Life cycle climate impacts of producing biochar from forest residues *via the Takachar reactor*

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Executive Summary

With an abundance of woody biomass emerging from forest management, society is faced with significant opportunities and challenges. On one hand, this biomass can be transformed into valuable bioproducts such as biofuel, bioenergy, wood products, biochar, and other carbon removal pathways. The utilization of these residues may also provide benefits to long-term forest health and reduce the risk of devastating wildfires by facilitating forest thinning. However, these residues are costly to collect and transport and are typically burned onsite or landfilled, posing environmental, economic, and public health challenges. This issue is exacerbated for rural areas that face higher costs for collection and transport, and often manage resources that are more variable than biomass at larger commercial operations, where relatively homogeneous biomass is grown. As a result, these rural communities face disproportionate barriers to participating in the growing carbon market.

Recognizing this gap, Takachar has developed low-cost, portable reactor units that enable rural, hard-to-reach communities to upgrade biomass residues into biochar onsite. This innovation allows customers to reduce their cost of vegetation management while generating valuable bioproducts that can be consumed locally or transported and sold. While biochar application has been associated with many benefits (e.g. reduced need for synthetic fertilizer, improved soil structure, retention of soil moisture), its climate performance is variable and not consistently characterized.

Thus, the integrity of carbon crediting of biochar hinges on robust life cycle assessment that accurately compares the emissions from biochar production to those that would have occurred if biochar were not produced. This report presents an assessment of the climate impacts associated with utilizing forest harvest residue for biochar production—in particular, biochar produced by a mobile Takachar unit using residues generated from a thinning harvest in Sonoma County, California. This analysis was conducted using the California Biomass Residue Emissions Characterization (C-BREC) model (Fingerman et al, 2023).

The life cycle assessment (LCA) boundary begins with the existence of piled or scattered residue following a timber harvest or forest thinning treatment, and includes all CO_2, CH_4 and N_2O emissions from residue collection, grinding, and conversion to biochar using a Takachar system. In addition, C-BREC calculates the avoided emissions from the same quantity of biomass if left in the forest to decay and be exposed to wildfire or managed through controlled burning. The net sequestration attributable to biochar is therefore the difference between the emissions that occur due to the biochar generation and the emissions associated with this counterfactual outcome for the same biomass. Sensitivity analyses were conducted to investigate the effects of key variables, such as biochar carbon content, production efficiency, and biochar decay rate.

In determining the net climate impact of the biochar production, the biochar emissions were compared to the reference case emissions, resulting in 1.62 kg CO_2e/kg biochar where biomass would have otherwise been subject to a controlled burn and 1.22 kg CO_2e/kg biochar for biomass that would otherwise be left to decay. This study characterizes the climate impact of emissions associated with biochar production in a particular context and presents a comparison with avoided counterfactual cases. The results of this study highlight the significance of LCA methodological choices on the calculated climate benefit of biochar production and use. These findings also underscore the importance of robust, context-specific LCA methodologies in accurately assessing the climate impact of biochar production.

Introduction

Forest Health Treatment and Residue Mobilization

Many forestlands across the globe are facing crisis conditions. The increased drought and hotter, drier, windier weather conditions brought on by climate change have created increasingly severe wildfire conditions in forests already overstocked with biomass following decades of fire suppression and neglected forest management. Considering this ongoing ecological, climate, economic, and public health emergency, jurisdictions are prioritizing forest health treatment.

In especially impacted areas such as the western United States, aggressive goals are being pursued to deliver both climate change mitigation and adaptation. California's Wildfire and Forest Resilience Action Plan prioritizes increasing "the pace and scale of forest health projects to meet the goals of the Forest Carbon Plan"(Forest Climate Action Team, 2018; Governor's Forest Management Task Force, 2021). It sets the ambitious goal of treating up to 1 million acres of forestland annually by coordinating efforts across federal, state, and private forest landowners. Forest health treatments often involve thinning small diameter trees and produce significant non-merchantable timber residues. Diverting these residues for productive use can help reduce vulnerability to wildfire, support rural development, and promote carbon storage. California's Wildfire and Forest Resilience Action Plan identifies the development of, and access to, markets for these residues as a key barrier to conducting necessary treatment activities across priority landscapes in the state. To this end, state and federal agencies are working to attract private investment in a vibrant wood products market that will support high-value and carbon-negative uses for woody residues. Any plan to develop such markets will necessarily require reliable estimates of climate impact of these uses, motivating quantification efforts such as this research.

While woody forest residues hold promise as a feedstock for a variety of uses such as renewable energy, chemical (e.g. hydrocarbon or industrial biochemical) synthesis, carbon removal, and wood products, traditionally this material is difficult to handle because it is often dispersed in remote places. Transporting wet, loose, and bulky biomass over long distances is very costly. As such, in most rural places, the non-merchantable residues are often piled and burned, resulting in air pollution, greenhouse emissions, and increasing the risk of wildfire ignitions. Globally, about 4 billion tons/year of biomass residues are burned in open air, representing a ~$120 billion/year total market potential, as well as a significant contribution to global anthropogenic CO_2 emissions (Jacobson et al., 2014). Rural communities also face the challenge of having relatively variable feedstock, representing an additional barrier to entry into the carbon market. This gap serves as motivation for the project at hand and raises the importance of incorporating its outcomes into the verification of carbon offsets through life cycle assessment (LCA).

Takachar Residue Utilization

Takachar has developed hardware and software tools to dramatically increase the utilization of crop and forestry residues as carbon-negative bioproducts such as biochar for fertilizer blends. They are developing small-scale, low-cost, portable systems that can be latched onto tractors or placed in shipping containers for transport to remote locations. There, they can thermochemically convert biomass to densified biochar product without requiring external energy input. The Takachar system's mobility lowers the cost and emissions associated with transporting biomass out of the forest. The Takachar system is versatile in that operational properties can be adjusted to yield different products,

such as pre-densified material for fuel, highly porous material for soil amendments, or stable carbon as biochar.

Takachar has been targeting non-merchantable forestry residues generated by timber and agricultural harvest operations and electric utility vegetation management projects. Their systems can help landowners and managers reduce or even eliminate the logistical cost of vegetation removal, allowing them to safely treat a wider area given a limited budget, while complying with the pollution and carbon emission requirements imposed by the local authorities. For the purpose of this study, it was assumed that the Takachar system was operated such that the output from their units is a solid inert carbon-rich product (biochar). Biochar can offer a variety of benefits including reduced need for synthetic fertilizer, improving soil structure, and retaining soil moisture, among others. Biochar is also known for its long-term storage capabilities, with the potential to store carbon for centuries to millennia.

Biochar, Carbon Accounting, and the Carbon Market

A growing list of producers are facilitating carbon removal through biochar and engaging in the carbon removal marketplace (Salma et al., 2024). Despite its inclusion in these markets, the climate performance of biochar remains variable and is not consistently characterized. The integrity of carbon crediting of biochar hinges on robust life cycle assessment that accurately compares the emissions from biochar production to those that would have occurred if biochar was not produced. This LCA aims to estimate the climate impact of utilizing forest harvest residue for biochar production, specifically evaluating the use of a mobile Takachar system deployed to a generalized thinning harvest in Sonoma County. Additionally, we seek to evaluate key assumptions that influence the result.

This LCA approach offers a detailed assessment by comparing emissions from the use case (biochar production) to those from avoided counterfactual scenarios, without relying on assumptions about the impact of biogenic carbon to the climate. Transparent and thorough LCA's are essential for the credibility of biochar in carbon markets, and this report aims to contribute to that credibility by incorporating previously established methods for characterizing avoided emissions.

Methods

To evaluate the net climate impact of biochar production from forestry residues using the Takachar system, a life cycle assessment (LCA) was conducted. The purpose of the LCA is to track the emissions resulting from mobilization of woody forest residues and their conversion to biochar, and to compare these to emissions that would have otherwise occurred if the biomass remained in the forest (from controlled burning, wildfire and decay).

The LCA boundary begins with the piled or scattered residue following a timber harvest or forest thinning treatment and includes all CO_2, CH_4 and N_2O emissions from residue collection, grinding, and conversion to biochar using a Takachar system. The mobile Takachar unit was assumed to be deployed directly to the site of the harvest, with the resulting biochar left onsite. This portion of the LCA is represented by the blue dashed box in **Figure 1**. Additionally, the LCA boundary includes the avoided emissions from the same quantity of biomass if left in the forest to decay and to be exposed to wildfire or managed through controlled burning. The avoided emissions LCA boundary is represented by the red dashed box in **Figure 1**. The net sequestration attributable to biochar is therefore the difference

between the emissions that occur due to the biochar generation and the emissions from the debris that would have occurred under the counterfactual scenario (being left in the field or burned).

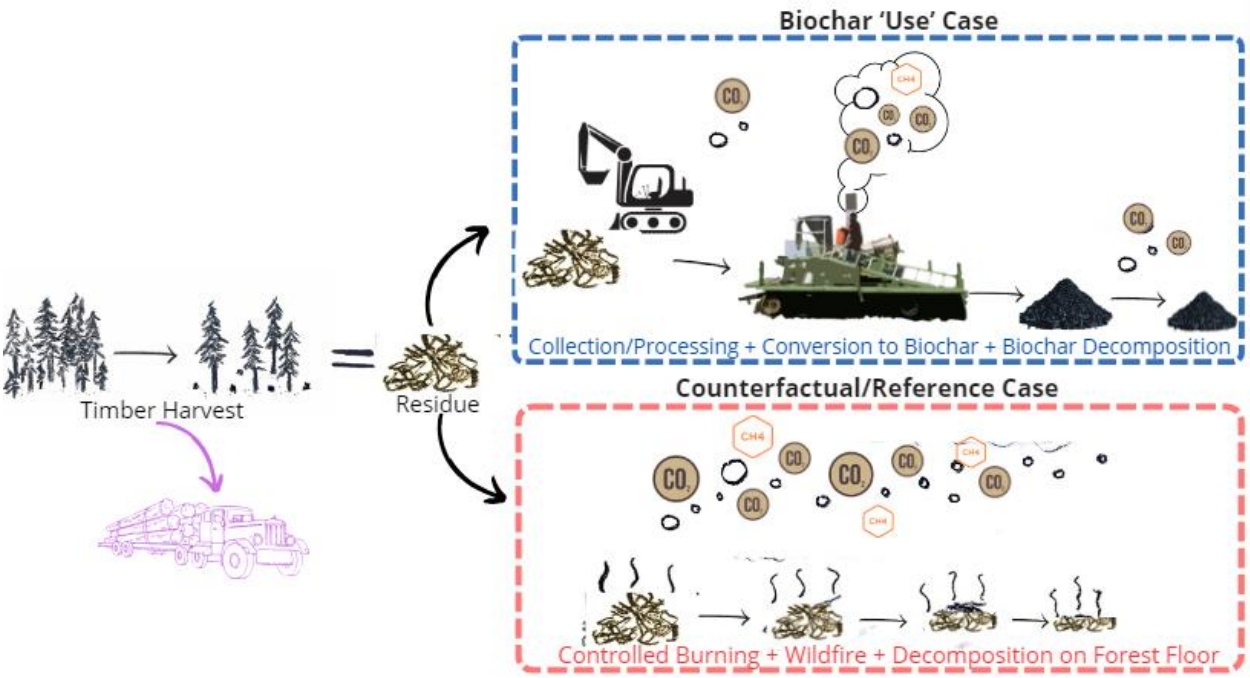

Figure 1*: LCA boundary. The area in blue represents the biochar 'use' case and the area in red represents the avoided 'reference' case. The net sequestration attributable to the biochar is the difference between the two. The primary forest management–timber harvest or thinning activity–is outside the LCA system boundary as the biomass is assumed to be a waste product from treatment that was already occurring.*

A note on system boundary

A central assumption underpinning the LCA framework is that the biomass source material is a true waste, in that it would not have been used at all were it not converted to biochar. As such, we assume that primary forest harvest activities are being conducted for the purpose of commercial timber extraction, or in pursuit of other forest health or wildfire risk mitigation goals rather than in order to manufacture biochar. Therefore, we do not allocate any of the primary harvest emissions - nor any of the forest carbon stock and flow implications of the primary harvest - to the biochar pathway.

This approach is aligned with the common Life Cycle Assessment practice of coproduct allocation on the basis of value fraction (Ardente & Cellura, 2012). Under this approach, if sawtimber represented 50% of the value derived from a landscape and pulpwood the other 50%, one would allocate half of the emissions associated with the primary forest management activity to the lumber and half to the pulp. As the residues represent none of the economic value generated by the primary treatment activity, they are allocated none of the emissions or sequestration associated with that activity.

C-BREC Model and Simplifications

Significant components of this LCA were modeled using the California Biomass Residue Emission Characterization (C-BREC) model. C-BREC is an LCA model developed to estimate spatially explicit greenhouse gas and air pollutant emissions resulting from forest residues left in the forest (from decay and wildfire), managed with a controlled burn, or mobilized and burned for power generation. Additional information on the C-BREC model and its applications is available online[1], and a detailed description of the model structure is available in the C-BREC documentation (Carman et al., 2021). The inputs to the model include a georeferenced polygon representing the forest treatment area, the type and intensity of the treatment activity, and the counterfactual or 'reference' fate of unremoved biomass (e.g. burned, piled). The model outputs include the amount of biomass residue produced from the forest treatment and a time-series of emissions associated with each source included in the different use and avoided management scenarios. In the context of this biochar LCA, the C-BREC model was used to estimate spatially variable 100-year emission profiles associated with the reference case (avoided emissions) and collection, processing, and equipment transportation emissions associated with the biomass to biochar pathway. The C-BREC model makes computations on a 30x30m resolution, but for this analysis, results were averaged across forested landscapes in California. See Appendix A for details on spatial averaging.

The C-BREC model includes more input variables than were necessary for this analysis, such as specific forest treatments, the configuration of residue, and portion of residue mobilized for use. Instead of finding a distinct result for each combination of options in C-BREC, a simplified set of model results was used. Model simplifications are described in Appendix A. In general, among other simplifications, the model results were generalized by:

- Forest Treatment Type
    - Thinning: Averaged across all 'Thin-From-Below' treatment types
    - Commercial Harvest: Averaged across all 'Thin-from-Above' and 'Clearcut' treatment types
- Reference Burn:
    - Controlled Burn: assumed broadcast and pile burn of all residues left onsite
    - No Burn: no control burning of residue (pile or broadcast)

The 'default' results of the LCA are based on both reference case burn options following a thinning forest treatment. With the other simplifications, this represents a scenario where the Takachar system would be mobilized to the forest following a thinning treatment, with residue otherwise piled and left or burned in the forest. Other scenarios were also evaluated to assess the sensitivity of some of these parameters, but in general this LCA is context specific and should be adjusted if any of the assumptions are different in practice. The sections below describe different sources of emissions in the LCA.

Emissions from Collection and Processing of Biomass

In order for the biomass to be converted into biochar, the biomass must be collected from the forest, transported to a landing (where it was assumed that the grinder and Takachar system would be

[1] www.schatzcenter.org/cbrec

located). The biomass (branches/limbs/tops) need to be ground into smaller pieces before going into the Takachar reactor. Additionally, the biomass requires loading into the grinder and into the Takachar system. Emissions estimates from this process were compiled from C-BREC model runs across the state.

Within C-BREC, emissions from each piece of equipment in the collection and processing process were estimated using equipment emissions factors, biomass quantities and distances to nearby roads. Expected equipment was chosen based on the slope of the forested areas and size of the timber harvest, (i.e. collection and processing parameters have some spatial variability). Emissions from the hauling of equipment and crew to the site was estimated assuming a commute distance of 50 miles. For more information on the details on collection and processing emissions, see documentation on the C-BREC model (Carman et al., 2021).

In addition to the collection and processing of biomass, some emissions associated with mobilization of the Takachar reactor were included. This was estimated using emissions factors for hauling equipment divided by an estimated minimum biochar produced per project. The assumed amount of biochar produced per project was 10 metric tons. The assumed haul distance was 50 miles and the assumed average speed of hauling was 36 miles per hour (consistent with C-BREC equipment haul computations).

Direct Emissions from Biomass-to-Biochar Conversion

Direct emissions from the thermochemical conversion (of biomass to biochar) were estimated using a simplified carbon balance equation (Eq. 1). This equation was adapted from Sparrevik et al. (2015) and Pennise et al. (2001). Oil and solid byproducts were assumed to be negligible in this analysis.

$$C_{feedstock} - C_{biochar} = C_{CO2} + C_{CO} + C_{CH4} + C_{NMVOC} + C_{TSP} + C_{oil/solid\ byproducts}$$

Eq. 1

The carbon present in the feedstock was estimated using C-BREC, based on the forest species composition in the region. The carbon content in the biochar was estimated by multiplying an assumed conversion efficiency of 0.35 kg biochar produced per kg of biomass fed into the Takachar system and multiplying by an assumed carbon content of 0.65 kg C per kg biochar (conversion efficiency and carbon content provided by Dr. Kevin Kung). These values were taken to be default but serve as placeholders for more specific operational measurements. The methane emissions from the Takachar systems were measured at 0.287 kg CH_4 per tonne of biochar and the larger unit is 0.184 kg CH_4 per tonne of biochar (*See Appendix B*), back calculated from their CO_2e unit. For this analysis, the more conservative higher methane emission rate reported was used. None of the other possible gaseous or oil/solid byproducts (Eq. 1) were measured or estimated by Takachar and were therefore assumed to be negligible. The mass of carbon dioxide emitted during conversion was then calculated by rearranging the carbon balance equation.

Aside from the carbon-based emissions, N_2O emissions from the conversion were assumed to be negligible. This assumption is consistent with biochar emissions characterization by Amonette et al. (2023), who estimated less than 0.2 g N_2O/kg biomass for all reactor types analyzed. Other air pollutants with environmental and health impacts were not estimated.

Decay of Biochar

Biochar is recognized for its ability to stabilize carbon, allowing for long term storage (Kuzyakov et al., 2014; Wang et al., 2016; Woolf et al., 2010). However, not all carbon in biochar is stable and some fraction decomposes over time (Kuzyakov et al., 2014). Biochar decay rates vary with biochar properties, soil properties, abiotic and biotic factors (Wang et al., 2016). According to the European Biochar Certification (EBC), the decay rate for biochar (with $H:C_{org}$ ratio below 0.4) is conservatively estimated at 0.3% per year when applied to soils (Schmidt et al., n.d.). This decay rate was used to estimate carbon loss over the analyzed time period, resulting in approximately 74% of the biochar remaining stable over a 100-year timeframe. The remaining fraction after 100 years was consistent with other LCA's default permanence values in the range of 80% assumed stable (Matuštík et al., 2020; Roberts et al., 2010), although some used a different decay equation (Matuštík et al., 2022). It was assumed that the decayed fraction of the biochar had a consistent carbon mass ratio with the original biochar and that all carbon lost during decomposition was emitted as carbon dioxide.

Avoided Fire and Decay Emissions

If the biomass was not mobilized for biochar production, it was assumed to either be left in the forest or managed with a controlled burn. Using the C-BREC model, we estimate the emissions from decay, wildfire (on a probabilistic basis), and controlled burning that would be avoided by mobilizing the biomass. To do this, the emissions associated with wildfire, decay, and open burning from the reference conditions (no biomass removal) were compared to the emissions from the same sources in a case where 70% of the biomass was removed, which is assumed to be the maximum technically recoverable portion of wood biomass per the U.S. Department of Energy (2011). The rate of decay is spatially variable, depending on wood properties and climatic conditions such as precipitation and temperature (Blasdel, 2020).

Aside from emissions, C-BREC also estimates the unburned and charred material left over after a wildfire or controlled burn. The unburned material was assumed to decay at the rate estimated for the region and the char was assumed to decay at 0.3% per year (consistent with the biochar decay assumption). The series of emissions from controlled burning and decay of leftover biomass was taken to be the avoided emissions when the avoided management would have been controlled burning of the residues. Since this LCA is not for a specific treatment, leaving biomass in the forest and burning it were evaluated as two plausible counterfactual fates.

Climate Impact Metrics

The methodology above outlines the quantification of emissions at various points in time but does not address their climate impact. A key challenge in quantifying the climate impact of biochar is that the emissions–and therefore the radiative forcing–associated with the reference and use cases are offset in time. When we create biochar from wood that would otherwise have decayed slowly in the field, we shift some CO_2 emission earlier in time by volatilizing some of the wood's carbon content, while also shifting some emission later by tying some of the carbon up in a slower-decaying form.

Similar to financial accounting's use of the time value of money for comparing expenses or revenues at different points in time, emerging approaches in LCA aim to account for the "time value" of emissions or sequestration over time in terms of their differing climate forcing effects over specific policy-relevant timescales. One such approach is to choose an analytic horizon and then integrate the cumulative of radiative forcing (CRF) over time, accounting for emissions occurring at different times

within the time horizon and computing the equivalent amount of CO_2 that–if emitted at the start of the project–would cause the same amount of total forcing over the analytic horizon (Liu et al., 2017). This approach as discussed by has recently been implemented in several publications related to the emissions profile of biomass energy (Fingerman et al., 2023; Giuntoli et al., 2015). This mirrors the approach taken by the Intergovernmental Panel on Climate Change in its calculation of CO_2 equivalent GWP values for different GHGs (Myhre et al., 2013). In the biomass life cycle assessment literature, this is sometimes called GWP_{bio}; in other carbon accounting literature, it is known as tonne-year accounting.

In many biomass LCA's, the timing of GHG emissions is not considered(Roberts et al., 2010). Instead, total CO_2 emissions from the 100-year period are summed and all other GHGs are converted to 'present-day' CO_2e using the same method described above but using standard GWP values for different gases (e.g. 28 for CH_4, 298 for N_2O). To evaluate the sensitivity of our results to this methodological decision, we also calculated the CO_2e emissions summed over the 100-year timeframe.

Results and Discussion

This section begins with the results of a biochar production scenario in Sonoma County, where biomass is sourced from a forest thinning operation for a real-world deployment of a Takachar reactor. Next, the spatial variability of these results is explored for similar contexts in other regions of California. This is followed by an analysis of the sensitivity of these results to key biochar production parameters. Finally, the impact of different climate impact metrics is assessed and compared to methodological choices in other biochar LCAs.

The results of the LCA of biochar production from forest thinning residues in Western and Southern Sonoma County is visualized in **Figure 2**. The graph shows the components that contribute to the emissions involved in biochar production on the left bar, totaling 3.36 kg CO_2e/kg biochar. This sum includes equipment emissions from collection and processing of the biomass at the timber harvest site, direct emissions from the thermochemical conversion, and decomposition of some of the carbon in the produced biochar. The right bars show two different 'reference case' scenario emissions - one where the biomass would have been left in the forest with no further management, and one where the residue would have been managed with a controlled burn. In the 'no burn' reference case, emissions would have occurred from decomposition and potential exposure to wildfire. In the 'burn' reference case, emissions would have been generated mostly from combustion in the controlled burn.

By calculating the full emissions associated with both the production of biochar as well as the counterfactual or "reference" fate of the same feedstock, we are able to take the difference between the two to ascertain the net climate impact of the biochar production. We find the net C sequestration associated with the Sonoma County base case biochar production to be 1.62 kg CO_2e/kg biochar, if the biomass would otherwise have been burned in place and 1.22 kg CO_2e/kg biochar for biomass that would otherwise be left to decay. This illustrates the impact of assumptions as to the counterfactual fate of woody residues. In the case where the biomass would have been left in the forest without a controlled burn, the net sequestration of the biochar is significantly less (~24%) than if the biomass would have otherwise been burned. This is largely due to the timing of emissions; in a controlled burn, most carbon in the biomass would be emitted immediately, whereas if left in the forest, the biomass carbon would have been emitted more slowly (through decay and/or eventual wildfire), causing a smaller climate impact during the 100-year timeframe.

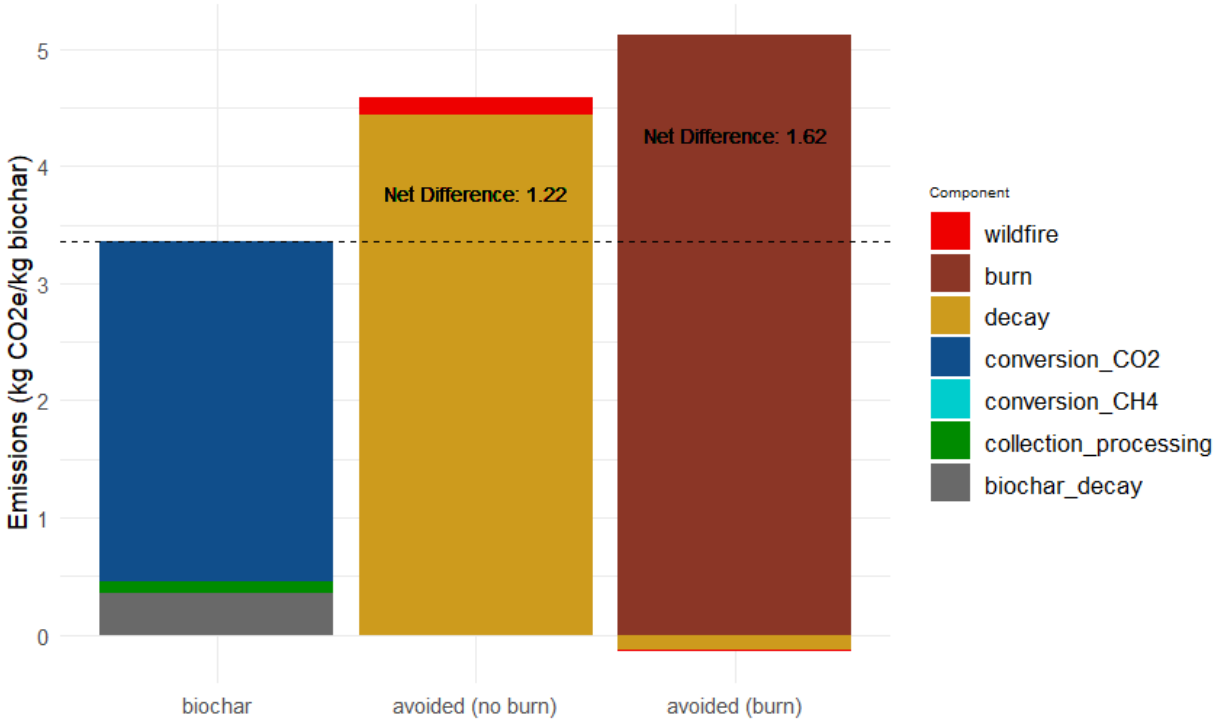

Figure 2: *Net Sequestration from biochar production. The bar on the left shows the sources of emissions in the biochar use case. The other two bars show avoided emissions if the biomass otherwise would have been left in the field (middle) or managed with a controlled burn (right). The net sequestration is the difference between the avoided emissions and the biochar emissions.*

It bears noting that in **Figure 2**, there is a slight negative avoided emission from decay and wildfire in the 'Burn' reference case. This is because C-BREC imposes a 70% maximum biomass collection rate due to the impracticality and ecological concern of collecting *all* biomass (U.S. Department of Energy, 2011). This leaves 30% of the biomass on the forest floor to decay in the biochar use case. In the case where biomass would have otherwise been burned in situ, that broadcast burn would have consumed more than 70% of the biomass, leaving less biomass for decay and exposure to wildfire than in the use case.

Figure 2 displays the modeled emissions for biochar production in the specific study region in Sonoma County. However, there is spatial variability associated with biomass properties, climate, decay rate and likelihood of wildfire - all of which contribute to net sequestration attributable to biochar production. Figure **3** shows the same biochar production from thinning residues modeled across all forested ecoregions in California for both (controlled burn and left in place) counterfactual scenarios. A similar figure zoomed in on Sonoma County can be found in Appendix C, **Figure 5**.

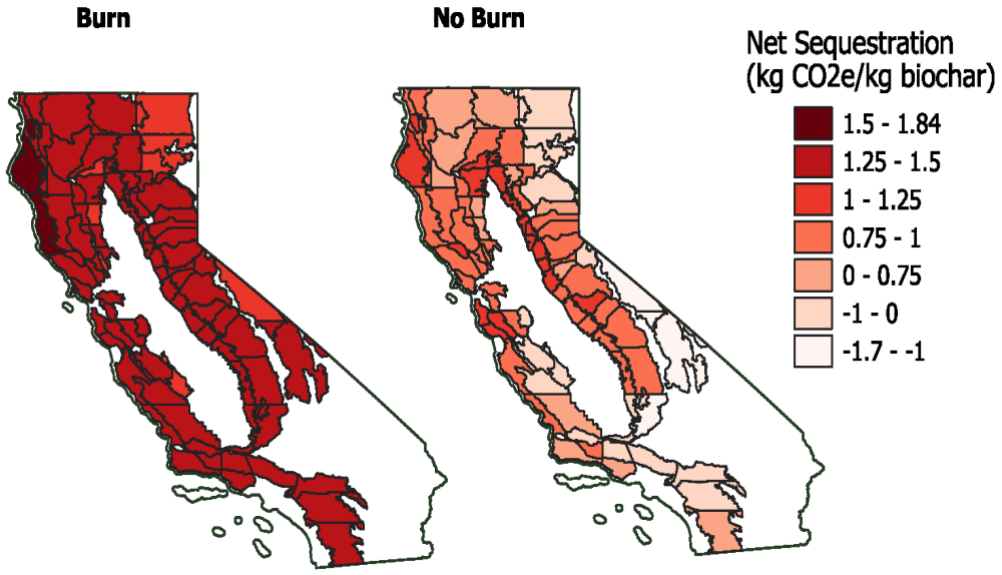

Figure 3: *Spatial and system variability in net sequestration by biochar. Biochar produced from residues generated via thinning treatments where the biomass would have otherwise been managed with a controlled burn (left) or left in the field (right).*

In general, the net sequestration attributable to biochar production from forest thinning residues is greater if the biomass would have otherwise been burned. This is shown in **Figure 3**, by larger (and all positive) net sequestration values in the 'burn' reference case map (on the left) as compared with the 'no burn' reference case (on the right). In the case where the biomass would have been left in the field to decay and be exposed to wildfire (i.e. 'no burn'), the net sequestration value of biochar tends to be lower, and in some extreme conditions (4 ecoregions) may result in a net negative sequestration. This implies that leaving the biomass in the field would result in a lower 100-year climate impact than converting it to biochar. We see this in areas with slow decomposition and low probability of wildfire, such as in the high desert and dry areas along the California-Nevada border. In these locations, the carbon in woody debris is sequestered for decades as the biomass decays slowly, resulting in a low 100-year climate impact (possibly even lower than converting the biomass to biochar because doing so emits approximately 55% of the carbon right away in the conversion process itself). This means that the climate impact of producing biochar would require a longer timeframe to become net positive, since the avoided emissions are themselves also delayed. However, these few ecoregions are edge cases in our modeling, and moreover are unlikely locations for biochar production.

The results above relied on various assumptions about the biochar production, including the char production efficiency, methane emissions from conversion, biochar carbon content and biochar stability. Each has an impact on the biochar net sequestration result. We explored the sensitivities to these assumptions by adjusting their values by 25% while keeping the rest of the variables constant. Table 1 shows the default value, the range of values tested (±25% of the default) and the range of net sequestration results for the biomass sourced from a thinning harvest in Sonoma County, where the reference case scenario involved leaving the biomass piled in the forest (no controlled burn). All the variables tested had a linear relationship with the net sequestration result except the biochar

production efficiency and graphs of the results can be found in Appendix C, **Figure 6**-**Figure 9**. The average sensitivity coefficient over the range of tested variable values was taken to be the percent difference from default net sequestration result divided by the percent difference from default value for each variable tested. The sensitivity coefficient allows comparison of relative impact on the result by changes in the various parameters.

Table 1: *Sensitivity analysis of biochar assumptions. The impact of altering individual variables on the net carbon sequestration was assessed while keeping all other factors constant. The results are based on biomass conversion from a thinning treatment in Sonoma County, where the biomass would have otherwise been piled and left in the field (without controlled burning).*

Variable	Variable Value			Net Sequestration (kg CO_2e/kg biochar)			Sensitivity Coefficient (% change in y/ % change in x)
	Default - 25%	Default Value	Default + 25%	low	default, no burn	high	
Biochar Carbon Content *(kg C/kg biochar)*	0.487	0.65	0.813	0.713	1.22	1.73	1.66
Biochar Production Efficiency *(kg biochar/kg biomass)*	0.263	0.35	0.438	0.958	1.22	1.38	0.839
CH_4 emissions *(kg CH_4/tonne biochar)*	0.215	0.287	0.359	1.22	1.22	1.22	-0.00594
Biochar Decay Rate *(annual % of biomass lost)*	-0.375%	-0.3%	-0.225%	1.14	1.22	1.30	0.261

Variation in biochar carbon content had the most significant effect on net sequestration (when all other variables remain the same), suggesting that optimizing biochar production settings to maximize carbon content in biochar could substantially increase net sequestration. In the range evaluated, the net sequestration result was least sensitive to variations in methane emissions during conversion. However, the impact of methane emissions was based on the 100-year global warming potential of methane, whereas some crediting protocols, such as the European Biochar Certification (Schmidt et al., n.d.) argue that shorter term climate metrics are needed for short-lived climate pollutants like methane, which would increase the sensitivity to methane emission rate. We did not investigate the interactions between the biochar variables tested, and any changes to one variable likely influences others.

It is important to note that this analysis evaluated the sensitivity of a static ±25% change in the baseline assumptions for the biochar, rather than any externally validated range in input assumptions. For instance, the biochar decay rates used in carbon crediting methodologies, such as those in the

Climate Action Reserve's Biochar Protocol (*US & Canada Biochar Protocol*, n.d.) are based on permanence factors linked to soil temperature, developed by Woolf et al. (2021). These factors, specific to California and assuming a conservative H:C ratio of 0.7, correspond to decay rates as high as 0.589% loss per year (assuming decomposition follows exponential decay). A map of the spatially variable permanence factor estimates (remaining material after 100 years) and QGIS code for this analysis are shown in Appendix D. Incorporating these decay rates into our sensitivity analysis would have resulted in net sequestration value for the Sonoma default scenario as low as 0.942 kg CO_2e per kg biochar. This broader range of decay rates highlights the potential for a greater impact on net sequestration and suggests that the relative sensitivity of this variable within its actual range of variation could be more significant than implied by the static ±25% sensitivity sweep. In addition, Takachar methane emissions testing showed more significant variability than was evaluated in this sensitivity analysis (Appendix B). We conservatively used their higher methane emissions results as the default, but methane emissions may vary with operational settings. Specific testing of biochar production and biochar characteristics would be necessary to further refine these values.

In addition to the variables mentioned above, certain methodological choices in the LCA have a significant impact on results. In particular, we would point to the inclusion of biogenic CO_2 emissions and counterfactuals as well as the choice to account for time on the basis of 100-year GWP. Many biomass and bioenergy LCAs and policies consider biogenic CO_2 emissions as carbon-neutral, assuming that the carbon will eventually be reabsorbed by new biomass growth, thereby having little time in the atmosphere to contribute any significant radiative forcing impact (Hammond et al., 2011; Puettmann et al., 2020; Schmidt et al., n.d.). However, as Liu et al. (2017) argue, this neutrality assumption can systematically underestimate the climate impact of emissions. Rather than make assumptions about the biogenic carbon, C-BREC rigorously quantifies emissions in the use case (biochar) and avoided counterfactual cases and treats the difference as net emissions.

Furthermore, most biochar LCAs and carbon crediting structures (even those that *do* include biogenic CO_2 emissions) do not account for the timing of emissions as it relates to the climate impact, as some studies such as (Vogtländer et al., 2014) argue that discounting delayed CO_2 is unnecessary. Generally, they assume that emissions over the 100-year timeframe have equivalent climate impact over that period and simply sum all emissions. Many have suggested that the timing of emissions (and payback periods for biomass) need to be evaluated with their climate impact (Norton et al., 2019). In our modeling approach, the timing of emissions, including CO_2, is tracked by preserving the 100-year emissions profile for each case with the net emission profile used to calculate the climate impact (cumulative radiative forcing) over a 100-year period. With this time-explicit emissions profile, even a temporary delay in emission can cause a meaningful difference in resulting climate impact over a 100-year period from present.

The alternative approaches described above (carbon neutrality assumption of biogenic CO_2 emissions and ignoring the timing of emissions) may lead to significantly different results than our LCA. To compare, we estimated the net sequestration of biochar using these assumptions with our production parameters (0.65 kg C/kg biochar, 0.03% decay rate), resulting in net sequestration of 1.77 kg CO_2e/kg biochar. When factoring in collection, processing, transport, and non-CO_2 conversion emissions estimates from our analysis to this estimate, while still assuming biogenic CO_2 neutrality and not accounting for emission timing, the resulting "conventional LCA proxy" drops to 1.66 kg CO_2e/kg biochar. Our LCA approach, however, includes all emission sources, including biogenic CO_2, from both

the biochar and reference scenarios, normalizing across time on a 100-year GWP basis. Depending on whether the biomass would have been burned or left in the forest, our net sequestration results (in Sonoma County) are 2% or 26% lower (respectively) than the "conventional LCA proxy" estimate described above.

A comparison of results using various methodological choices for climate impact metrics, avoided reference cases, treatment of biogenic carbon emissions, and simple carbon sequestration estimates is shown in Table 2. For a region in California with the median net sequestration result in a 'no burn' reference case (Eastern Santa Clara), the difference from the conventional LCA estimate is larger (6% or 33% depending on the reference case). The distribution of our modeled results across California, compared to the conventional LCA proxy is shown in Figure 4. In most regions of California, the net sequestration suggested by conventional LCA is higher than our LCA results (using C-BREC), regardless of climate metric or reference case.

Table 2: *Net carbon sequestration created by biochar from biomass sourced from a forest thinning operation. This table presents results from our assessment of net sequestration for biomass sourced from a thinning operation in a California region with median net biochar sequestration in the 'no burn' reference case. Results are shown for the two avoided reference burn scenarios and various approaches for impact assessment. The first two rows (green) represent the baseline C-BREC results under the two modeled counterfactual fates for biomass (burn and no-burn), reporting net sequestration on the basis of net 100-year climate forcing effect. The following two rows (blue) report net carbon sequestration by biochar as total net CO_2 emission avoided, regardless of emission timing. The final three rows (red) represent the values that would result from more conventional approaches for calculating net sequestration via carbon content of the biochar without consideration of the counterfactual fate of biomass.*

Counterfactual Burn	*Carbon accounting method*	*Result Sequestration (kg CO_2e/kg biochar)*
No Burn	*Net GWP over 100 years*	*1.11*
Burn	*Net GWP over 100 years*	*1.55*
No Burn	*Net GHG emissions over 100 years*	*1.52*
Burn	*Net GHG emissions over 100 years*	*1.32*
-	*Total C in Biochar as CO_2e*	*2.38*
-	*Stable C in Biochar as CO_2e*	*1.77*
-	*Stable C in Biochar as CO_2e minus fossil emissions, non-CO2 conversion emissions (referred to as 'Conventional LCA')*	*1.66*

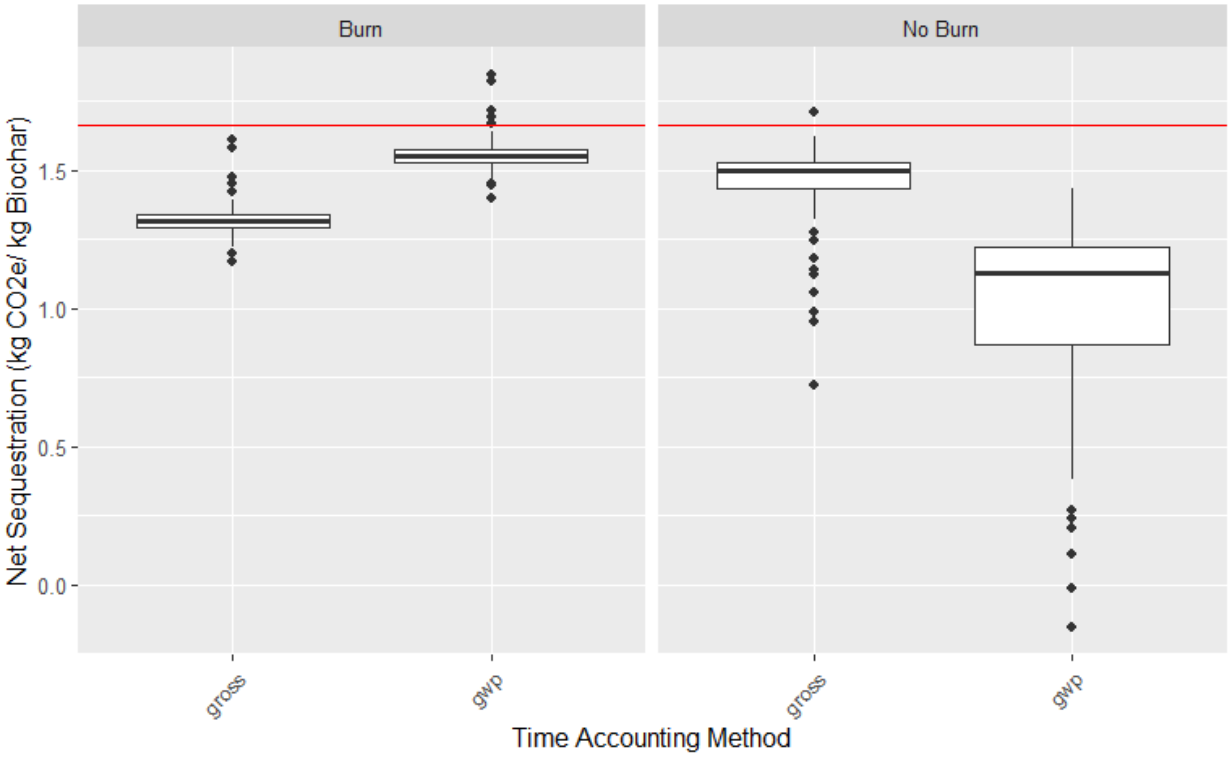

Figure 4: *Ecoregion distribution of Net Sequestration. Distribution of net sequestration across ecoregions in California using 100-year CO_2e and total gross emissions over the* 100-year *period (no time accounting). The panel on the left shows results for the scenario in which the avoided fate of the biomass was a controlled burn and on the right the scenario where the residues would have been left in the forest (no burn). For reference, the red line represents the result of a conventional LCA approach, where net sequestration was estimated as stable carbon stored in the biochar as CO_2e minus non-CO_2 conversion emissions and fossil emissions associated with the biochar production. Two outlier* ecoregions *in southeastern California were excluded from this graphic because their extreme climates led to projected decay rates outside the realistic range, and they are not expected to be sources of wood waste that could be used for biochar manufacture.*

Conclusion

This LCA attempts to comprehensively characterize the climate impact of emissions associated with both biochar production and the avoided fate of the same biomass. This was accomplished by estimating 100-year emissions profiles from the various emission sources of each case, including biomass collection and processing, biochar conversion emissions, and biochar decomposition in the use case, and controlled burn emissions, decomposition of biomass, and emissions from exposure to wildfire on a probabilistic basis in the avoided reference case. This LCA offers a thorough assessment of the climate impact of converting forest residues to biochar and provides results for specific scenarios. It also reveals the importance of key system parameters, biochar properties, and the counterfactual fate of the biomass, meaning that any rigorous biochar LCA should use empirical data on these system attributes to ensure accuracy.

Takachar's innovative approach to biomass utilization offers a promising solution to timber harvest and forest thinning residue management. This LCA indicates that biochar production from

residues provides a meaningful climate benefit across most of California, through carbon sequestration in the biochar and the reduction of climate impacts that would have otherwise occurred under the avoided reference scenario. For biomass sourced from a thinning treatment in Sonoma County, where a Takachar reactor was deployed, the net carbon sequestration from biochar production is estimated at 1.22 kg CO_2e/kg biochar if the biomass would have otherwise been left in the forest, and 1.62 kg CO_2e/kg biochar if it otherwise would have been burned.

The main result of the LCA (with default values) is dependent on estimated values for biochar conversion efficiency, biochar carbon content, conversion emissions and biochar decay rate. Direct emissions of non-CO_2 and non-CH_4 carbon compounds from the thermochemical conversion to biochar were assumed to be 0, which may be an underestimate that could slightly increase the climate impact of the thermochemical conversion. These results should therefore be refined by testing these variables and updating the model accordingly. It is also important to note that this LCA does not include any secondary effects from biochar application to the soil, positive or negative. Biochar application to the forest soil may promote faster regrowth rates (Lorenz et al., 2014) and impact soil greenhouse gas fluxes (Hawthorne et al., 2017; He et al., 2017; Joseph et al., 2021; Li et al., 2018), though both have shown variable results. In addition, spreading the biochar is likely to cause some of the fine biochar particles to aerosolize, leading to reductions in air quality and potentially significant climate impact (Tisserant & Cherubini, 2019).

The climate impact of biochar production under the default scenario varied depending on the location and avoided management practices. The greatest net sequestration potential was observed in coastal Humboldt and Mendocino Counties, when the counterfactual management was controlled burning of the biomass. In contrast, regions with drier conditions, such as in eastern California, showed much lower (at times, negative) climate impact where biomass would otherwise be left to decay, as the climate in those regions may lead to very slow decomposition of bulk biomass, where biochar production leads to immediate emission of 55% of embedded carbon. The impact of counterfactual burn management shows the importance of identifying the avoided fate of the biomass if it were not converted to biochar. In the region with the median net sequestration result for biochar produced from biomass that would have otherwise been left in the field, the biochar net sequestration result would be about 40% greater if the avoided fate of the biomass was a controlled burn compared to if the biomass would have been left piled in the forest. These findings emphasize the importance of context-specific quantification of carbon sequestration.

The results of this study highlight the significance of LCA methodological choices on the climate impacts of biochar production. Unlike many traditional biomass and bioenergy LCAs, which often assume CO_2 emissions are carbon-neutral, C-BREC's approach of accounting for all reference- and use-case emissions allows us to characterize the significant spatial variability in the result. Moreover, we highlight the significance of time in accounting for the climate impact of biochar, especially given that forest and woody biomass systems respond on a longer time horizon than e.g. agricultural bioenergy or biomaterial pathways. Compared to standard methods in biochar crediting, which often simplify sequestration estimates based on the stable carbon content of biochar, this LCA produced lower net sequestration values. For instance, the median region's net sequestration for biochar produced from forest thinning residues that would have otherwise been left in the forest, is approximately 33% lower than if the net sequestration was calculated following a conventional LCA approach (assuming the stable carbon in biochar is net sequestration). These findings underscore the importance of robust,

transparent, and context-specific LCA methodologies in accurately assessing the climate impact of biochar production.

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Appendix A: C-BREC Model Simplifications

This LCA is not intended to be specific to any particular forest harvest treatment, so C-BREC results were averaged across polygons in California, referred to as 'ecoregions'. The 'ecoregions' are based on USDA 'Ecological Units' (*USDA Ecoregion Sections, California | Data Basin*, n.d.), and further divided by California county delineations. Only ecoregions with more than 4% forested area were included in the analysis.

In practice, a treatment polygon is fed into C-BREC and the model makes computations at a 30m x 30m resolution, estimating a 100-year emissions time series at a 1-year resolution, consistent with built-in forest stand characteristics, decay rates, and wildfire probability rasters. Initially, each ecoregion was input as large treatment polygons, resulting in average outputs across all forested cells within the ecoregion. However, in many ecoregions, timber harvests and forest treatments are more likely to occur in certain areas within the region and with specific prescriptions. So recent timber harvest data (harvest perimeters and harvest descriptions) were compiled and fed into the C-BREC model. For ecoregions where more than 10 forest harvests were documented between 2016-2020 in either the 'Thinning' or 'Commercial Harvest' categories, the average C-BREC results from the real treatment boundaries and prescriptions were used in place of the average of all treatments in each category applied to the whole ecoregion. In ecoregions where data was limited, the ecoregion average was used.

Beyond spatial averaging, the C-BREC results were averaged over multiple forest treatment types and counterfactual burn scenarios. For every C-BREC model run, the user must choose specifics about the model scenario including forest treatment prescription, residue configuration following the logging operation and counterfactual management specifics. Instead of presenting results for each specific combination of scenario parameters, some of these were assumed constant and others were averaged over a set of values/options. For example, all residue left onsite after a timber harvest was assumed to be mostly configured in piles (70% by mass) and the rest scattered. Thinning treatments were assumed to be an average of thin-from-below treatments at various fraction basal area removal rates (20, 40, 60, 80%). Commercial Harvest was assumed to be an average of thin-from-above treatments at the same fraction basal area removal rates as well as clearcut (100% reduction in basal area).

Some input variables to C-BREC were held constant, rather than averaged over multiple options, such as the disposition portions of residues, the specifics of reference case burn type, the fraction of residue mobilized for biochar production, among others. Throughout this analysis, residue was assumed to be 70% piled and 30% scattered. All biochar use case results assumed that of the residual biomass from the forest treatment, all that was logistically recoverable was collected (as opposed to only the piles collected). Model input variable averages and assumed constants are described in **Table 3**.

Table 3: *Model parameters and groupings.*

C-BREC Input Variable	Category Average or Constant
Treatment	"Thinning" is an average of results from thin-

	from-below of 20, 40, 60 and 80% of basal area. "Commercial Harvest" is an average of results from thin-from-above of 20, 40, 60, 100% of basal area.
Residue Disposition	70% Piled, 30% Scattered
Residue Mobilization	All technically recoverable
Reference Burn Type	'Burn' is Pile and Broadcast burn 'No Burn' is no reference controlled burn

The 'default' results of the LCA represent a scenario where the Takachar system would be mobilized to the forest following a thinning treatment, with residue otherwise piled and either left in the forest or managed with controlled pile and broadcast burns. Other scenarios were also evaluated to assess the sensitivity of some of these parameters, but in general this LCA is context specific and should be adjusted if any of the assumptions are different in practice.

Appendix B: Takachar Methane Emission Testing Report

Data about methane emissions from Takachar systems was extracted from the report below, provided by Tristan Springer in June, 2024. For our LCA estimate, we used the greater emission rate.

CH4 Emissions per Functional Unit

Objective

The goal of this analysis is to determine the emissions factors for CH4 per tonne of biochar produced, focusing specifically on CH4 emissions. This information is crucial for presenting accurate emissions data to auditors.

Methodology

Gas Chromatography Analysis:

The gas concentrations in the exhaust stream were analyzed using gas chromatography (GC). The results showed the average concentration of CH4 to be 33.33 ppm (0.0033%).

Flow Rates:

Two biochar production units were evaluated:

- Unit 1: Produces 40 kg of biochar per hour with an assumed exhaust flow rate of 500 m^3/h.
- Unit 2: Produces 250 kg of biochar per hour with an assumed exhaust flow rate of 2000 m^3/h.

Gas Density:

The standard density for CH4 is 0.717 kg/m^3.

Global Warming Potential (GWP):

CH4: GWP = 25

Calculations

For Unit 1 (500 m^3/h, 40 kg/hour of biochar):

Mass Flow Rate of CH4:

Mass of CH4 (kg/hour) = 500 m^3/hour × 0.0000333333 × 0.717 kg/m^3 = 0.0114912 kg/hour

Convert to CO_2e:

CH_4 CO_2e = 0.0114912 kg/hour × 25 = 0.28728 kg/hour

Normalize to Per Tonne of Biochar:

Biochar production rate = 40 kg/hour = 0.04 tonnes/hour

Emissions per tonne = 0.28728 kg/hour / 0.04 tonnes/hour = 7.182 kg CO_2e/tonne

For Unit 2 (2000 m^3/h, 250 kg/hour of biochar):

Mass Flow Rate of CH_4:

Mass of CH_4 (kg/hour) = 2000 m^3/hour × 0.0000333333 × 0.717 kg/m^3 = 0.0459648 kg/hour

Convert to CO_2e:

CH_4 CO_2e = 0.0459648 kg/hour × 25 = 1.14912 kg/hour

Normalize to Per Tonne of Biochar:

Biochar production rate = 250 kg/hour = 0.25 tonnes/hour

Emissions per tonne = 1.14912 kg/hour / 0.25 tonnes/hour = 4.59648 kg CO_2e/tonne

Summary of CH4 Emissions Per Tonne of Biochar

- Unit 1: 7.182 kg CO_2e per tonne of biochar
- Unit 2: 4.59648 kg CO_2e per tonne of biochar

Conclusion

These calculations provide a clear and concise measure of the CH_4 emissions factors for the flue gas per tonne of biochar produced. By focusing on CH_4 emissions and converting these to their CO_2 equivalents (CO_2e), we can present accurate and reliable data to auditors.

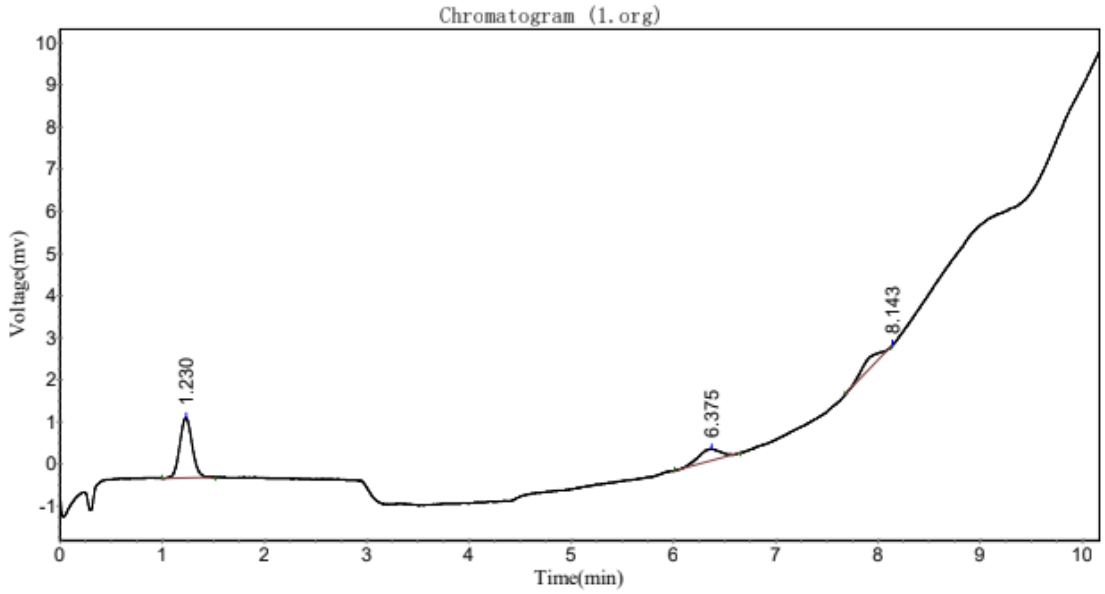
Supporting Data

The detailed chromatogram analysis for CH_4 concentration is attached in the provided PDF file. The key chromatogram data used is summarized below:

- Peak No. 1 (Retention Time: 1.230):
  - Height: 1425.275
  - Area: 11966.400
  - Concentration: 60.5278 ppm
- Peak No. 2 (Retention Time: 6.375):
  - Height: 275.825
  - Area: 4346.650
  - Concentration: 21.9860 ppm
- Peak No. 3 (Retention Time: 8.143):
  - Height: 4.190
  - Area: 3457.043
  - Concentration: 17.4862 ppm

Date/Time: 2024-05-30,18:37:56
Data File: F:\CS-200\Aakash B\Mayank indus sam\sam 1\fid\1.org
Method File: F:\CS-200\TCD.mtd

Analyst:
Date/Time: 2024-06-01,21:59:52



Results

Peak No.	Peak ID	Ret Time	Height	Area	Conc.
1		1.230	1425.275	11966.400	60.5278
2		6.375	275.825	4346.650	21.9860
3		8.143	4.190	3457.043	17.4862
Total			1705.290	19770.094	100.0000

Appendix C: Additional Figures

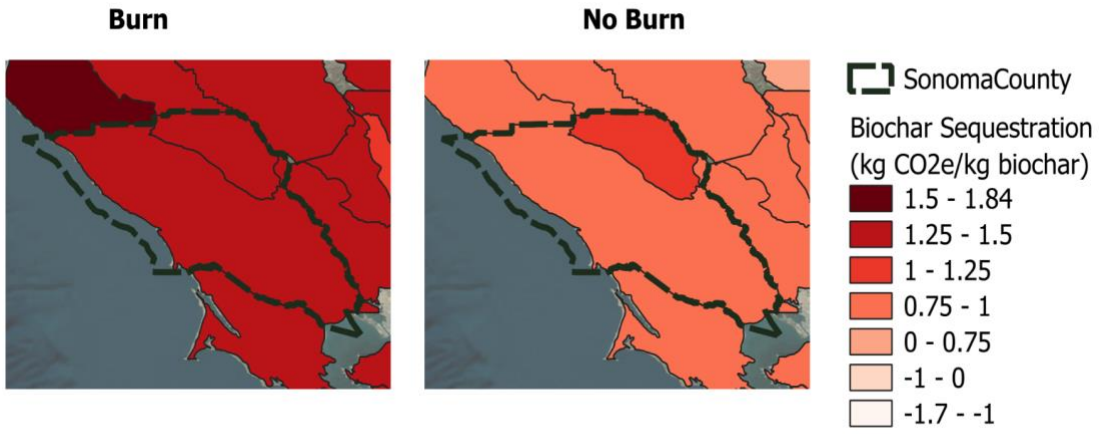


Figure 5: *Biochar Sequestration in Sonoma County. The LCA result when the biomass otherwise would have been managed with a controlled burn is shown on the right, and the result if the biomass otherwise would have been left in-situ is shown on the right.*

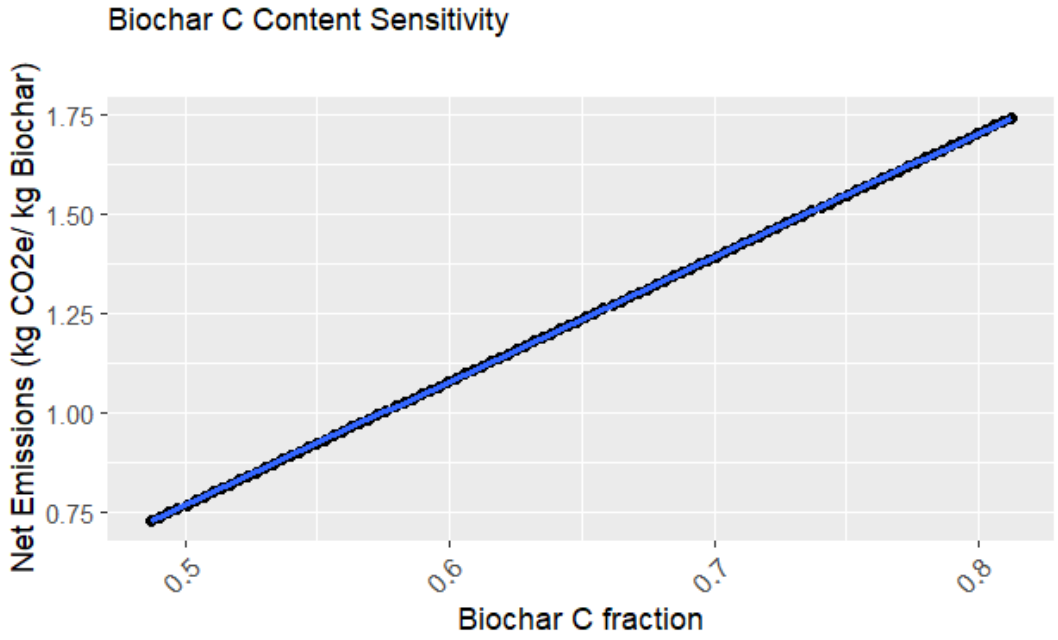


Figure 6: *Linear effect of varying biochar carbon content (kg C/kg biochar) on modeled net sequestration (kg CO2e/kg biochar)*

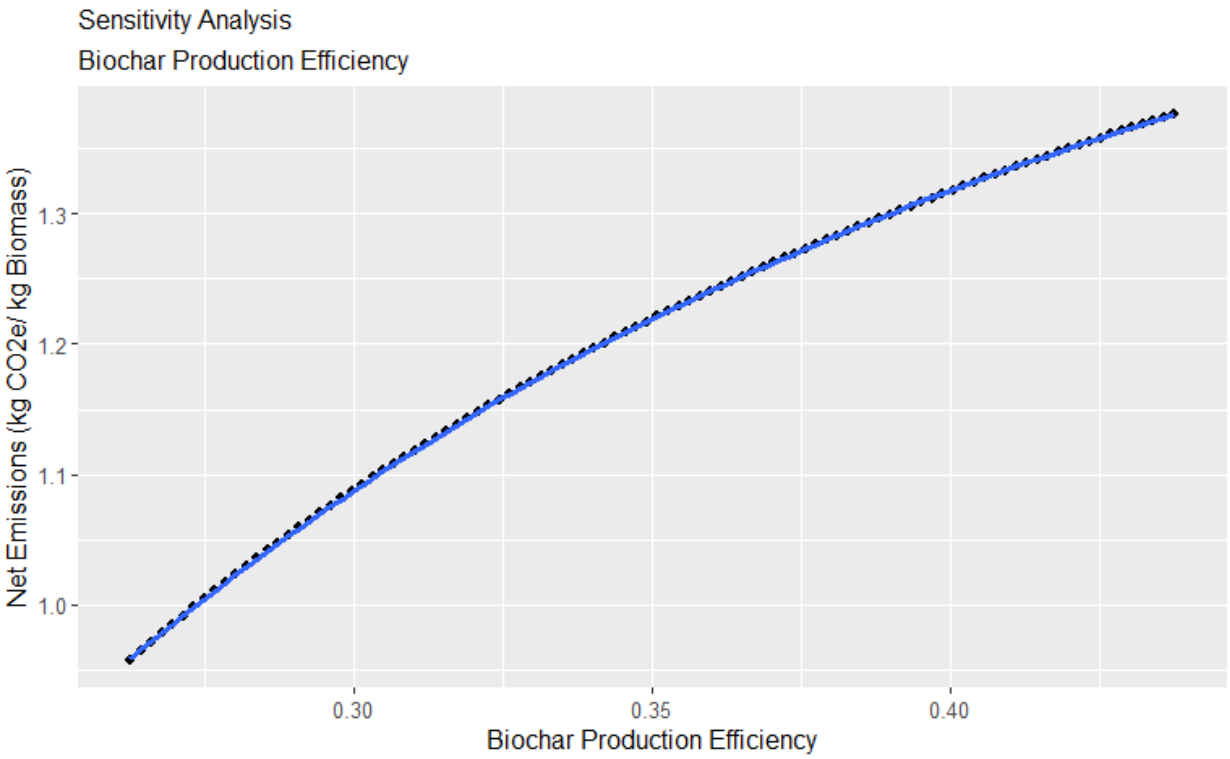


Figure 7*: Non-linear effect of varying biochar production efficiency (kg biochar/kg biomass) on modeled net sequestration (kg CO2e/kg biochar)*

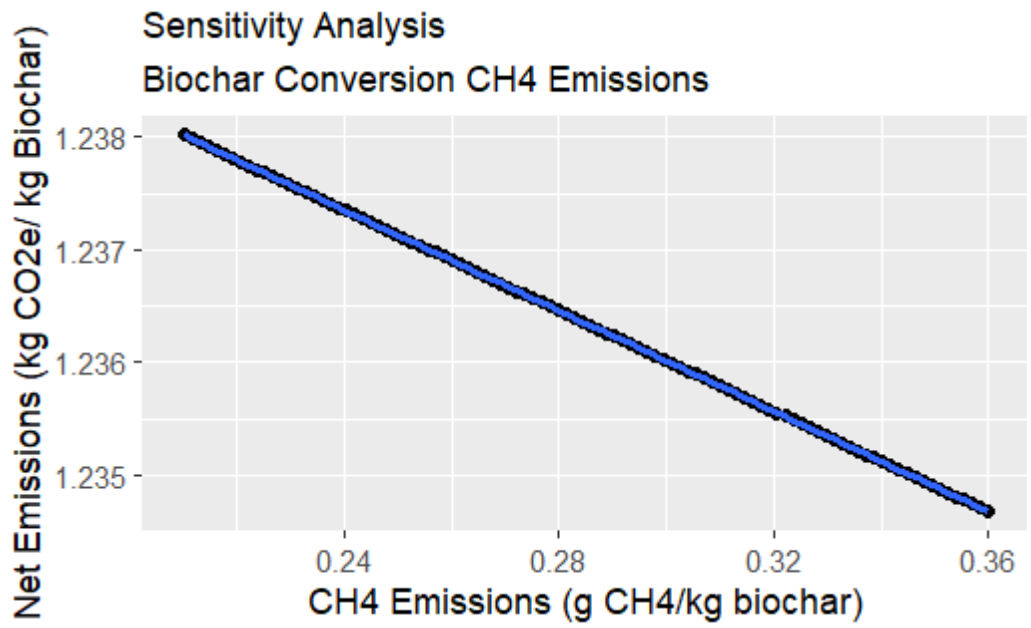


Figure 8: *Linear effect of varying methane emissions from conversion (g CH4/kg biomass) on modeled net sequestration (kg CO2e/kg biochar)*

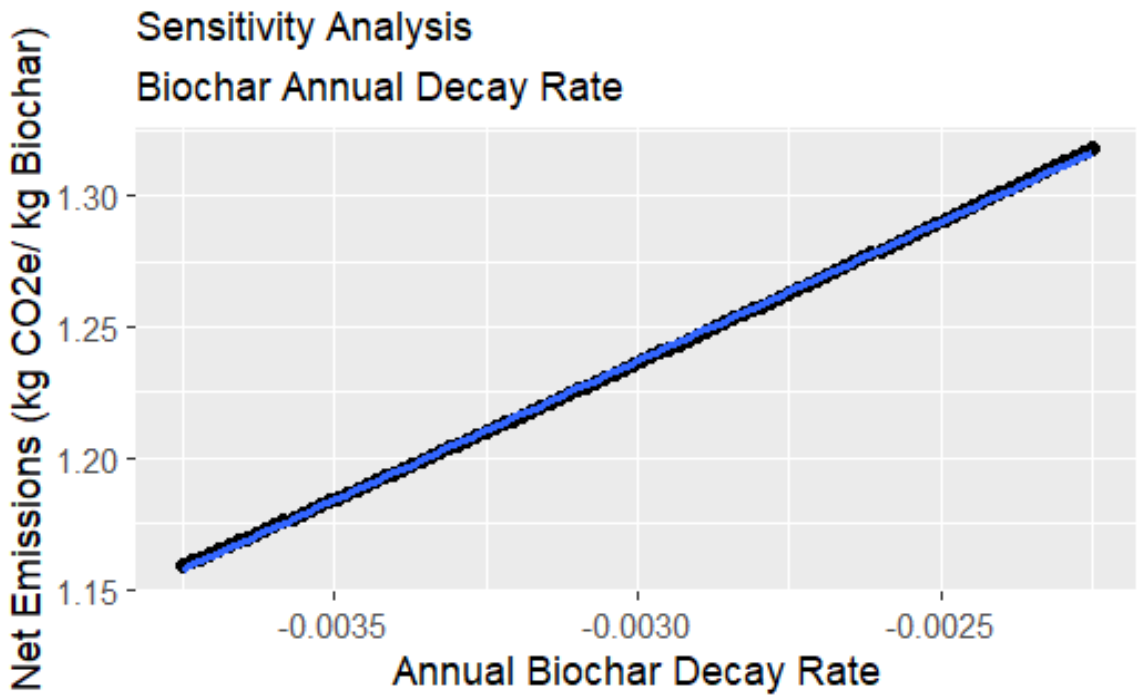


Figure 9: *Linear effect of varying biochar decay rate (kg biochar loss/kg biochar/year) on modeled net sequestration (kg CO2e/kg biochar)*

Appendix D: Climate Action Reserve Biochar Permanence

Based on the Climate Action Reserve's biochar protocol (*US & Canada Biochar Protocol*, n.d.), the soil temperature raster was imported into QGIS and transformed using the biochar permanence equations assuming a conservative H:C ratio of 0.7 (maximum H:C ratio for biochar to be eligible for Climate Action Reserve's biochar protocol). Below is the QGIS Raster Calculator script to used:

```
if ( "Annual_Mean_Temp_clipped_CA@1" <= 5, 1.13-0.46*0.7,
     if ("Annual_Mean_Temp_clipped_CA@1" <= 10, 1.1-0.59*.7,
          if ("Annual_Mean_Temp_clipped_CA@1" <= 15,1.04-0.64*0.7,
               if ("Annual_Mean_Temp_clipped_CA@1" <= 20,1.01-
0.65*0.7, 0.98-0.66*0.7))))
```

The median permanence factor for each forested ecoregion is shown in the figure below.

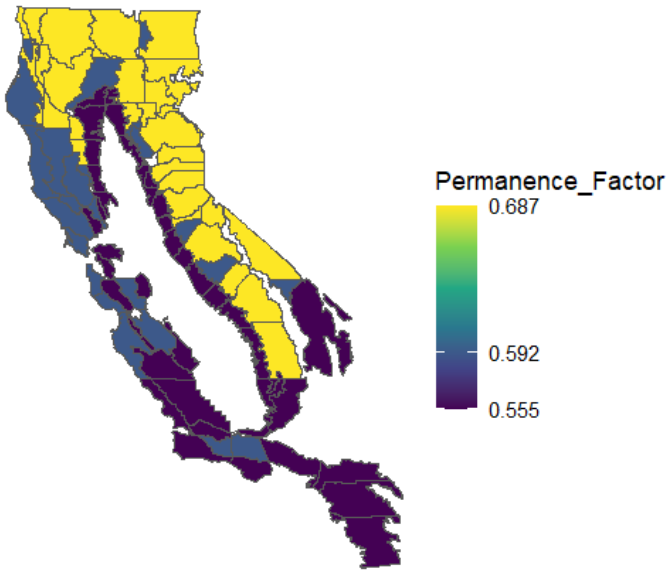


Figure 10: *Ecoregion median permanence factor for biochar with H:C ratio of 0.7 applied to California soils.*

The annual decay rate (assuming the biochar decomposes following exponential decay) was calculated by rearranging the exponential decay equation (Equation 2) to solve for the annual rate of decay (r).

Equation 2: Exponential Decay

$$C_t = C_0 e^{rt}$$

The calculated annual decay rate based on the median permanence factor of the forested ecoregions is shown in the figure below.

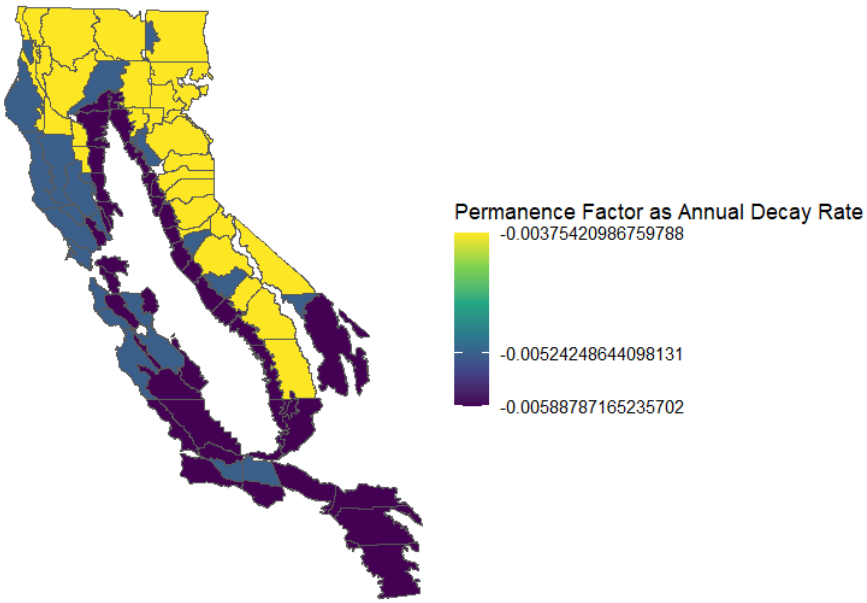


***Figure 11**: Climate Action Reserve Biochar Protocol annual decay rate for H:C ratio of 0.7 and assuming exponential decay.*