight into where biomass utilization might offer the most and least air quality mitigation potential. Figure 3 below illustrates these spatial trends by exhibiting the mapped distribution in net 10-year aggregate emissions of $PM_{2.5}$ in cases where residue would otherwise have been exposed to prescribed burn.

Figure 3: Spatial Variation in Net 10-Year Cumulative $PM_{2.5}$ Impacts



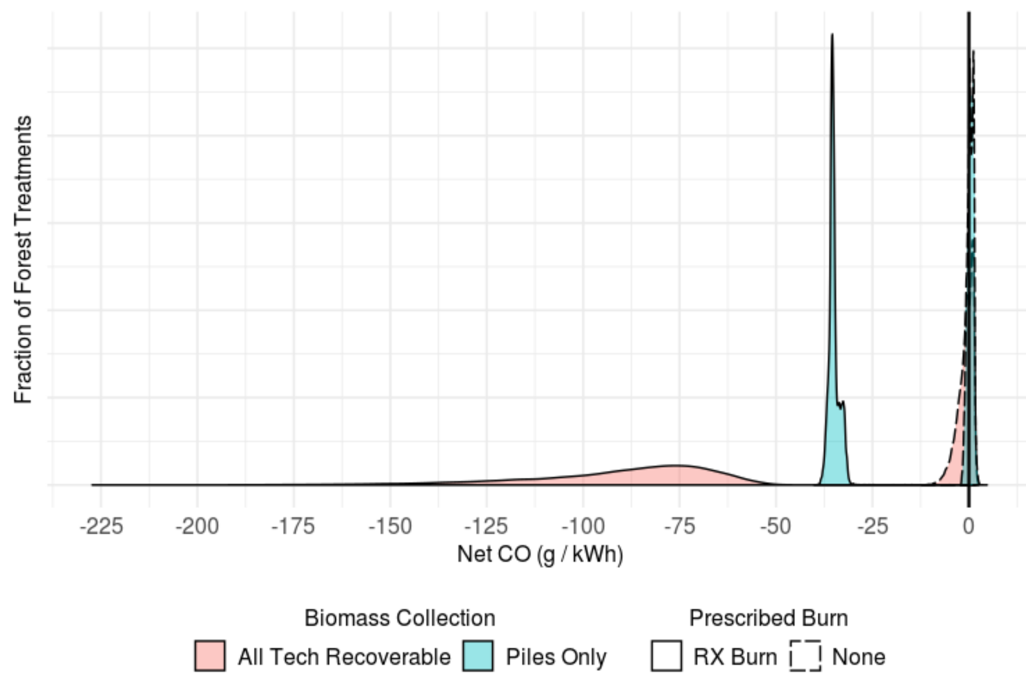
$PM_{2.5}$ is a very important air pollutant, especially because it is implicated in many of the most important human health effects of degraded air quality. However, many other air pollutant constituents are also important for human health and environmental degradation, and therefore warrant tracking. Figure 4 through Figure 8 below illustrate the distribution of net emissions of a variety of criteria air pollutants from generation of biopower from forest residuals across the California recent treatments dataset.

Figure 4: Net 10-Year Cumulative PM_{10} Impacts



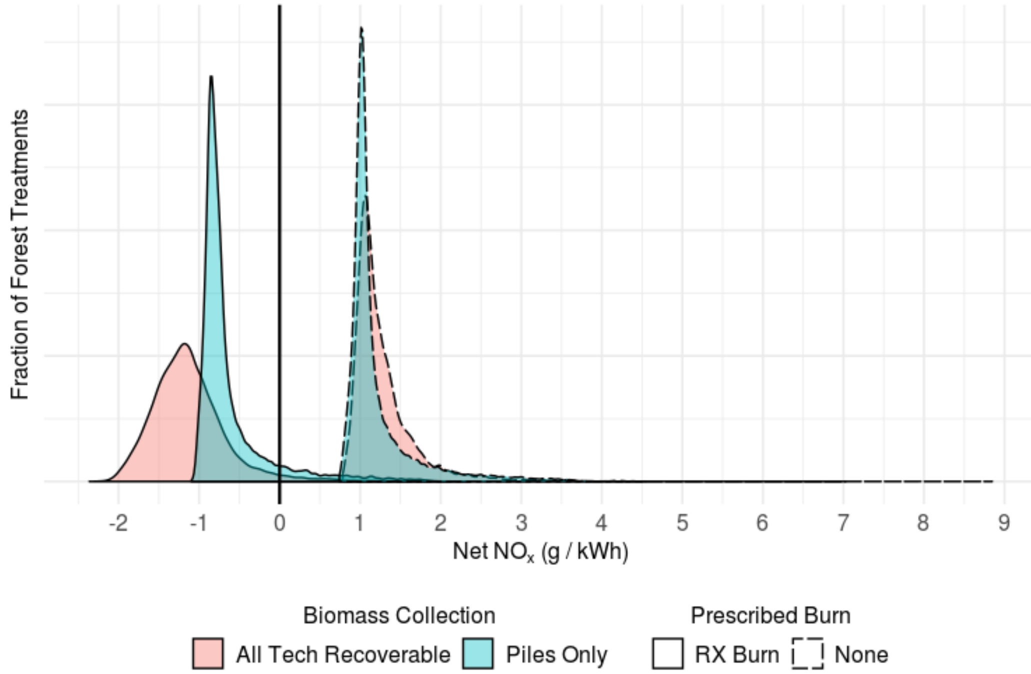
Distribution of 10-year aggregate PM_{10} emissions from different residue mobilization and counterfactual scenarios across the California recent treatments dataset. The average PM_{10} emission factor for existing biomass power plants in California is 0.338 g/kWh.

Figure 5: Net 10-Year Cumulative CO Impacts



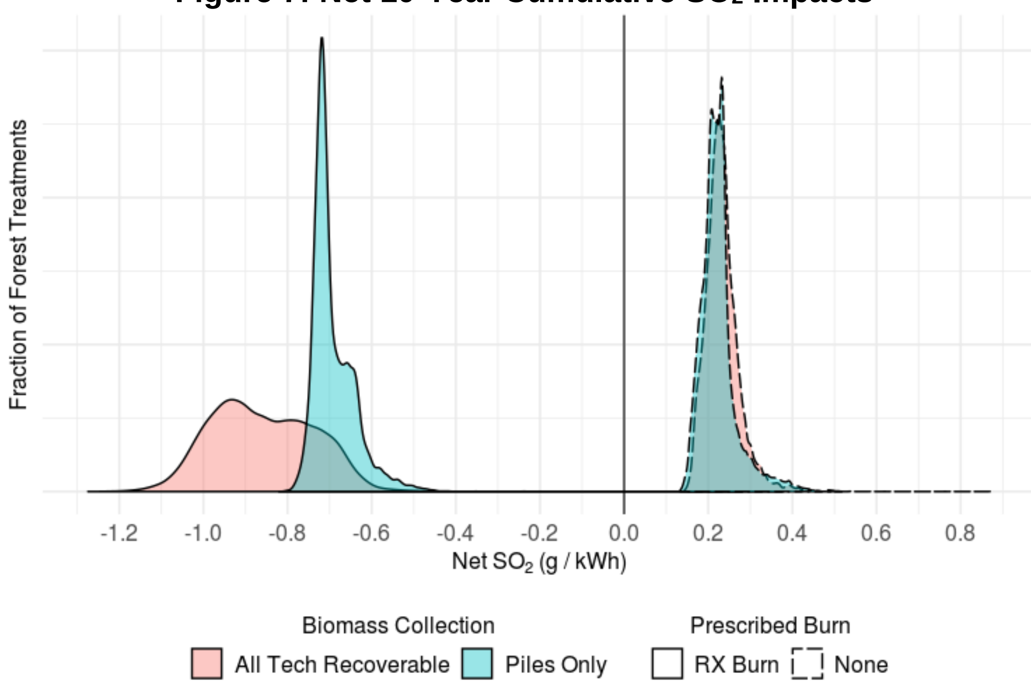
Distribution of 10-year aggregate CO emissions from different residue mobilization and counterfactual scenarios across the California recent treatments dataset. The average CO emission factor for existing biomass power plants in California is 4.11 g/kWh.

Figure 6: Net 10-Year Cumulative NO_X Impacts



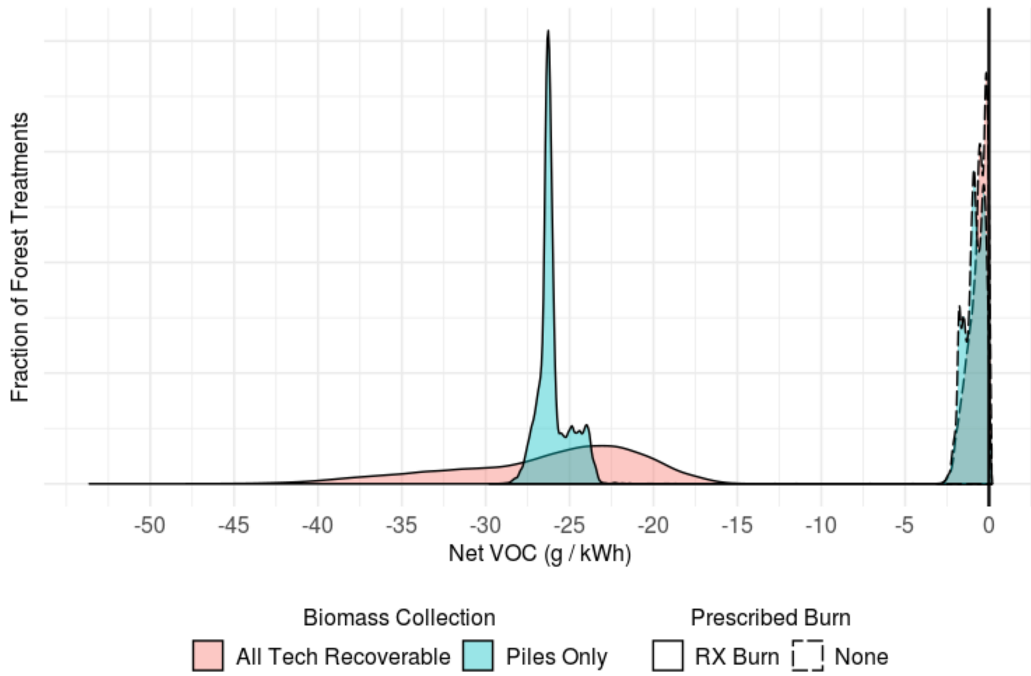
Distribution of 10-year aggregate NOx emissions from different residue mobilization and counterfactual scenarios across the California recent treatments dataset. The average NO_X emission factor for existing biomass power plants in California is 1.15 g/kWh.

Figure 7: Net 10-Year Cumulative SO_2 Impacts



Distribution of 10-year aggregate SO_2 emissions from different residue mobilization and counterfactual scenarios across the California recent treatments dataset. The average SO_2 emission factor for existing biomass power plants in California is 0.157 g/kWh.

Figure 8: Net 10-Year Cumulative VOC Impact



Distribution of 10-year aggregate VOC emissions from different residue mobilization and counterfactual scenarios across the California recent treatments dataset. The average VOC emission factor for existing biomass power plants in California is 0.128 g/kWh.

The emissions distributions displayed in Figure 4 through Figure 8 are all similar in that diverting residues that would otherwise have been burned offers more significant emission avoidance than where residues would have been left in place. This is to be expected, as open prescribed burning generates higher emission of criteria pollutants than combustion of the same material in a power plant. The shapes of the distributions are also instructive. Scenarios in which only piled material would be collected and a pile burn is therefore the reference fate (solid-line curves shaded blue) exhibit much less variability than those in which a broadcast burn is the reference fate (solid-line curves shaded red). This is because pile burns are relatively uniform in their combustion dynamics, whereas in broadcast burning more wood is exposed to fire but the dynamics of that fire vary significantly across residue types and conditions.

However, these emissions distributions also differ in some significant ways. First, they differ in whether removing piled material that would otherwise have been subjected to a pile burn offers more or less emission avoidance than scattered material that would otherwise have been subjected to broadcast burning. This is due to the differing fire behavior and emission dynamics between these two prescribed burn types. Smoldering fires typically emit more criteria pollutants than flaming fires, and broadcast burns smolder more than pile burns due to the effects of fuel moisture and fire weather, which are more significant when fuels are spread out. For the same set of reasons, however, broadcast burning also typically consumes less of the exposed material than pile burning. The differential in emissions between smoldering and flaming varies by pollutant type, and for some pollutants (e.g. NO_X, SO_2, CO) this differential is large enough to outweigh the lower total consumption of broadcast burning to yield a higher total emission rate per ton of material exposed to fire. For other pollutants (e.g. $PM_{2.5}$ and

PM_{10}), the reduced consumption rate in broadcast burning has a larger effect, yielding lower total emissions than for the same material exposed to a pile burn. More detail on the approach and the models deployed in characterizing fire for the C-BREC model can be found in the model framework (Carman et al., 2021) and fire modeling (Kane & Wright, 2020) reports available at schatzenergy.org/cbrec/.

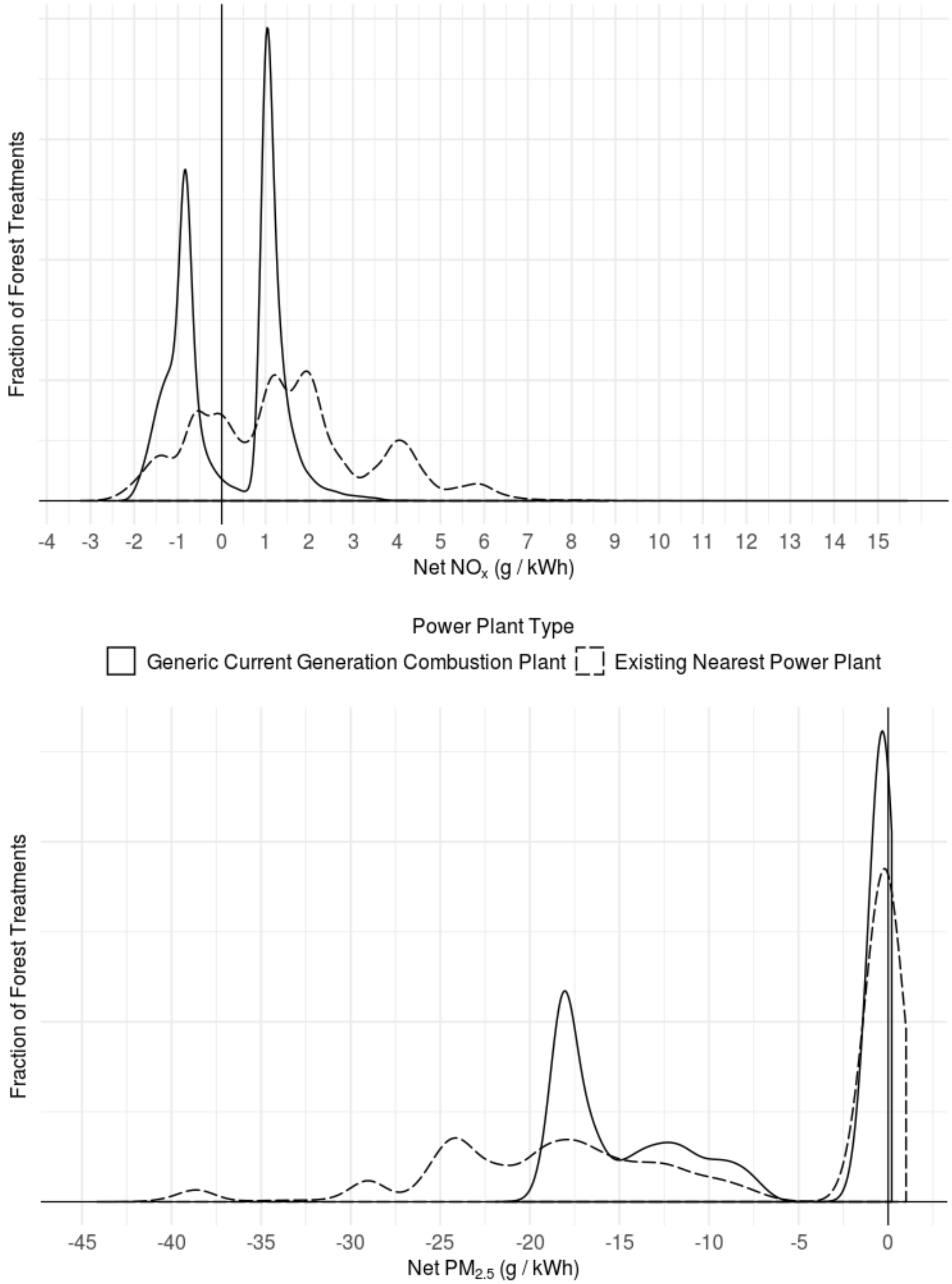
Another notable difference in the distributions of these different criteria pollutants is in the sign of the net emissions from biopower when material would otherwise have been left in situ. There are criteria pollutants present in both reference and use cases of this analysis. In the use case, criteria pollutants emerge from collection, distribution, and power generation where in the reference case, these emissions mostly stem from uncontrolled combustion. Where a prescribed burn is the reference case, those fire emissions far exceed the comparatively small emissions from the use case, leading to the significantly negative numbers discussed above. Where biomass would be left in situ, there is more variation. For most of the pollutants tracked by C-BREC (PM, CO, and VOCs), the expected emissions from wildfire over a 10-year period are enough to exceed the emissions from the use case, leading to a slightly negative net emission rate. The exceptions are SO_2 and NO_X. These pollutants are particularly tied to fossil fuel consumption, which is only present in the use case. As a result, biopower generation from residues that would otherwise be left in the field was found to lead to higher emissions of SO_2 and NO_X.

Sensitivity Analysis

The C-BREC model also enables a rigorous evaluation of the extent to which those emissions depend on specific characteristics of the system being modeled and the assumptions underlying the model itself. Through these sensitivities, additional divergence can be seen between the criteria pollutants that are primarily driven by the presence of fire in the system (PM, CO, and VOCs) and those that are primarily driven by the equipment deployed in the use case and its associated combustion of fossil fuels (SO_2 and NO_X).

For example, Figure 9 illustrates the sensitivity of $PM_{2.5}$ and NO_X emission intensity to the characteristics of the power plant in which the residue is burned. The actual power plants closest to each treatment location (dashed line distribution) have different emission profiles and hauling distance than the uniform power plant conditions assumed in the "generic current generation combustion plant" case (solid line distribution). As a result, plotting net NO_X emissions for the actual nearest power plant (Figure 9) causes the bimodal distribution seen elsewhere in the data to disappear, as the NO_X emission variation stemming from differing biomass transport distances and power plant emission profiles overwhelms the comparatively small difference between prescribed burning and retention of residues. The net emission of $PM_{2.5}$ also exhibits sensitivity to power plant characteristics, but for a different reason. As discussed above, the dominant driver of PM emissions is prescribed burn and wildfire. While these are not affected by the power plant characteristics, California biopower facilities also differ in the efficiency with which they convert biomass to electricity. Therefore, the avoided emission per kWh varies by power plant as a given ton of diverted biomass yields different amounts of electricity in different facilities.

Figure 9: Sensitivity of Net 10-Year Cumulative NO_X and $PM_{2.5}$ to Power Plant Technology and Location



The baseline generic combustion plant distribution assumes a uniform 50km hauling distance and average facility stack emissions where the existing nearest power plant case assigns residue from each forest treatment polygon to the nearest biopower facility, incorporating that facility's emission profile and hauling distance from the site.

In a similar vein, Figure 10 and Figure 11 below illustrate the sensitivity of net NO_X emissions to haul distance and collection & processing equipment system respectively. In both cases, the same analysis run for $PM_{2.5}$ shows so little sensitivity as to be impossible to visually discern on this type of distribution curve figure. Net NO_X and SO_X emission, however, both of which emerge significantly from the diesel fuel consumption required for collection and hauling of the biomass, prove to be very sensitive to these types of use-case system characteristics.

Figure 10: Sensitivity of Net 10-Year Cumulative NO_X to Hauling Distance

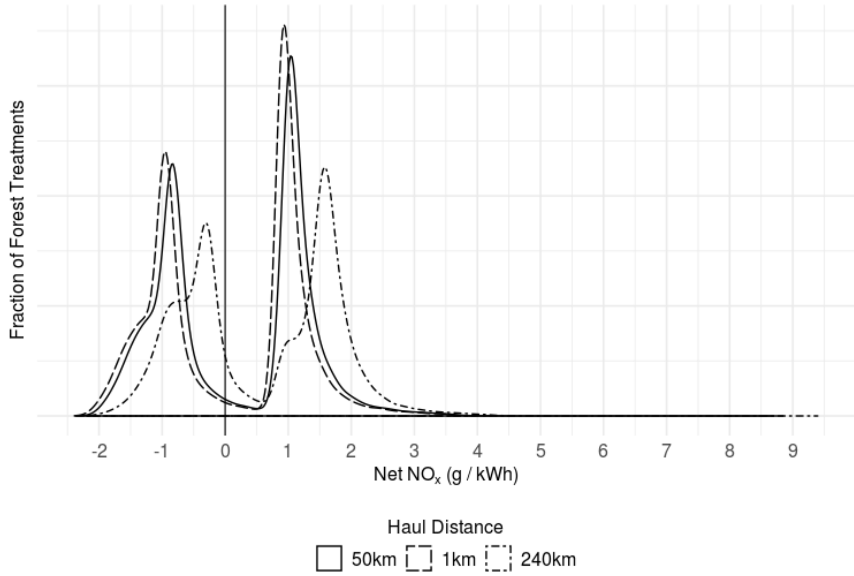
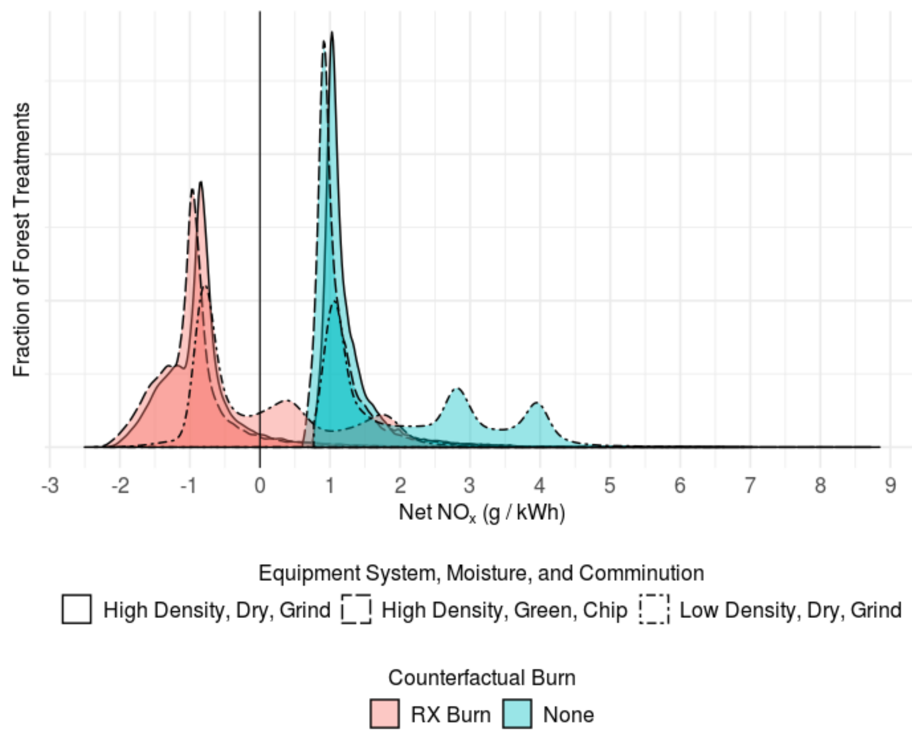


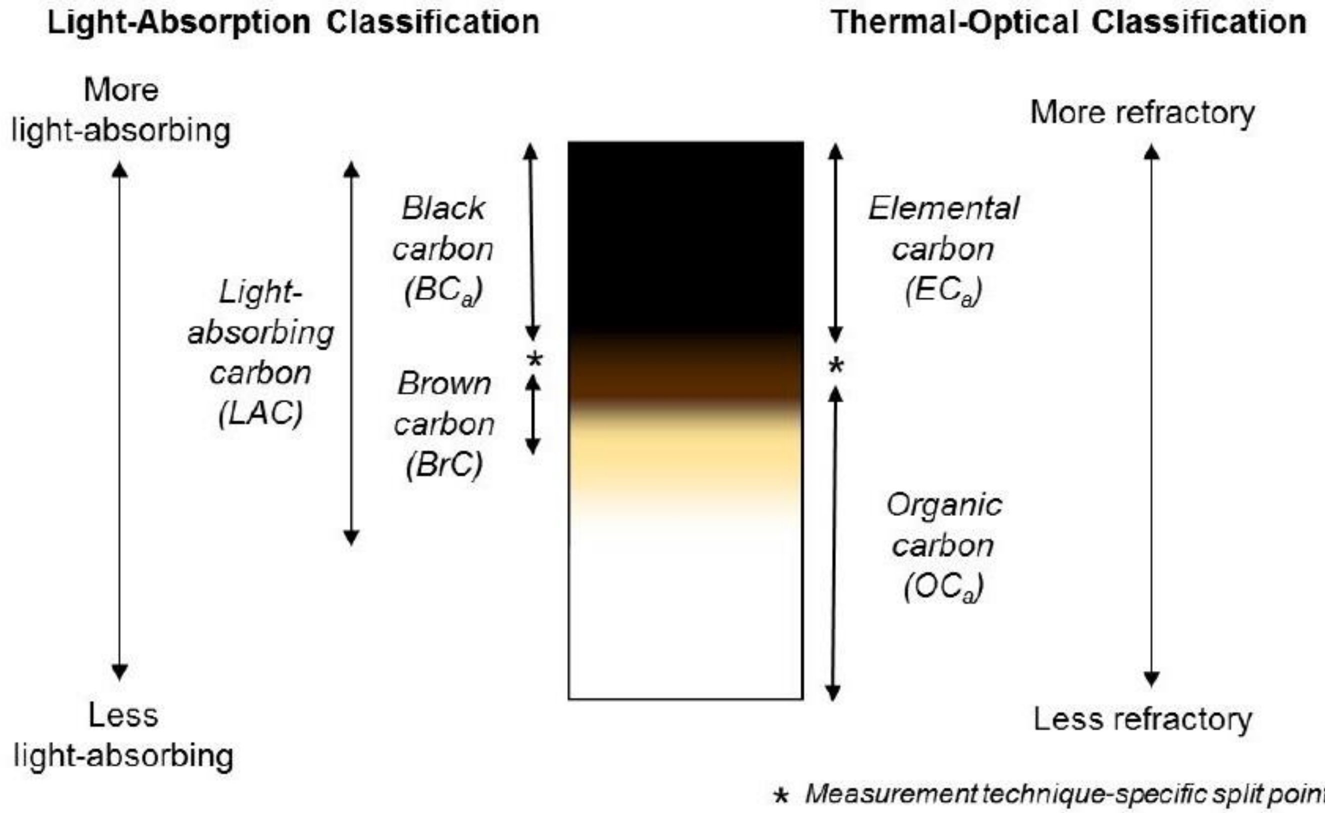
Figure 11: Sensitivity of Net 10-Year Cumulative NO_X to Mobilization Equipment System, Material Moisture, and Comminution Type



4. Discussion of Black Carbon

Black carbon comes from incomplete combustion and is important because it is both a powerful climate forcer and an air pollutant that affects air quality and human health. Black carbon (BC) is the most widely used term for light-absorbing carbonaceous aerosols. The term refers to carbonaceous aerosols that have a strong absorption profile across a wide spectrum of visible wavelengths (Figure 12). The term black carbon is sometimes used as a synonym for elemental carbon (EC), which is an operational definition based on the stability of carbon at elevated temperatures, as opposed to its light-absorption characteristics. EC and BC concentrations can be correlated – especially for important sources affecting human populations – but this is not always the case and is source-dependent. In this report, EC and BC are treated as synonyms for the purposes of collecting a range of emissions factors via literature review.

Figure 12: Definition of Black and Organic Carbon



Source: (United States Environmental Protection Agency, 2012)

BC is a component of particulate matter (PM), a pollutant that is among the most reliable indicators of health risk from exposure to air pollution. There is also evidence from epidemiological research that BC may be an important additional risk indicator to PM when the sources of PM in an area are dominated by combustion sources (Janssen et al., 2011). At present, however, most major air quality guidelines do not distinguish BC from PM at any size class. As such, most efforts to reduce BC exposure generally target PM overall. Both are indicators of air pollution, meaning that increased exposure concentrations are often associated with increased risk of various diseases, but may not be entirely responsible for driving health risk. While the toxicity of the pollutant mixture may vary, PM sources are generally detrimental to health, and their reduction is a common, and important, air quality goal.

The climate impact of black carbon emission is much more complex. Because of its low albedo, BC is a strong absorber of sunlight. Although a particle rather than a gas, it is the second largest driver of climate change in today's atmosphere, following carbon dioxide (CO_2) (Bond et al., 2013). Although black carbon remains in the atmosphere for only a few days, one gram of black carbon can have a climate impact hundreds of times greater than one gram of CO_2 does over 100 years (Myhre et al., 2013). As a result, BC is classified as a short-lived climate pollutant (SLCP) – a powerful climate forcer that remains in the atmosphere for a much shorter period of time relative to CO_2.[1] Mitigation of BC and other SLCPs is often prioritized by policymakers because reductions today would lead to relatively rapid reductions in atmospheric concentrations.

Table 1 lays out the estimated climate forcing effect of black carbon emissions as quantified via both Global Warming Potential (GWP) over a 100-year period and Global Temperature Potential (GTP) of the climate state 100 years in the future as well as the uncertainty range around these values (Bond et al., 2013). Further detail on these climate forcing metrics and their application to the C-BREC model can be found in the model framework report (Carman et al., 2021) available at schatzcenter.org/cbrec/.

Table 1: Estimate of Total Climate Forcing of Black Carbon

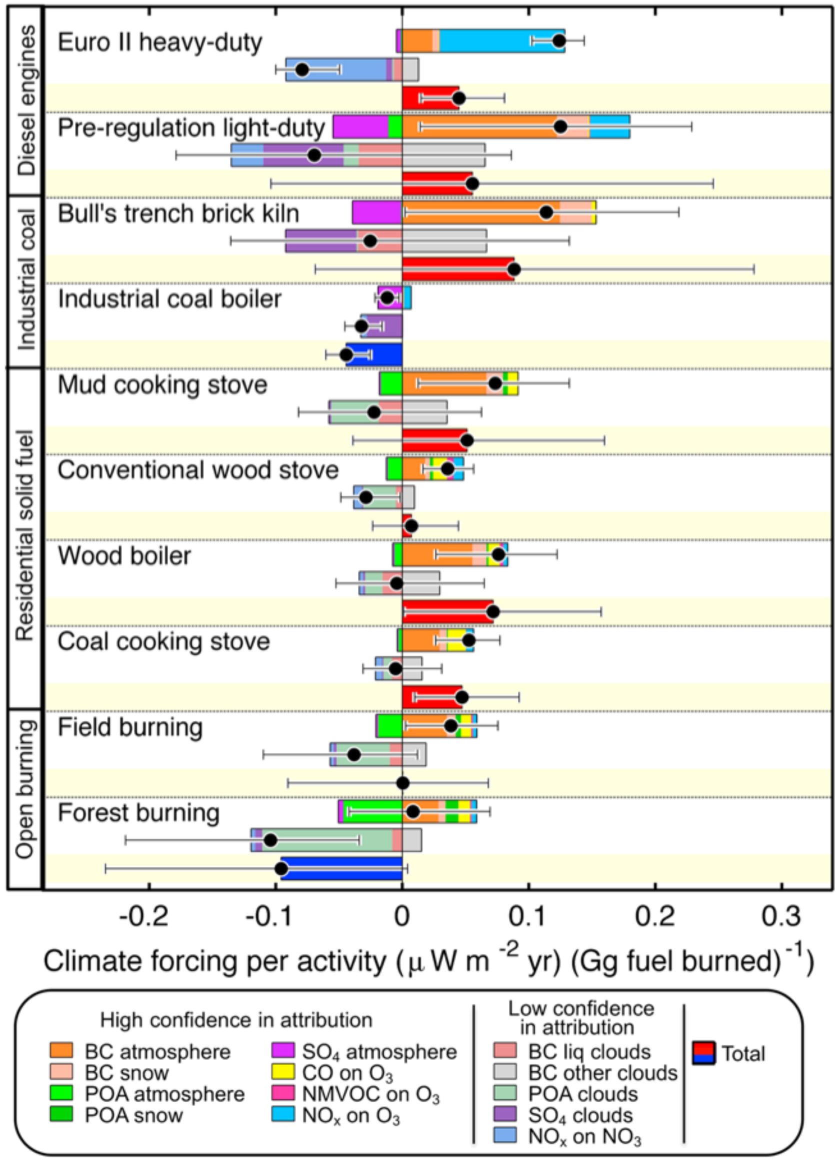
Climate forcing metric	Total climate forcing estimate	Uncertainty range
100-year GWP	900	100 – 1,700
100-year GTP	130	5 - 340

Source: (Bond et al., 2013)

Moreover, sources of BC also emit other particles and gases that impact climate, but not always in the same direction. For example, organic carbon (OC) and sulfate aerosol precursors, are typically co-emitted with BC via combustion and are known to have a net cooling effect due to their role in increasing atmospheric reflectance (Bond et al., 2013; Myhre et al., 2013). Many of these pollutants can have climate forcing effects that vary – even in its sign – based on source, location, context, and season of emissions (Bond et al., 2013). Thus, the impact of mitigating BC on climate can vary dramatically depending on the emission source and the net effect of its pollutant mixture Figure 13.

[1] Other important SLCPs include methane, tropospheric ozone, and hydrofluorocarbons.

Figure 13: Estimate of Climate Impact from Black Carbon by Source

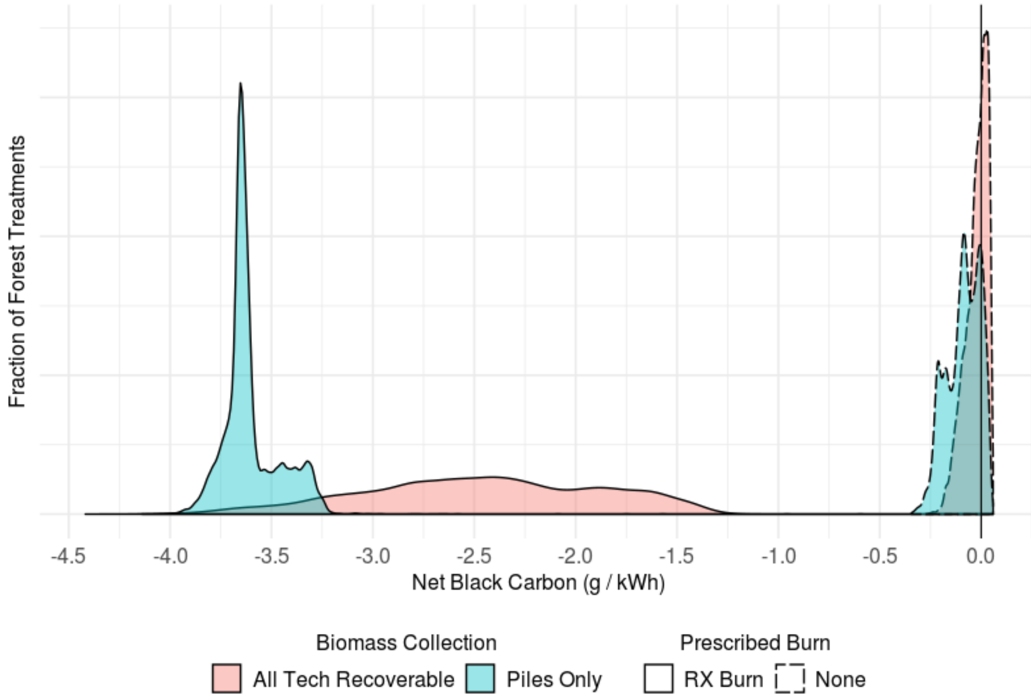


Source: (Bond et al., 2013)

It is entirely possible—especially in agricultural and forest biomass management—to reduce a source of BC while having a net warming impact due to the attendant reduction in co-occurring emissions species. Policymakers have pointed to this uncertainty as well as raising the concern that integrating the warming impact of short-lived climate forcers in carbon accounting for policy purposes could reduce the focus on CO_2 emission reduction to global detriment (Bond et al., 2013).

Because of the large uncertainties inherent in the quantification of the climate forcing effects of black carbon as well as the fact that it co-occurs in varying concentrations with climate-cooling pollutants, neither black carbon nor other particulates are included in calculations of life-cycle climate forcing in the C-BREC model. This is aligned with the existing LCA literature on biopower from woody biomass. However, unlike many existing LCA models, total net black carbon emissions are modeled. Figure 14 shows estimated net black carbon emissions. The climate impact of black carbon can be integrated into the C-BREC model pending further convergence in LCA protocols or policy guidance. As discussed earlier, black carbon is derived from $PM_{2.5}$ emissions using source-specific speciation factors (California Air Resources Board, 2016b).

Figure 14: Net 10-Year Cumulative Black Carbon Emissions



5. References

Abatzoglou, J. T. (2013). Development of gridded surface meteorological data for ecological applications and modelling. *International Journal of Climatology*, *33*(1), 121–131. https://doi.org/10.1002/joc.3413

Abatzoglou, J. T., & Brown, T. J. (2012). A comparison of statistical downscaling methods suited for wildfire applications. *International Journal of Climatology*, *32*(5), 772–780. https://doi.org/10.1002/joc.2312

Akagi, S. K., Yokelson, R. J., Wiedinmyer, C., Alvarado, M. J., Reid, J. S., Karl, T., Crounse, J. D., & Wennberg, P. O. (2011). Emission factors for open and domestic biomass burning for use in atmospheric models. *Atmos. Chem. Phys.*, *11*(9), 4039–4072. https://doi.org/10.5194/acp-11-4039-2011

Andreae, M. O., & Merlet, P. (2001). Emission of trace gases and aerosols from biomass burning. *Global Biogeochemical Cycles*, *15*(4), 955–966. https://doi.org/10.1029/2000GB001382

Andrews, P. L. (2012). Modeling wind adjustment factor and midflame wind speed for Rothermel's surface fire spread model. *Gen. Tech. Rep. RMRS-GTR-266. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 39 p.*, *266*. https://doi.org/10.2737/RMRS-GTR-266

Bond, T. C., Doherty, S. J., Fahey, D. W., Forster, P. M., Berntsen, T., DeAngelo, B. J., Flanner, M. G., Ghan, S., Kärcher, B., Koch, D., Kinne, S., Kondo, Y., Quinn, P. K., Sarofim, M. C., Schultz, M. G., Schulz, M., Venkataraman, C., Zhang, H., Zhang, S., … Zender, C. S. (2013). Bounding the role of black carbon in the climate system: A scientific assessment. *Journal of Geophysical Research: Atmospheres*, *118*(11), 5380–5552. https://doi.org/10.1002/jgrd.50171

Bond, T. C., Streets, D. G., Yarber, K. F., Nelson, S. M., Woo, J.-H., & Klimont, Z. (2004). A technology-based global inventory of black and organic carbon emissions from combustion. *Journal of Geophysical Research: Atmospheres*, *109*(D14), D14203. https://doi.org/10.1029/2003JD003697

California Air Resources Board. (2016a). *CARB Pollution Mapping Tool*. EmissionsByFacility.Csv Datafile. https://ww3.arb.ca.gov/ei/tools/pollution_map/

California Air Resources Board. (2016b). *California's Black Carbon Emission Inventory Technical Support Document, 2015 Edition*. https://ww3.arb.ca.gov/cc/inventory/slcp/slcp.htm

California Energy Commission. (2018). *QFER CEC-1304 Power Plant Owner Reporting Database*. https://ww2.energy.ca.gov/almanac/electricity_data/web_qfer/index_cms.php

Carman, J., Severy, M., Barrientos, C., Blasdel, M., Geronimo, C., Harris, A., Hsu, C.-W., Kane, J., Rios-Romero, S., Wright, M., & Fingerman, K. (2021). *California Biomass Residue Emissions*

Characterization (C-BREC) Model Framework: Version 1.2 (EPC-16-047). Schatz Energy Research Center.

Cohen, J. D., & Deeming, J. E. (1985). The national fire-danger rating system: Basic equations. *Gen. Tech. Rep. PSW-82. Berkeley, CA: Pacific Southwest Forest and Range Experiment Station, Forest Service, U.S. Department of Agriculture; 16 p*, *082*. https://doi.org/10.2737/PSW-GTR-82

Forest Climate Action Team. (2018). *California Forest Carbon Plan: Managing Our Forest Landscapes in a Changing Climate* (p. 178).

Janssen, N. A. H., Hoek, G., Simic-Lawson, M., Fischer, P., Bree, L. van, Brink, H. ten, Keuken, M., Atkinson, R. W., Anderson, H. R., Brunekreef, B., & Cassee, F. R. (2011). Black Carbon as an Additional Indicator of the Adverse Health Effects of Airborne Particles Compared with PM10 and PM2.5. *Environmental Health Perspectives*, *119*(12), 1691–1699. https://doi.org/10.1289/ehp.1003369

Kane, J. M., & Wright, M. (2020). *California Biopower Impact Project: Fire Emissions and Fuels Report* (EPC-16-047). Schatz Energy Research Center.

Larkin, N. K., O'Neill, S. M., Solomon, R., Raffuse, S., Strand, T., Sullivan, D. C., Krull, C., Rorig, M., Peterson, J., Ferguson, S. A., Larkin, N. K., O'Neill, S. M., Solomon, R., Raffuse, S., Strand, T., Sullivan, D. C., Krull, C., Rorig, M., Peterson, J., & Ferguson, S. A. (2010). The BlueSky smoke modeling framework. *International Journal of Wildland Fire*, *18*(8), 906–920. https://doi.org/10.1071/WF07086

Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.-F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T., & Zhang, H. (2013). Anthropogenic and Natural Radiative Forcing. In T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Doschung, A. Nauels, Y. Xia, V. Bex, & P. M. Midgley (Eds.), *Climate Change 2013—The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (pp. 659–740). Cambridge University Press. http://ebooks.cambridge.org/ref/id/CBO9781107415324A026

North American Black Carbon Emissions Estimation Guidelines: Recommended Methods for Estimating Black Carbon Emissions (p. 89). (2015). Commission for Environmental Cooperation.

Prichard, S. J., Ottmar, R. D., & Anderson, G. K. (2006). Consume 3.0 user's guide. *Pacific Northwest Research Station, Corvallis, Oregon*.

United States Environmental Protection Agency. (2012). *Report to Congress on Black Carbon* (EPA-450/R-12-001).

United States Environmental Protection Agency. (2021). *GHG Emission Factors Hub*. https://www.epa.gov/climateleadership/ghg-emission-factors-hub

Westerling, A. L. (2018). *Wildfire Simulations for California's Fourth Climate Change Assessment: Projecting Changes in Extreme Wildfire Events with a Warming Climate* (No.

CCCA4-CEC-2018–014; California's Fourth Climate Change Assessment, California Energy Commission, p. 57). University of California, Merced. cal-adapt.org/tools/wildfire

Appendix A: Black Carbon Speciation Values

The following table provides a literature review of black carbon speciation values as a fraction of $PM_{2.5}$ mass.

Table 2: Literature Review of Black Carbon Speciation Values

Emissions Source		BC Fraction $(\frac{m_{BC}}{m_{PM2.5}})$	Notes	Citation
Prescribed Burning	Forest Management Burning	0.202594	ID 463	(California Air Resources Board, 2016b)
		$0.02^{+0.05}_{-0.01}$	50th ± 10th and 90th %ile, Table A1-5, includes forestland, grassland, rangeland, wetland	(United States Environmental Protection Agency, 2012)
		0.095	Sourced from the SPECIATE database	(*North American Black Carbon Emissions Estimation Guidelines: Recommended Methods for Estimating Black Carbon Emissions*, 2015)
	Orchard Prunings	0.22457	ID 450	(California Air Resources Board, 2016b)
	Agricultural Burning	0.161796	ID 430, Field crops	(California Air Resources Board, 2016b)
		$0.10^{+0.03}_{-0.05}$	50th ± 10th and 90th percentile, Table A1-5	(United States Environmental Protection Agency, 2012)
		$0.12^{+0.07}_{-0.033}$	Ratio of BC and PM2.5 values, range reflects std. dev., Table S13	(Akagi et al., 2011)
		0.109	Sourced from the SPECIATE database	(*North American Black Carbon Emissions Estimation Guidelines: Recommended Methods for Estimating Black Carbon Emissions*, 2015)

Emissions Source		BC Fraction $(\frac{m_{BC}}{m_{PM2.5}})$	Notes	Citation
		$0.18^{+0.030}_{-0.036}$	Ratio of BC and PM2.5 values, agricultural residues, Table 1	(Andreae & Merlet, 2001)
Wildfire		0.2		(California Air Resources Board, 2016b)
		$0.043^{+0.082}_{-0.025}$	Ratio of BC and PM2.5 values, extratropical forests, Table 1	(Andreae & Merlet, 2001)
		$0.09^{+0.07}_{-0.06}$	50th ± 10th and 90th percentile, Table A1-5	(United States Environmental Protection Agency, 2012)
Diesel	Off-road Equipment	0.610165	ID 6209, model year 2020	(California Air Resources Board, 2016b)
	On-road trucks	0.181326	ID 6202, model year 2020, HDDT-Cruising	(California Air Resources Board, 2016b)
		0.0998 0.0861	Model year 2007+ with DPF. Both values are offered as an option. Table C-10.	(United States Environmental Protection Agency, 2012)
	Off-road HDDT	0.77	Single data point, Table A1-5, without DPF	(United States Environmental Protection Agency, 2012)
		0.1	Section A2.2.6.2, with DPF	(United States Environmental Protection Agency, 2012)
		0.109	Weighted average with and without emissions controls	(*North American Black Carbon Emissions Estimation Guidelines: Recommended Methods for Estimating Black Carbon Emissions*, 2015)

Emissions Source		BC Fraction ($\frac{m_{BC}}{m_{PM2.5}}$)	Notes	Citation
Power Plant	Wood Fired Boiler	0.14	Single data point, Table A1-5	(United States Environmental Protection Agency, 2012)
		0.033	Energy sector combustion of wood and bark waste	(*North American Black Carbon Emissions Estimation Guidelines: Recommended Methods for Estimating Black Carbon Emissions*, 2015)
		0.02	Calculated as $F_{BC} \cdot F_{cont}$. Biomass stoker, Table 5. Assumes $F_{cont} = 0.4$ for advanced emissions controls.	(Bond et al., 2004)
	Biomass gasification	Unknown	No data sources found	