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Climate and air pollution impacts of generating biopower from forest management residues in California

Kevin R Fingerman[1,2,*], Jerome Qiriazi[2], Cassidy L Barrientos[2], Max Blasdel[2], Jeffrey M Comnick[3], Andrew R Harris[2], Carisse Geronimo[1,2], Chih-Wei Hsu[1,2], Jeffrey M Kane[1], Elaine Oneil[4], Sabrinna Rios-Romero[1,2], Luke W Rogers[3], Mark Severy[5] and Micah C Wright[2]

[1] California State Polytechnic University, Humboldt, Arcata, CA, United States of America
[2] Schatz Energy Research Center, Arcata, CA, United States of America
[3] Natural Resource Spatial Informatics Group, University of Washington, Seattle, Washington DC, United States of America
[4] Consortium for Research on Renewable Industrial Materials, Corvallis, OR, United States of America
[5] Pacific Northwest National Laboratory, Richland, Washington DC, United States of America
* Author to whom any correspondence should be addressed.

E-mail: kevin.fingerman@humboldt.edu

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Abstract

California faces crisis conditions on its forested landscapes. A century of aggressive logging and fire suppression in combination with conditions exacerbated by climate change have created an ongoing ecological, economic, and public health emergency. Between commercial harvests on California's working forestlands and the increasing number of acres the state treats each year for fire risk reduction and carbon sequestration, California forests generate millions of tons of woody residues annually—residues that are typically left or burned in the field. State policymakers have turned to biomass electricity generation as a key market for woody biomass in the hope that it can support sustainable forest management activities while also providing low-carbon renewable electricity. However, open questions surrounding the climate and air pollution performance of electricity generation from woody biomass have made it difficult to determine how best to manage the risks and opportunities posed by forest residues. The California Biomass Residue Emissions Characterization (C-BREC) model offers a spatially-explicit life cycle assessment framework to rigorously and transparently establish the climate and air pollution impacts of biopower from forest residues in California under current conditions. The C-BREC model characterizes the variable emissions from different biomass supply chains as well as the counterfactual emissions from prescribed burn, wildfire, and decay avoided by residue mobilization. We find that the life cycle 'carbon footprint' of biopower from woody residues generated by recent forest treatments in California ranges widely—from comparable with solar photovoltaic on the low end to comparable with natural gas on the high end. This variation stems largely from the heterogeneity in the fire and decay conditions these residues would encounter if left in the field, with utilization of residue that would otherwise have been burned in place offering the best climate and air quality performance. California's energy and forest management policies should account for this variation to ensure desired climate benefits are achieved.

1. Introduction

Bioenergy is currently the most widely deployed renewable energy source in the world. About 47% of all renewable energy consumed globally in 2020 was bioenergy, about four times the combined contribution of wind and solar photovoltaics (REN 21 2021). In the electric power sector, solid biomass use nearly doubled between 2011 and 2021 (REN 21 2021), and is expected to grow significantly in coming decades (Reid *et al* 2020). In a 2018 Special Report, the Intergovernmental Panel on Climate Change reviewed 85 pathways to achieving a maximum warming of 1.5 °C and determined that biomass electricity systems employing carbon capture and sequestration (CCS) will need to make up a

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median of 26% of primary energy supply by 2050, in order to meet temperature targets (Rogelj *et al* 2018). We highlight these findings not to advocate for the growth of the biopower sector, but in recognition of the fact that it is likely to play a significant role in a carbon-constrained energy future, and should therefore be structured to ensure that it delivers the intended climate and environmental performance.

Concerns surrounding the climate impact of biopower, as well as other ecological impacts such as those on biodiversity and water resources, have led to a shift in attention toward the use of waste and residue materials, such as forest treatment residues rather than purpose-harvested whole trees. There is now an emergent interest in biopower as a component of sustainable forest management strategies, as it represents a use pathway for material that would otherwise decay in place or be subject to prescribed fire (Cabiyo *et al* 2021). This is particularly relevant in California, where a century of intensive logging and aggressive fire suppression in combination with conditions exacerbated by climate change have created an ongoing ecological, economic, and public health emergency (Baker *et al* 2020).

Almost a half-century of literature has established life cycle assessment (LCA) as an effective tool for evaluating the total impact of a product or action, and it is the tool commonly employed in shaping bioenergy policies to deliver climate benefit. However, there is sufficient variation in analytical methods and results from LCA studies of bioenergy from forest biomass[6] that its climate impact remains contentious (Creutzig *et al* 2015, Ter-Mikaelian *et al* 2015, Sterman *et al* 2018).

Most early LCAs of woody biopower made the simplifying assumption that CO_2 emissions from combustion of biomass ('biogenic' emissions) do not contribute to climate change because they represent a closed loop from biomass growth to combustion. Using this assumption, these studies typically found significant net reductions in greenhouse gas (GHG) emissions when biopower displaces fossil fuel-based energy. One meta-analysis of 94 LCA studies of biomass electricity systems found only one case study which accounted for the climate impact of biogenic CO_2 emission (Cherubini and Strømman 2011). This carbon neutral treatment of biogenic emissions is a continued practice in LCA research (Xu *et al* 2021) and government protocols (US EPA 2018). However, recent literature has called this assumption into question, pointing out that near-term emissions lead to increased climate forcing over policy-relevant time frames even if it is assumed that the CO_2 emitted is eventually re-sequestered in forest regrowth or, as in the case of residues, would have been emitted later by decay or wildfire (Buchholz *et al* 2016, Brack 2017, Cornwall 2017, Sterman *et al* 2018, Agostini *et al* 2020).

Emerging from this literature is the consensus that the comprehensive approach to LCA for biopower from woody residues is to quantify emissions—including biogenic emissions—from both the use of residues and their counterfactual, or 'reference,' fate. While many recent studies have done so, these typically assume that all residues not removed for biopower will decay in place (McKechnie *et al* 2011, Jäppinen *et al* 2014, Gustavsson *et al* 2015, Giuntoli *et al* 2016, Madsen and Bentsen 2018) and that this decay will occur at a single rate regardless of residue type or location (Gustavsson *et al* 2015, Giuntoli *et al* 2016, Madsen and Bentsen 2018). This ignores the potential for in-field burning, either through a prescribed burn aimed at waste management or by wildfire (Ter-Mikaelian *et al* 2015, Buchholz *et al* 2016). In the few studies that have incorporated a burn counterfactual, it is typical to assume that the biomass is completely consumed through prescribed burning, leading to instantaneous emission of all carbon present, plus additional forcing from a fixed amount of methane and nitrous oxide release (Springsteen *et al* 2011, Miner *et al* 2014, Liu and Rajagopal 2019). This simplified approach fails to account for the fact that a fraction of biomass will remain unconsumed, and that some material undergoes thermally-driven changes that result in the formation of recalcitrant char material. Further, it does not capture the spatial and material-driven variation in combustion and decay dynamics (Ter-Mikaelian *et al* 2015).

This paper introduces the California Biomass Residue Emissions Characterization (C-BREC) model, a LCA tool that enables transparent accounting for the GHG and criteria air pollutant emissions associated with biopower generation from forest residues in the state of California under current technological, infrastructural, and ecological conditions. It improves on existing LCA approaches by capturing the significant spatial variability in life cycle emissions owing to differences in residue characteristics and climatic conditions which significantly influence decay processes and fire behavior. This aligns with an emerging recognition that geospatial techniques should play a key role in LCA of many bioenergy systems (van der Hilst 2018, Cabiyo *et al* 2021). Additionally, it is becoming increasingly clear that the timing of emissions must be considered in life cycle GHG accounting (Helin *et al* 2013, Buchholz *et al* 2016, Reid *et al* 2020). C-BREC applies time-explicit climate metrics in alignment with guidance put forth by United Nations Environment Programme and the Society for Environmental Toxicology and Chemistry

[6] The term 'biomass' refers generally to organic material, and specifically here to woody material that can be burned or otherwise converted to create electricity. Forest biomass residue typically includes the small-diameter treetops and branches that are not part of the merchantable portion of the whole tree.

(Levasseur *et al* 2016) and taken up by ISO standard for LCA (ISO 14067:2018 2018).

2. Methods

This section describes the methods used in the C-BREC model and the study presented here. More detail on every facet of the model, including its structure, assumptions, and underlying data, can be found in the C-BREC model framework available at http://schatzcenter.org/cbrec/. To evaluate the emissions associated with a forest residue-to-electricity system, C-BREC requires that key system characteristics be specified. These include the location of residue generation, the type of forest treatment activity being conducted, the reference fate of unremoved biomass (pile burned, broadcast burned, or left in place), and key supply chain characteristics such as biomass removal level, location of biopower generation, and end-use energy conversion technology. For a given biomass energy supply chain, the C-BREC model quantifies the emissions associated directly with a 'use' case in which biomass residues are removed from the field for use in biopower generation, and a 'reference' case representing their fate if not removed. The net emissions of the biopower system is the difference between these two fates for the same material. C-BREC reports gross and net emission profiles over a 100 year period for GHGs and criteria air pollutants[7]. Pollutant species tracked include the following: carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4), nitrous oxide (N_2O), volatile organic compounds (VOCs), oxides of nitrogen (NO_x), sulfur dioxide (SO_2), particulate matter (PM_{10} and $PM_{2.5}$), and black carbon.

2.1. Characterization of biomass residue base

To characterize the residue base generated by California forest management, C-BREC categorizes forest treatments into 13 different types, capturing the large majority of forestry activities practiced in California. The treatment activities modeled are:

- Clearcut.
- Thin from below (selecting for smaller-diameter trees) removing 20%, 40%, 60%, and 80% of total tree basal area.
- Thin from above (selecting for larger-diameter trees) removing 20%, 40%, 60%, and 80% of total tree basal area.
- Proportional thin (select equally across small and large diameter trees) removing 20%, 40%, 60%, and 80% of total tree basal area.

[7] These are the emission species regulated and tracked under the Clean Air Act and for which the U.S. Environmental Protection Agency establishes National Ambient Air Quality Standards.

For each of the above forest harvest activity types, we characterized the biomass residue—divided by species and size class—at 30 m spatial resolution. This modeling drew on tree list inventory data (Ohmann 2002), the US Forest Service's Forest Vegetation Simulator (Dixon 2022), and tree component ratios from (Jenkins *et al* 2003) and USFS (Bechtold and Patterson 2005). Using this dataset, C-BREC characterizes the residue base for any of the above treatments on any treatment polygon on California's forested landscape.

2.2. Scope and system boundary

A central assumption underpinning the C-BREC analytical framework is that the residual material being consumed is a true waste in that it would not have been used at all were it not mobilized for bioenergy. As such, it is assumed that the residues are not a driver of the primary forestry activity. Therefore, the utilization of the residues is not allocated any of the upstream emissions or sequestration associated with those activities, including any ongoing changes to forest carbon stock or flows that results from the primary treatment activity in question. This is aligned with the LCA practice of coproduct allocation on the basis of value fraction (Ardente and Cellura 2012). Since residues typically represent none of the net revenue derived from the primary forestry activity in today's wood products market (Swezy *et al* 2021), they are allocated none of those upstream emissions. Additionally, C-BREC intentionally does not account for avoided emissions from displaced electricity generation, which is a function of local and regional power system economics and policies. This enables direct comparison to other sources of electricity such as natural gas, solar, and wind.

2.3. Residue mobilization and use

Mobilization and use of biomass residues for electricity generation are characterized across the following three steps:

- *Collection and Processing*: This includes emissions from fuel use associated with transporting equipment, gathering, handling, and loading the residues to the processing stage followed by comminution, hauling to a transfer point, then loading onto hauling equipment. Variable emissions are a function of parameters such as terrain steepness, residue density (tons per acre), and residue type. Removal of 30%, 50%, and 70% of total biomass resource are modeled.
- *Transportation*: Round-trip travel of hauling processed residues between the transfer point and the power plant. C-BREC can allocate residue to any operational biomass power facility in the state, or to a notional facility given the proposed facility's location. The vehicle type used for a given harvest is a function of residue type, amount, and

ease of access. Emissions from transportation vary by vehicle type and depend on the distance to the power plant. Hauling trips are either volume or weight-limited based on moisture content.

- *Energy Conversion*: Specifications of existing power plants in California are based on data reported to the California Energy Commission and California Air Resources Board. Emissions are based on a specific existing generator or one of a set of 'generic' facility types—current generation combustion plant, next generation integrated gasification/combustion plant, next-generation thermochemical gasification facility, and small (<1 MW) mobile gasifier/generator.

2.4. Residue counterfactual fate

2.4.1. Emissions from decay

As is typical in the LCA literature on solid biomass (Gustavsson *et al* 2015, Giuntoli *et al* 2016, Madsen and Bentsen 2018) C-BREC characterizes decay using a negative exponential model (Olson 1963). However, unlike most other studies, we vary the rate of that decay across the landscape by species, size class and disposition, and climatic factors (Blasdel 2020).

We developed a database of decay constants that vary by species and size class from empirical studies and meta-analyses of decay (see e.g. Mackensen and Bauhus 1999, Yin 1999, Laiho and Prescott 2004, Weedon *et al* 2009). We then varied these baseline decomposition rates by size class and between scattered and piled material (Wagener and Offord 1972, Erickson *et al* 1985, Edmonds *et al* 1986). Finally, we applied a climate modifier for decay as a function of temperature and moisture based on a variation of the Demeter equations for climate effects (adapted from Foley 1995). All else being equal, decay is more rapid in smaller diameter material, in contact with the ground, and in wetter, warmer conditions. Detail on the modeling of decay can be found in Blasdel (2020).

2.4.2. Emissions from fire

Emissions from residue consumption by prescribed fire (pile burn or broadcast burning of scattered residue) and wildfires are modeled using the 'activity' fuels equations from the Consume software, version 4.2, created by the U.S. Forest Service (Prichard *et al* 2006). These equations provide estimates of fuel consumption for each size class, weighted by combustion phase: flaming, smoldering, and residual. The consumption estimates are then multiplied by emission factors specific to each pollutant species (e.g. CO, CO_2, CH_4) taken from the Bluesky modeling framework (Larkin *et al* 2010).

We model the emissions from a wildfire if one were to occur on the landscape in each of the next 100 years—both with and without woody residues left on the forest floor. Because it is not possible to predict when a fire will occur at a given site, the C-BREC model characterizes expected emissions from wildfire at each location in each year by taking the product of the emissions from a wildfire in that year and the probability of it occurring—each of which changes over time. This quantifies the expected annual emissions from wildfire *on average,* which is accurate at a landscape scale, but will necessarily differ from actual emissions at any specific site. Current and projected future wildfire probability across California is derived from the Cal-Adapt dataset (Westerling 2018).

2.4.3. Accounting for time

Biopower emissions occur in one pulse at roughly the time of primary treatment, whereas the emissions associated with the reference fate of the biomass may occur slowly over decades of biomass decay or in some future year via wildfire. Just as financial accounting must consider the time value of money in comparing expenses or revenues at different points in time, LCA can account for the 'time value' of emissions or sequestration over time in terms of their differing climate forcing effects over policy-relevant timescales.

The C-BREC model uses an 'emissions scenario' approach as described by the Intergovernmental Panel on Climate Change (Myhre *et al* 2013), elaborated on by (Aamaas *et al* 2012), and implemented in several publications related to the emissions profile of biomass energy (e.g. Giuntoli *et al* 2015). The result is a time-explicit 100 year absolute global warming potential (AGWP) profile that approximates the global aggregate radiative forcing associated with the emissions profile generated by the C-BREC model. The model uses these to calculate the mass of CO_2 equivalent (CO_2e) emissions for reporting all emissions on a uniform basis—that is the equivalent mass of CO_2 emitted in year one that would yield the same AGWP as of year 100. This mirrors the approach taken by the Intergovernmental Panel on Climate Change in its calculation of CO_2 equivalent GWP values for different GHGs, except applied across time as well as across emission species. It also mirrors the approach taken in calculating GWPbio values for biogenic emissions (Liu *et al* 2017), but applied in a case-specific manner.

3. Results

This study applies the C-BREC model to the forest treatment activities conducted in California in the years 2016–2019 (figure 1) to investigate the net GHG and air pollution emissions that would have resulted had the residues of those treatments been mobilized for biomass electricity generation.

Figure 2 demonstrates the relative contribution of the different emission sources to reference and use-case emissions and how these vary by collection and burn scenario as well as across different climate zones in California. Use-case emissions from residue mobilization and power generation are arrayed above

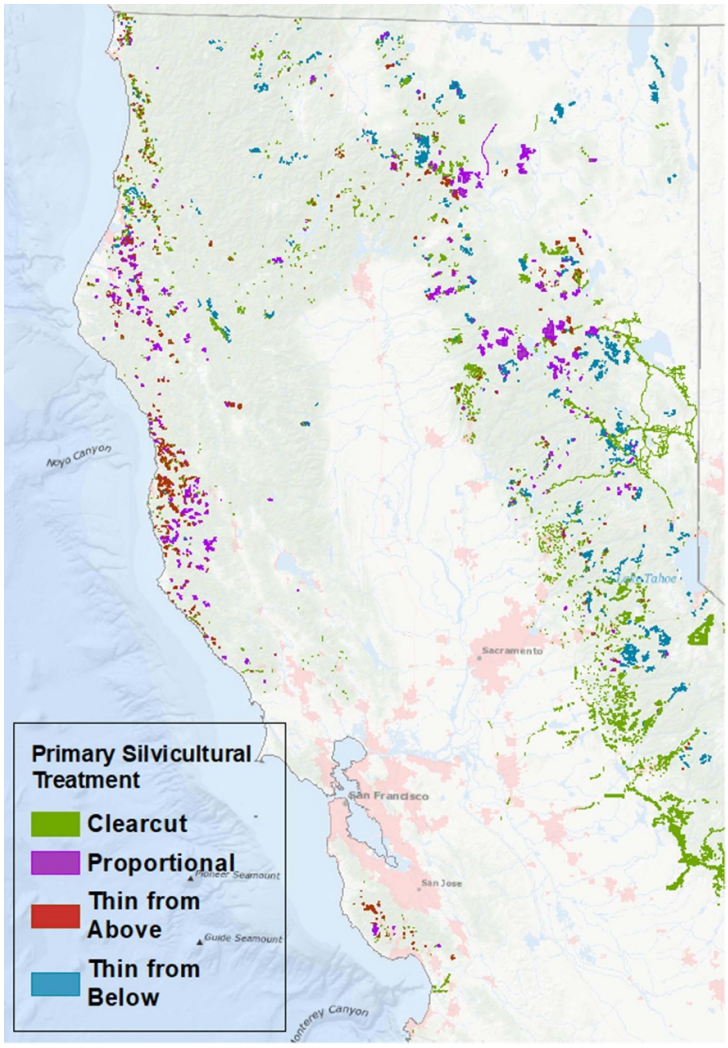


Figure 1. Forest treatments in California 2016–2019. The 11 035 individual forest treatment activities that make up the case study detailed in this paper. This map focuses on the northern region of California as it contains the majority of the working forests in the state and therefore almost all of the treatments evaluated for this study.

the *x*-axis, where reference-case emissions from the counterfactual fate of the same biomass are arrayed below the *x*-axis as these represent 'negative' emissions, avoided by residue mobilization. The difference between the two cases is net emission from biopower generation and is indicated by the black point in each column.

3.1. Net climate impact varies greatly by reference fate and location

The carbon intensity of biopower generation from forest residues varies across system characteristics such as forest treatment type, residue disposition, transport distance, and power plant technology as well as geographic characteristics such as residue species, decay rate, and wildfire probability. To explore key variables, the following figures are based on C-BREC model runs assuming a uniform base case of biopower system configuration. Unless otherwise noted, these runs assume biopower to be generated 50 km from the feedstock source and using a combustion plant of statewide average efficiency without combined heat and power (CHP) capability. Emission time series are normalized to CO_2e using 100 year GWP equivalencies as this is the common analytical framework in California policy structures.

While the actual fate of woody residues from recent forest treatments is not known, figure 3 displays the carbon intensity of the resultant electricity if they had been mobilized for power generation. It is clear that a major driver of the net carbon footprint of biopower from woody residues is the counterfactual (or 'reference') fate of the biomass—that is, whether it would have been burned or left to decay on site. This is because these figures are reported on a 100 year GWP basis, meaning that the delay in CO_2 emissions from residues left in the field to decay results in a lower CO_2e in the reference case than if those same materials had been burned in place.

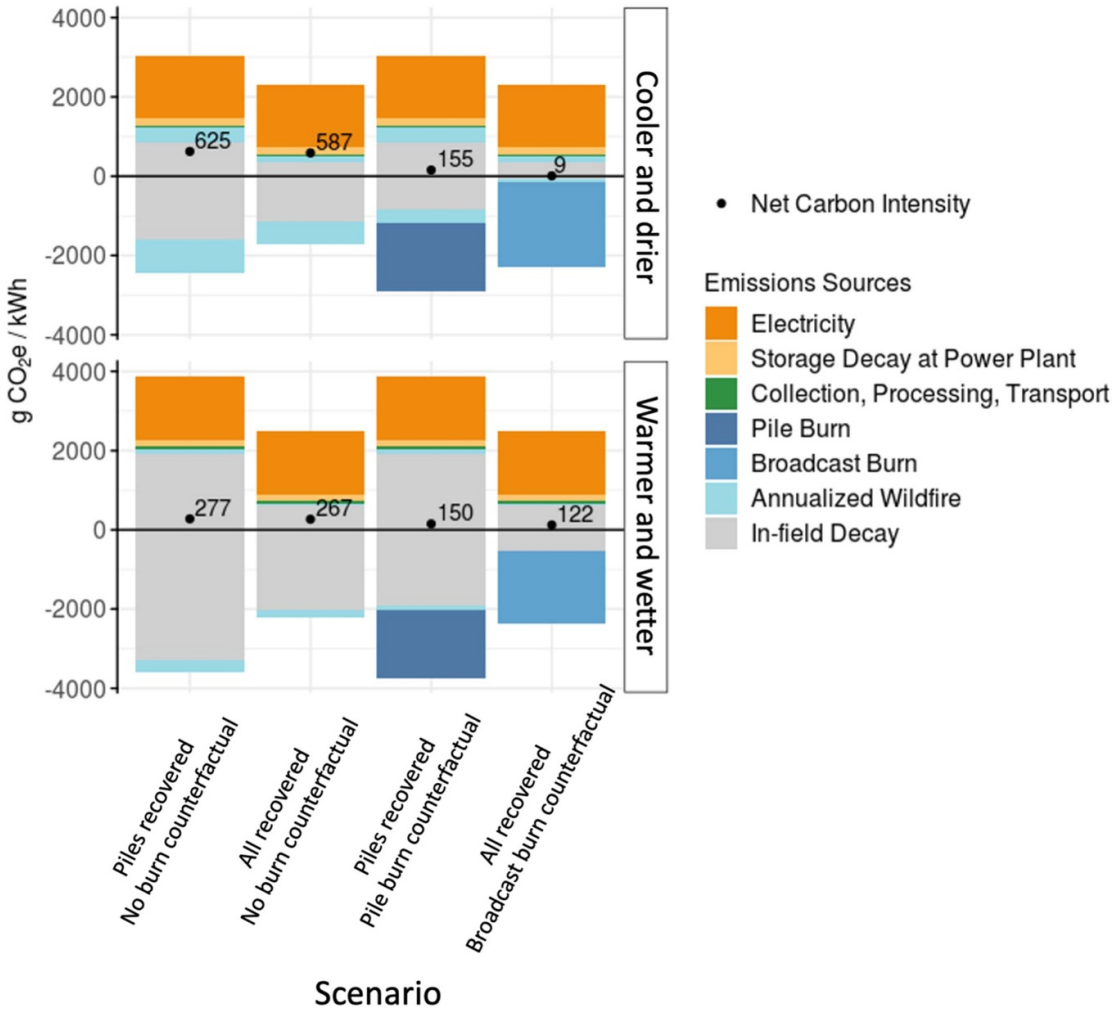


Figure 2. Example emissions from each source for four collection and burn scenarios in both use case (above the *x*-axis) and reference case (below the *x*-axis) at two individual treatment sites in California representative of different climatic zones. Net emissions (black points in each column) from biopower generation represent the difference between the two cases. All emissions are in present-day CO_2e, normalized based on 100 year GWP.

The shapes of the distributions displayed in figure 3 are instructive. Scenarios in which only piled material would be collected, and a pile burn is therefore the reference fate, exhibit the least variability because pile burns are relatively uniform in their combustion dynamics. Broadcast burning and decay, on the other hand, are more sensitive to the spatial variability of climate and material-type.

In addition, long 'tails' are evident, especially for residues with no prescribed burn reference fate. These outlier treatments are predominantly those with very low total residue base and/or very low residue density. In such cases, the fixed emissions associated with mobilizing collection equipment to field locations can become a dominant source of emissions since they are distributed across a very small number of total kWh. These outlier cases are likely not logistically or economically viable for residue mobilization.

The variation within each of the curves displayed in figure 3 is driven by factors that vary geographically, such as the species and size class characteristics of the residue base as well as the climatic drivers of decay and wildfire emissions. Mapping the net emissions from biomass use (figure 4) allows these geographic variations to be assessed.

Figure 4(a) displays the range in carbon intensity of biopower generation from forest treatment residue if that residue would otherwise have been subject to a prescribed burn. The spread in carbon intensity stems primarily from variation in emissions from prescribed burning owing to residue species, size class distribution, and climate (i.e. fuel moisture). Figure 4(b) displays the range in carbon intensity of biopower from residues of the same treatments if those residues would otherwise have been left in place, subject to decay and a subsequent wildfire. The spread in carbon intensity stems primarily from climatic and residue-type variables driving differing decay rates and wildfire probability.

3.2. Air quality impacts of mobilizing woody biomass

Beyond GHGs, we also investigated the net emissions of VOCs, carbon monoxide (CO), oxides of nitrogen

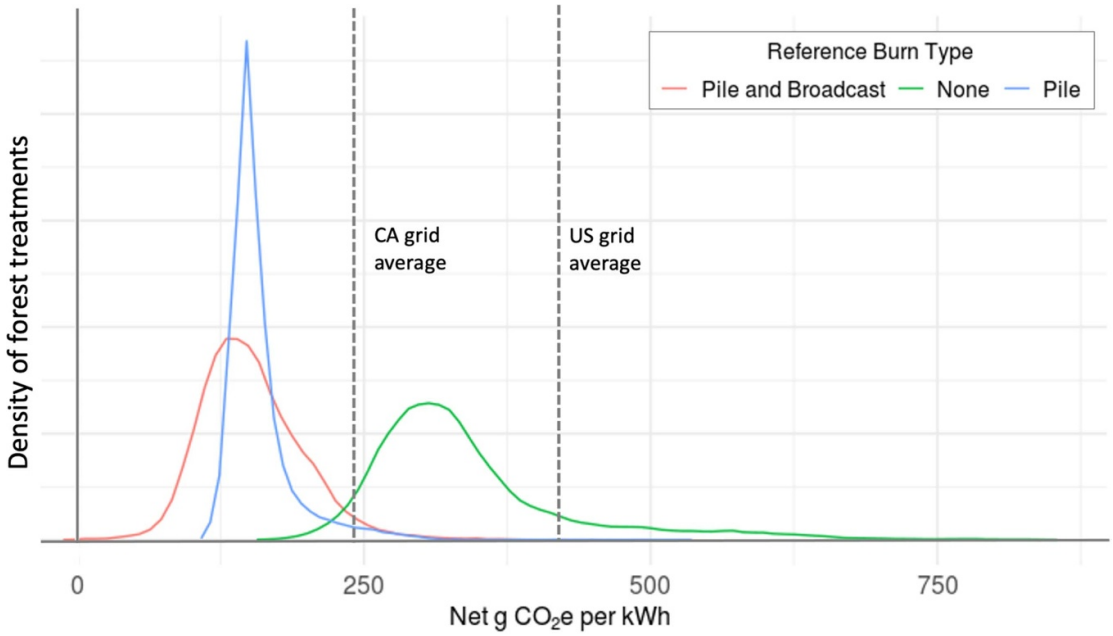


Figure 3. Distribution of carbon intensity results (net g CO_2e kWh^{-1}) across the California recent treatments case study, disaggregated to illustrate the difference across reference case prescribed burn scenarios. These distributions are smoothed histograms, with carbon intensity displayed on the horizontal axis and relative prevalence of a given range of results represented on the vertical axis. Grid average values are on a life-cycle basis and are derived from Chen and Wemhoff (2021).

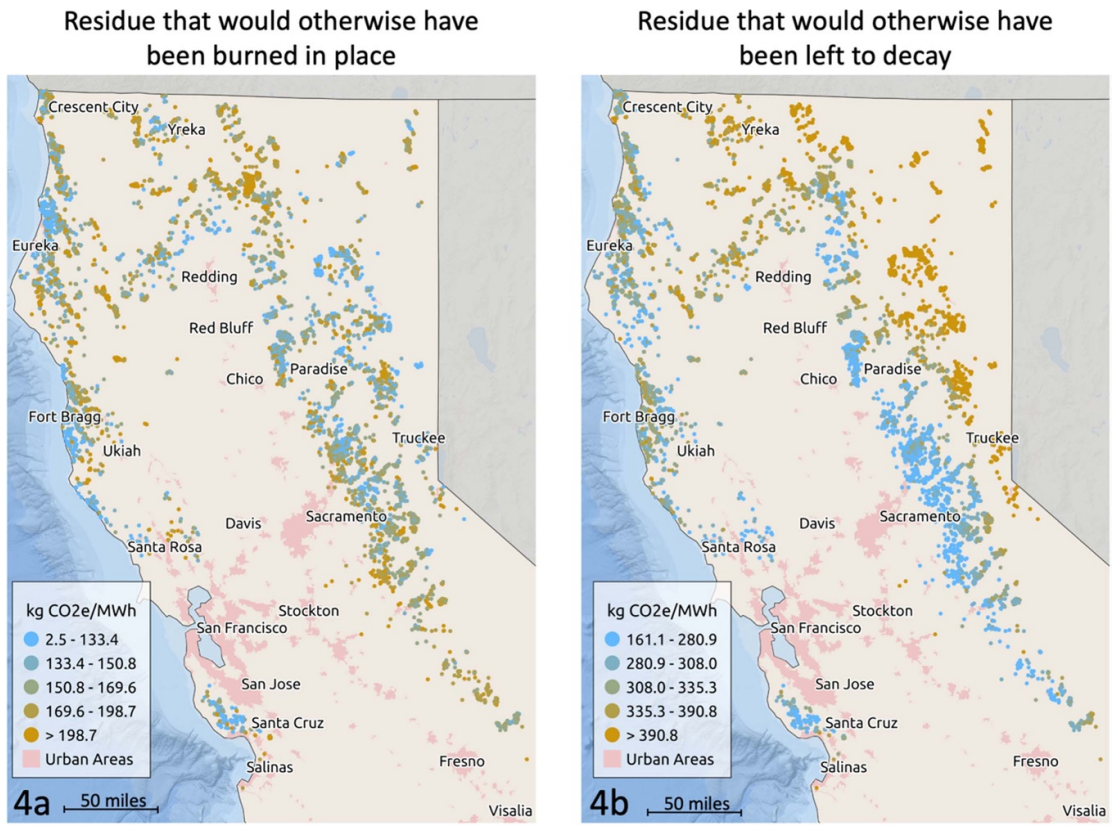


Figure 4. Carbon intensity of biopower from residues of recent forest treatments in Northern California. These demonstrate the spatial variation of carbon intensities (within each map) as well as how net carbon intensity is influenced by the counterfactual fate of residues (across the two maps).

(NO_x), sulfur dioxide (SO_2), and particulate matter (both $PM_{2.5}$ and PM_{10}). We find that mobilizing forestry residues for biopower generation typically leads to a reduction in cumulative mass of emissions per ton of residue for most criteria air pollutants. Figure 5 shows this effect across four key criteria

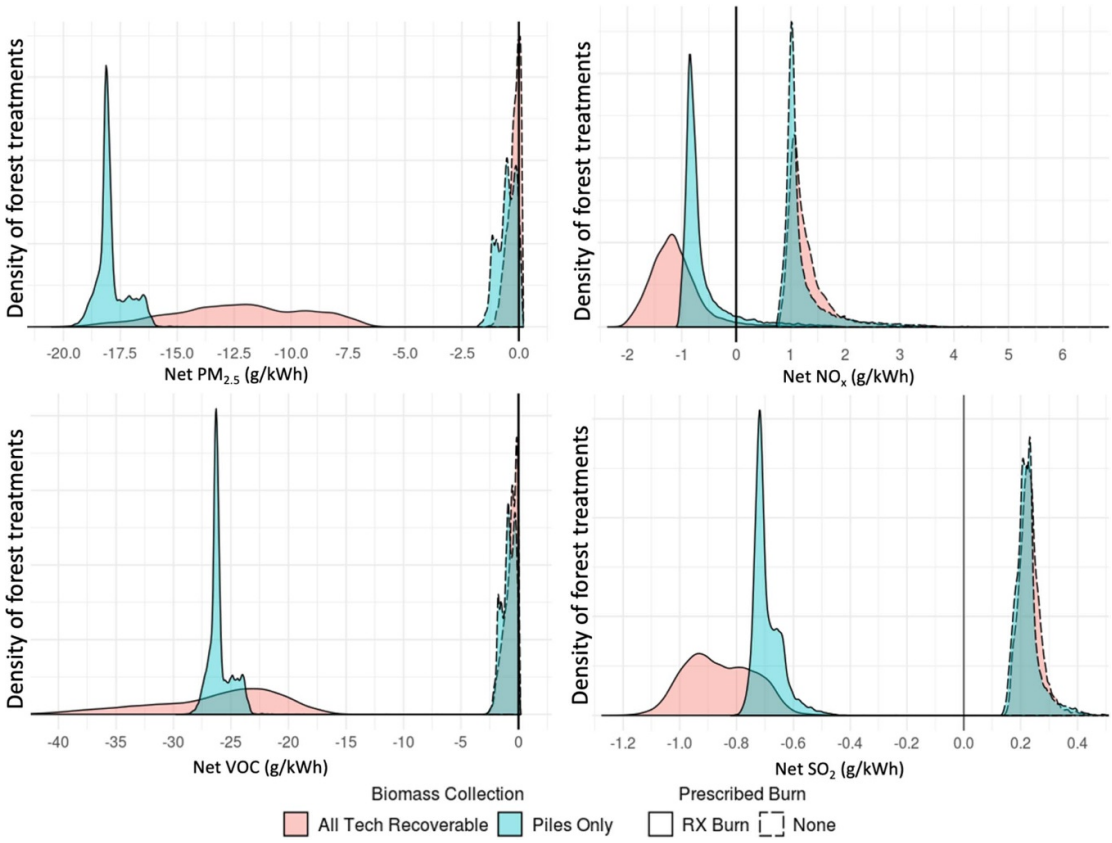


Figure 5. Net 10 year cumulative emissions of $PM_{2.5}$, NO_x, VOCs, and SO_x across the California recent treatments case study, disaggregated to illustrate the difference across reference case burn scenarios.

pollutants. The reduction in emissions is unsurprisingly strongest for biomass that 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 criteria pollutant emissions from a ton of biomass are significantly reduced compared to burning that same ton in the field. Where residues would otherwise have been left in the field to decay rather than subjected to a prescribed burn, mobilization for biopower generation generally yields slightly lower PM and VOC emissions over 10 years (because of probabilistic exposure to wildfire), but higher emissions of SO_2 and NO_x, owing to fossil fuel consumption in the bioenergy supply chain.

4. Discussion and conclusions

We find that the primary drivers of climate and air quality performance of biopower from forest residuals are the counterfactual fate of the biomass in question and the climatic conditions of the landscape from which it was harvested. Biopower generated from residues that would otherwise have been burned on site consistently has a lower climate impact over 100 years than if those residues would otherwise have remained in place. In addition, mobilizing residues from regions—such as northwestern California and the western Sierra Nevada range—where a moist climate facilitates relatively rapid decay of residues left in place leads to lower-carbon biopower than residues from other regions. Finally, more efficient supply chains, where residues can be used nearby their source, by efficient generators, and without long-term open-air storage offer improved climate performance.

We find there to be almost no circumstances under business-as-usual conditions in which biopower from woody residues has a zero or net negative carbon intensity, with the possible exception of a facility employing efficient CHP or CCS, though these pathways are outside the scope of this analysis. The avoided emissions of CH_4 and N_2O that can emerge from prescribed burns are typically more than offset by the fossil carbon emerging from a biopower supply chain, and the fact that prescribed burns do not combust the residue as completely as a biopower system can. However, biopower does not need to have a negative carbon footprint to offer a benefit in some circumstances; there are very few products or processes in existence that can claim a negative carbon intensity.

The air quality benefits offered by mobilizing residues that would otherwise have been burned in the field may be substantial and should be considered alongside climate, wildfire, and ecosystem impact.

While mobilization of residues typically reduces the total mass of particulates emitted per metric ton of residue, it also aggregates this emission to a point source, and one that may be closer to human populations. This paper does not evaluate the human exposure to these pollutants, nor the equity of distribution of that health burden across populations. This is an important area for future research that will be enabled by the modeling tools and datasets developed under this project.

This analysis does not account for carbon emissions or sequestration implications of the primary treatment activity that yields the woody residues in question. This is because under current market conditions, payment for residues is not driving those activities. If biomass removal is a necessary part of forest management activities that reduce fire risk or improve the carbon storage on the landscape or both, biopower that facilitates these activities by offering an outlet for residues could provide further climate benefit not quantified here. However, these benefits do not accrue uniquely to biomass electricity, future research and policy should consider alternate uses such as biochar, liquid fuels, or durable wood products that may provide stronger climate performance alongside or as an alternative to biopower generation.

Most policies that support biopower are predicated on the assertion that the pathways being promoted offer a climate benefit compared to a scenario in which this biopower was not produced. The C-BREC model has shown that the climate performance of biopower from forest residues is highly variable across supply chains, feedstock types, and geographies in California. It is therefore incumbent upon policymakers in California and elsewhere to design biopower and woody residue utilization policies that prioritize pathways offering the intended climate and/or other environmental and human benefits. For example, biopower supports under California's BioMAT and BioRAM programs, aimed at creating a market for residues from forest treatment activities, could be structured to ensure or to preferentially support supply chains that offer the most climate and/or air quality benefit. In addition, California's low-carbon fuel standard (LCFS) is structured to deliver a financial incentive to fuel producers based on the life-cycle climate impact of fuel pathways. LCFS evaluation of any pathways delivering transportation fuels derived from woody biomass should take into account the spatial and supply-chain variability in both reference and use-case emissions revealed by this analysis.

The C-BREC model can be useful in shaping the biomass energy system and other uses for woody residues, enabling activities to be targeted where they offer the greatest benefit. In particular, it can:

- Identify the geographic locations and forest treatment types in which utilization of residues offers the greatest climate and air pollution benefit in order to structure incentives accordingly.
- Aid in shaping residue mobilization and conversion supply chains to minimize emissions by identifying what improvements will offer the greatest life cycle emissions reduction potential.
- Provide project-level analysis for policies aiming to reduce GHG emissions from California's forestlands and energy systems.

Future work can expand the findings and utility of this analysis by extending the C-BREC analytical framework. For example, using C-BREC's criteria pollutant emission profiles to evaluate human exposures would enable us to evaluate the human health burden associated with these emissions or the equity of the distribution of this burden. Expanding C-BREC to other end uses of woody biomass such as liquid fuels, biochar, bioenergy with CCS (BECCS), or durable wood products is ongoing, and will enable it to support integrated analysis and policy in the broader forest practice and wood products space.

5. Code implementation

The open-source C-BREC model is built using the R programming language and is available on GitHub. A limited version of the model is available for exploration via an interactive web tool. The web tool allows a user to identify a specific project area in California and specify the key project characteristics for the use and reference fates, producing a report of biomass residue harvested, electricity generation, and net emissions. Links to the webtool and the GitHub repository for the model code and can be found at schatzcenter.org/cbrec/.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://schatzcenter.org/cbrec.

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ORCID iD

Kevin R Fingerman https://orcid.org/0000-0002-0860-8868

References

Aamaas B, Peters G P and Fuglestvedt J S 2012 A synthesis of climate-based emission metrics with applications *Earth Syst. Dyn. Discuss.* **3** 871–934

Agostini A, Giuntoli J, Marelli L and Amaducci S 2020 Flaws in the interpretation phase of bioenergy LCA fuel the debate and mislead policymakers *Int. J. Life Cycle Assess.* **25** 17–35

Ardente F and Cellura M 2012 Economic allocation in life cycle assessment *J. Ind. Ecol.* **16** 387–98

Baker S E *et al* 2020 *Getting to Neutral: Options for Negative Carbon Emissions in California* (Livermore, CA: Lawrence Livermore National Lab (LLNL))

Bechtold W and Patterson P L 2005 The enhanced forest inventory and analysis program—national sampling design and estimation procedures *Gen. Tech. Rep. SRS-80* (Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station) vol 85 pp 080

Blasdel M 2020 Decay of woody residues as the counterfactual treatment to mobilization for bioelectricity generation *Thesis* (Humboldt State University) (available at: https://digitalcommons.humboldt.edu/etd/420)

Brack D 2017 *The Impacts of the Demand for Woody Biomass for Power and Heat on Climate and Forests* (available at: www.chathamhouse.org/2017/02/impacts-demand-woody-biomass-power-and-heat-climate-and-forests) (Accessed 27 March 2021)

Buchholz T, Hurteau M D, Gunn J and Saah D 2016 A global meta-analysis of forest bioenergy greenhouse gas emission accounting studies *GCB Bioenergy* **8** 281–9

Cabiyo B, Fried J S, Collins B M, Stewart W, Wong J and Sanchez D L 2021 Innovative wood use can enable carbon-beneficial forest management in California *Proc. Natl Acad. Sci.* **118** e2019073118

Chen L and Wemhoff A P 2021 Predicting embodied carbon emissions from purchased electricity for United States counties *Appl. Energy* **292** 116898

Cherubini F and Strømman A H 2011 Life cycle assessment of bioenergy systems: state of the art and future challenges *Bioresour. Technol.* **102** 437–51

Cornwall W 2017 The burning question *Science* **355** 18–21

Creutzig F *et al* 2015 Bioenergy and climate change mitigation: an assessment *GCB Bioenergy* **7** 916–44

Dixon G E 2022 *Essential FVS: A User's Guide to the Forest Vegetation Simulator* Internal Report (Fort Collins, CO: U. S. Department of Agriculture, Forest Service)

Edmonds R L, Vogt D J, Sandberg D H and Driver C H 1986 Decomposition of Douglas-fir and red alder wood in clear-cuttings *Can. J. For. Res.* **16** 822–31

Erickson H E, Edmonds R L and Peterson C E 1985 Decomposition of logging residues in Douglas-fir, western hemlock, Pacific silver fir, and ponderosa pine ecosystems *Can. J. For. Res.* **15** 914–21

Foley J A 1995 An equilibrium model of the terrestrial carbon budget *Tellus* B **47** 310–9

Giuntoli J, Agostini A, Caserini S, Lugato E, Baxter D and Marelli L 2016 Climate change impacts of power generation from residual biomass *Biomass Bioenergy* **89** 146–58

Giuntoli J, Caserini S, Marelli L, Baxter D and Agostini A 2015 Domestic heating from forest logging residues: environmental risks and benefits *J. Clean. Prod.* **99** 206–16

Gustavsson L, Haus S, Ortiz C A, Sathre R and Truong N L 2015 Climate effects of bioenergy from forest residues in comparison to fossil energy *Appl. Energy* **138** 36–50

Helin T, Sokka L, Soimakallio S, Pingoud K and Pajula T 2013 Approaches for inclusion of forest carbon cycle in life cycle assessment—a review *GCB Bioenergy* **5** 475–86

ISO 14067:2018 2018 *Greenhouse Gases—Carbon Footprint of Products—Requirements and Guidelines for Quantification* (Geneva: International Organization for Standardization) (available at: www.iso.org/standard/71206.html)

Jäppinen E, Korpinen O-J, Laitila J and Ranta T 2014 Greenhouse gas emissions of forest bioenergy supply and utilization in Finland *Renew. Sust. Energ. Rev.* **29** 369–82

Jenkins J C *et al* 2003 National-scale biomass estimators for United States tree species *For. Sci.* **49** 12–35

Laiho R and Prescott C E 2004 Decay and nutrient dynamics of coarse woody debris in northern coniferous forests: a synthesis *Can. J. For. Res.* **34** 763–77

Larkin N K, O'Neill S M, Solomon R, Raffuse S, Strand T, Sullivan D C, Krull C, Rorig M, Peterson J and Ferguson S A 2010 The BlueSky smoke modeling framework *Int. J. Wildland Fire* **18** 906–20

Levasseur A *et al* 2016 Greenhouse gas emissions and climate change impacts *Global Guidance for Life Cycle Impact Assessment Indicators* (Paris: United Nations Environment Programme)

Liu B and Rajagopal D 2019 Life-cycle energy and climate benefits of energy recovery from wastes and biomass residues in the United States *Nat. Energy* **4** 700–8

Liu W, Zhang Z, Xie X, Yu Z, von Gadow K, Xu J, Zhao S and Yang Y 2017 Analysis of the global warming potential of biogenic CO_2 emission in life cycle assessments *Sci. Rep.* **7** 39857

Mackensen J and Bauhus J 1999 The decay of course woody debris *National Carbon Accounting System Technical Report* 6 (Canberra: Australian Greenhouse Office)

Madsen K and Bentsen N S 2018 Carbon debt payback time for a biomass fired CHP plant—a case study from Northern Europe *Energies* **11** 807

McKechnie J, Colombo S, Chen J, Mabee W and MacLean H L 2011 Forest bioenergy or forest carbon? Assessing trade-offs in greenhouse gas mitigation with wood-based fuels *Environ. Sci. Technol.* **45** 789–95

Miner R A *et al* 2014 'Forest carbon accounting considerations U S Bioenergy Policy' *J. Forestry* **112** 591–606

Myhre G *et al* 2013 Anthropogenic and natural radiative forcing *Climate Change 2013—The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* ed T F Stocker *et al* (Cambridge: Cambridge University Press) pp 659–740 (available at: http://ebooks.cambridge.org/ref/id/CBO9781107415324A026)

Ohmann J 2002 'Predictive mapping of forest composition and structure with direct gradient analysis and nearest neighbor imputation in coastal Oregon, U.S.A.' *Can. J. For. Res.* **32** 725–41

Olson J S 1963 Energy storage and the balance of producers and decomposers in ecological systems *Ecology* **44** 322–31

Prichard S J, Ottmar R D and Anderson G K 2006 *Consume 3.0 User's Guide* (Corvallis, OR: Pacific Northwest Research Station)

Reid W V, Ali M K and Field C B 2020 The future of bioenergy *Glob. Change Biol.* **26** 274–86

REN 21 2021 *Renewables 2021 Global Status Report* (Paris: REN 21 Secretariat) (available at: www.ren21.net/wp-content/uploads/2019/05/GSR2021_Full_Report.pdf) (Accessed 26 October 2022)

Rogelj J et al 2018 Mitigation pathways compatible with 1.5 °C in the context of sustainable development *Global Warming of 1.5 °C. An IPCC Special Report on the Impacts of Global Warming of 1.5 °C above Pre-industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty* ed V Masson-Delmotte *et al* (Paris: IPCC/WMO) pp 93–174 (available at: www.ipcc.ch/site/assets/uploads/sites/2/2019/05/SR15_Chapter2_Low_Res.pdf)

Springsteen B, Christofk T, Eubanks S, Mason T, Clavin C and Storey B 2011 Emission reductions from woody biomass waste for energy as an alternative to open burning *J. Air Waste Manage. Assoc.* **61** 63–68

Sterman J D, Siegel L and Rooney-Varga J N 2018 Does replacing coal with wood lower CO_2 emissions? Dynamic lifecycle analysis of wood bioenergy *Environ. Res. Lett.* **13** 015007

Swezy C, Bailey J and Chung W 2021 Linking federal forest restoration with wood utilization: modeling biomass prices and analyzing forest restoration costs in the Northern Sierra Nevada *Energies* **14** 2696

Ter-Mikaelian M T, Colombo S J and Chen J 2015 The burning question: does forest bioenergy reduce carbon emissions? A review of common misconceptions about forest carbon accounting *J. Forestry* **113** 57–68

US EPA, O 2018 *EPA's Treatment of Biogenic Carbon Dioxide Emissions from Stationary Sources that Use Forest Biomass for Energy Production* (available at: www.epa.gov/air-and-radiation/epas-treatment-biogenic-carbon-dioxide-emissions-stationary-sources-use-forest) (Accessed 25 October 2022)

van der Hilst F 2018 Location, location, location *Nat. Energy* **3** 164–5

Wagener W W and Offord H R 1972 *Logging Slash: Its Breakdown and Decay at Two Forests in Northern California* Research Paper (USDA Forest Service—Pacific Southwest Forest and Range Experiment Station)

Weedon J T, Cornwell W K, Cornelissen J HC, Zanne A E, Wirth C and Coomes D A 2009 Global meta-analysis of wood decomposition rates: a role for trait variation among tree species? *Ecol. Lett.* **12** 45–56

Westerling A L 2018 *Wildfire Simulations for California's Fourth Climate Change Assessment: Projecting Changes in Extreme Wildfire Events with a Warming Climate* CCCA4-CEC-2018–014 (Merced: University of California) p 57 (available at: cal-adapt.org/tools/wildfire) (Accessed 1 June 2019)

Xu H, Latta G, Lee U, Lewandrowski J and Wang M 2021 Regionalized life cycle greenhouse gas emissions of forest biomass use for electricity generation in the United States *Environ. Sci. Technol.* **55** 14806–16

Yin X 1999 The decay of forest woody debris: numerical modeling and implications based on some 300 data cases from North America *Oecologia* **121** 81–98