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Maximizing Biochar Climate Change Mitigation Impact Through Optimized Logistics

David Lefebvre¹  | Matthieu Heitz² | Jack Edgar¹ | Xiaotao Bi³ | Jeroen Meersmans⁴ | Jean-Thomas Cornelis¹ 

¹Faculty of Land and Food Systems, University of British Columbia, Vancouver, British Columbia, Canada | ²Department of Mathematics, University of British Columbia, Vancouver, British Columbia, Canada | ³Department of Chemical and Biological Engineering, University of British Columbia, Vancouver, British Columbia, Canada | ⁴TERRA Teaching and Research Center, Gembloux Agro-Bio Tech, University of Liège, Gembloux, Belgium

Correspondence: David Lefebvre (david.lefebvre@ubc.ca)

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ABSTRACT

Carbon dioxide removal (CDR) practices are essential to mitigating the adverse impacts of climate change. Some CDR practices depend on the availability and accessibility of feedstocks. The climate change mitigation potential of these practices relies on the difference between their location-specific efficiency and the greenhouse gas (GHG) emissions associated with establishing them. Focusing on biochar from forestry harvest residues in British Columbia (Canada), this manuscript demonstrates that optimizing the selection of biochar application areas and transportation routes can double the climate change mitigation potential of the practice across the province, as compared to random selection. We argue that spatially explicit ex-ante modeling of CDR potential and transportation optimization should become the norm for any new relevant CDR project to ensure the maximization of its climate change mitigation potential.

1 | Introduction

As greenhouse gas (GHG) emissions continue to rise, urgent actions are needed to mitigate the adverse impacts of climate change. This includes an imperative reduction in fossil fuel consumption, the prevention of emissions from land-use changes, and the implementation of carbon dioxide removal (CDR) techniques (Friedlingstein et al. 2023). Among CDR techniques, some necessitate accessing and transporting specific feedstocks (e.g., biochar, enhanced weathering, and ocean fertilization). The effectiveness of these practices hinges upon the availability of feedstocks to remove CO₂ from the atmosphere. Regardless of their renewability, their availability will ultimately determine the bottleneck of these practices' mitigation potential. Hence, acknowledging the urgency of the climate crisis, there is a critical need to better understand and quantify CO₂ emissions related to

the accessibility and transportation of these CDR techniques if we are to maximize their potential for climate change mitigation.

Among these CDR practices, biochar production is rapidly gaining traction (Cowie 2023), and currently stands as the largest engineered (i.e., excluding natural system (e.g., reforestation and cover cropping)) method for delivering CDR (Höglund et al. 2024). However, its climate change mitigation efficacy is influenced by a multitude of factors not yet sufficiently quantified. While certain factors, such as production parameters and feedstock characteristics, are controllable and already well studied, others are intricately linked to environmental and logistic parameters (Lehmann et al. 2021). Additionally, assessing the potential of any CDR practice mandates accounting for emissions associated with its setup and operation. Notably, feedstock-dependent CDR practices, including biochar, require transportation for their implementation.

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The emissions associated with transportation can accumulate, potentially offsetting a significant portion, if not all, of the practice's climate change mitigation potential (Lefebvre et al. 2019). Understanding these adverse factors is critical to maximizing CDR practices' potential.

Building upon an existing assessment of biochar's climate change mitigation potential in British Columbia (Lefebvre et al. 2024), this study employs a life cycle assessment (LCA) approach and transport optimization algorithm to assess the emissions linked to the production, transport, and application of forestry harvest residue-derived biochar in the province of British Columbia, Canada. The novelty of this approach not only enhances the predictive capabilities of CDR practices by considering emissions associated with feedstock accessibility and biochar transportation at large scale but also provides a new standard and comprehensive assessment of biochar potential for carbon sequestration, providing actionable insights for wider application.

The dispersed and remote nature of forestry and agricultural activities across the province, coupled with the diverse response of agricultural soils to biochar addition (Lefebvre et al. 2024), provides an ideal context to observe the impact of application area and transport route optimization on biochar's climate change mitigation potential. By unraveling these intricacies, we aim to demonstrate the significant impact of effective planning on the efficacy of biochar in BC and beyond, and promote the use of similar approaches for all feedstock and location dependent CDR practices.

2 | Methods

Previous biochar potential assessments (Ayer and Dias 2018; Brassard et al. 2018; Hammond et al. 2011; Lugato et al. 2013; Marzeddu et al. 2021; Rajabi Hamedani et al. 2019; Sahoo et al. 2021) model biochar transportation emissions using a single or a limited number of representative travel distances. In this paper, we refine this approach by mapping individual forests, fields, and biochar production hubs, and considering the length of individual routes from each forest to each hub and from each hub to each agricultural field.

This manuscript studies the impact of optimizing two aspects of the entire CDR process: the selection of biochar application areas and the transportation of the biochar. Optimizing the first aspect means favoring fields with higher capture potential, instead of spreading the biochar evenly on all agricultural land. Optimizing the second aspect means favoring the forests and fields that are closer to production hubs, to decrease the total distance traveled. We use an optimization algorithm (see Section 2.4) that determines how much biochar to transport from each forest to each production hub, and from each production hub to each field, in order to minimize the total (GHG) emissions.

2.1 | Assumptions

This study relies on a set of requirements and assumptions regarding forest harvest residue production and biochar yield and application rate. First, this study assumes that 157,314 ha forest

were harvested in 2021 (Government of Canada 2023), and that 25 dry tonnes of forestry harvest residues are produced, on average, per hectare of forest harvested (Blackburn 2017). Therefore, 3.9 Mt of forestry harvest residues were produced in 2021, estimates in line with available numbers for different years (Smyth et al. 2020; Wang et al. 2020). We have assumed that the harvest residues are collected at 40% moisture, which affects the weight of forest residues transported and hence their emissions (Jacobson et al. 2021).

Second, we have assumed a biochar yield of 22% by weight, based on Veksha et al. (2014). This value represents a slightly conservative estimate for wood processed in advanced pyrolysis systems and was selected to ensure the robustness of our estimates and maintain consistency with the first phase of this project (Lefebvre et al. 2024). Hence, residues from 2021 harvested stands could have produced a total of 865,228 oven dry tonnes of biochar. If evenly spread over the 746,166 ha of agricultural land considered in this study (Lefebvre et al. 2024) the average biochar application rate would reach 1.16 oven dry tonnes per hectare. In addition, we have assumed a maximum biochar application rate on any field of 10 tonnes per hectare as a realistic investment for farmers. This assumption also prevents the optimization algorithm from choosing to transport all produced biochar to the single closest field. Finally, we have considered eight relatively high population areas as potential biochar production hubs throughout the province (Figure 6).

While alternative assumptions on biochar yield or production parameters could have been used, the values selected are supported by the literature and ensure consistency with the first phase of this project described in Lefebvre et al. (2024). Crucially, this study aims to assess the influence of application area and transport route optimization on the CDR potential of the practice, which remains relevant regardless of the specific production parameters assumed.

2.2 | Scenarios

Four optimization scenarios were explored in this study. In the "Optimal" scenario, both aspects previously mentioned (field selection and transportation routes) are optimized. This means that both the modeled climate change mitigation potential of each field and the route distances are considered to maximize climate change mitigation. In the "Even" scenario, we optimized transportation routes but maintained the same biochar application rate across all fields, disregarding the area-specific climate change mitigation potential. In the "Random" scenario, no optimization is performed as both the production hub and field for biochar application are selected randomly. Finally, the "Worst-Case" scenario represents the extreme inverse of the "Optimal" scenario. In this scenario, transportation routes and field selection are determined to minimize climate change mitigation efforts.

The distinction between the first two scenarios (Optimal and Even) underscores the impact of targeting application in fields with higher relative climate change mitigation potential. On the other hand, the "Worst-Case" scenario, though improbable across the entire province, provides insight into the detrimental

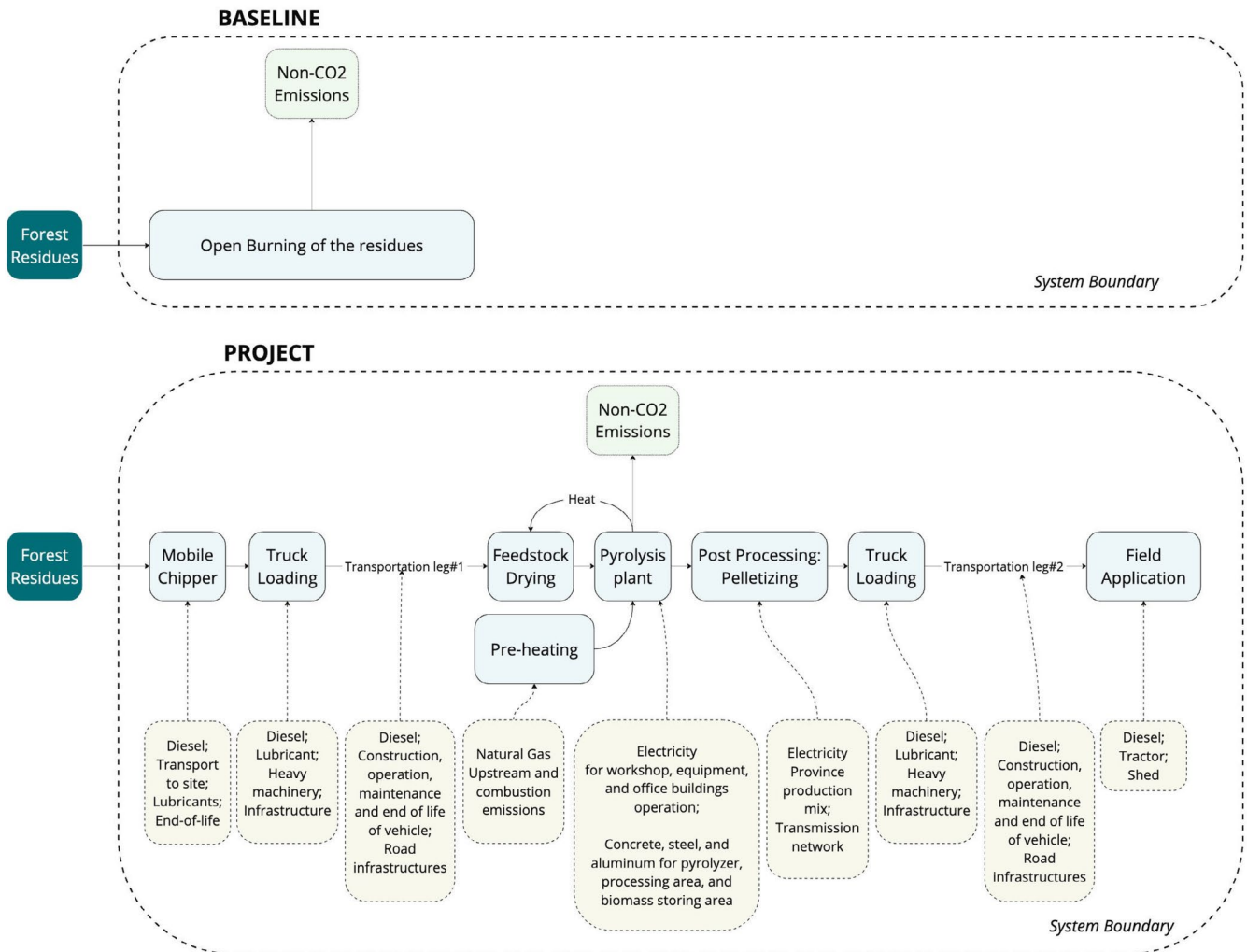


FIGURE 1 | Life cycle assessment system boundary. Blue represents the different processes with their associated input source in yellow. The boundary account for the non-CO₂ emissions associated with the open combustion and pyrolysis process.

effects of extended transportation routes and suboptimal field selection, which may result from specific commercial partnerships or lack of insight.

2.3 | Life Cycle Assessment

This study relies on an attributional “cradle to grave” LCA approach to quantify the emissions associated with the biochar production, transportation, and use (Figure 1). When available, processes were extracted from the EcoInvent database version 3.9.1 for consistency (Wernet et al. 2016). We selected the IPCC 2021 impact category, using global warming potentials at 20-year period (GWP—20years) to correspond with the biochar climate change mitigation potential modeled in Lefebvre et al. (2024). This study looked at a unique application of 1 tonne of biochar, hence the impacts were modeled considering a 20-year time horizon to account for the duration and magnitude variation over time of biochar effect on plant biomass and nitrous oxide emissions from soil (Lefebvre et al. 2024). The functional unit of this assessment is “per dry tonne of biochar produced and applied to agricultural field”. Additionally, we have assumed that the bio-oil and syngas

generated alongside biochar during pyrolysis are combusted during the process. Consequently, all emissions are attributed solely to biochar production.

In the absence of a project, it is assumed that forestry harvest residue piles are burnt on site in the fall, following wildfire prevention regulations (BC Hydro, and Industrial Forestry Service Ltd 2018; Wang et al. 2022) (Figure 1).

Our project scenario starts with the chipping of harvest residues at the forest road using a diesel mobile chipper. Those chipped residues are then loaded onto trucks and transported to a pyrolysis plant. The pyrolysis plant is assumed to be an industrial-scale continuous facility, capable of processing 10 tonnes of dry biomass per hour and with an estimated lifetime of 20 years. It utilizes natural gas for preheating while excess heat during steady operation from pyrolysis is employed to dry incoming feedstock. This assumption is supported by several biochar LCAs, which report excess electricity generation even after utilizing part of the heat for drying incoming feedstock (Hammond et al. 2011; Leme et al. 2018; Muñoz et al. 2017; Quirk et al. 2012; Rajabi Hamedani et al. 2019). The plant processes the feedstock at approximately 600°C.

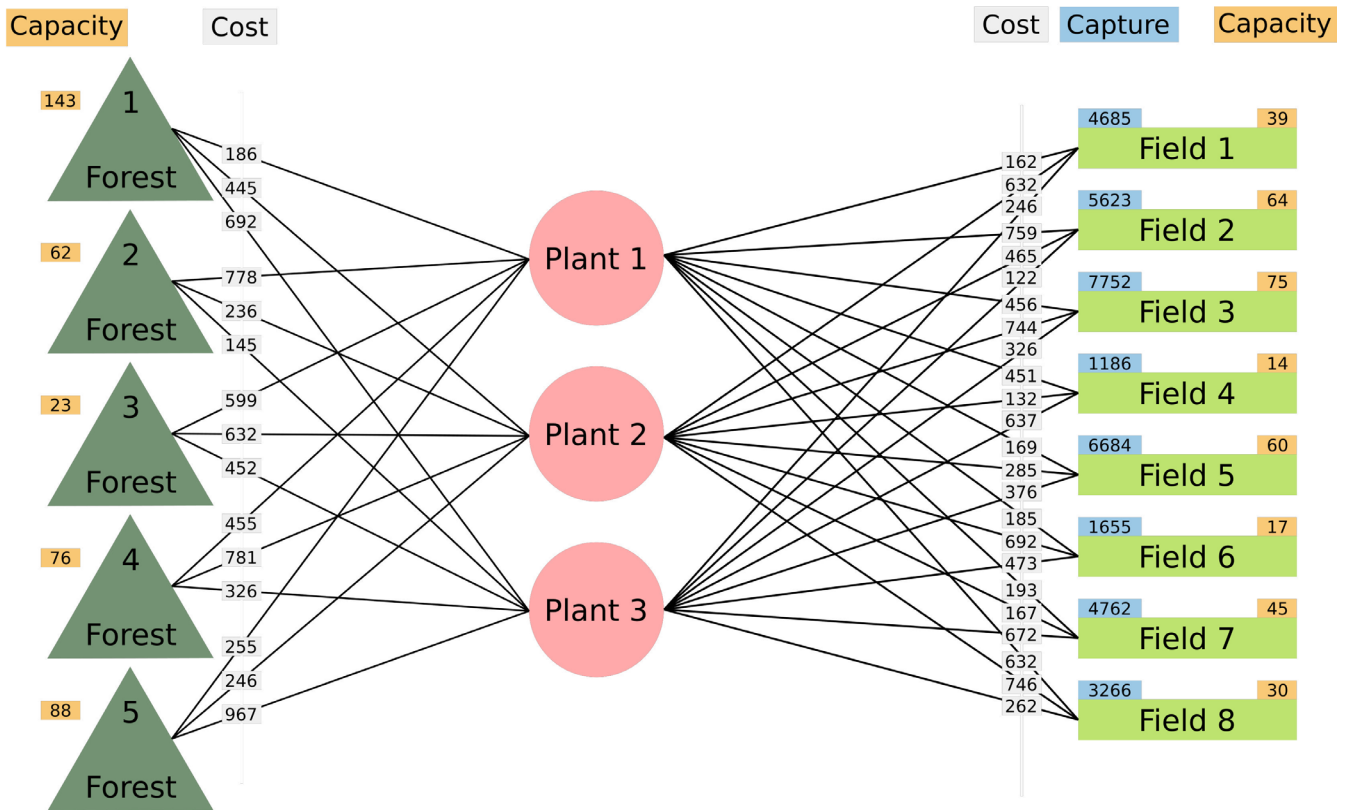


FIGURE 2 | Graph model for the transport optimization. Each forest has a production capacity, each route a transportation cost, and each field a climate change mitigation potential and an application capacity (all arbitrary units). The network simplex algorithm is used to find the way of transporting the biochar from the forests to the fields through the pyrolysis plants, that minimizes cost and maximizes capture. The demands and supplies at each forest and field are not shown here as they are optimized by the algorithm, see [Supporting Information](#) for more details.

Once the biochar exits the pyrolizer, it undergoes pelletization, a regular process to ease handling and enhance health and safety. Subsequently, the biochar is loaded onto trucks and transported to the receiving area and spread on the topsoil using an agricultural spreader (Figure 1).

We conducted the uncertainty analysis using the Monte Carlo method with 10,000 iterations. Additional information, including a comprehensive list of data and processes utilized for the LCA and Monte Carlo analysis, is available in the [Supporting Information](#).

2.4 | Transport Optimization Algorithm

Our analysis relies on the optimization of biochar transportation routes and the selection of biochar application areas at the provincial level of BC. Our model is a graph, where each node represents either a forest, a field, or a biochar producing plant, and edges connect each forest to each plant, and each plant to each field (see Figure 2 for a simplified case).

We then define attributes that reflect the desired flow of feedstock (biochar) in the graph: demand, capacity, and cost. The demand describes how much feedstock is needed, while supply describes availability at each location. The cost describes the transport cost, and capacity refers to the maximum feedstock flow along each route. Note that field climate change

mitigation potentials can be seen as negative CO₂e costs. These attributes can thus define a minimum-cost flow problem (Ahuja et al. 1993) on the graph, that is, finding a flow of feedstock through the graph, from the supply nodes to the demand nodes, that minimizes the flow cost while respecting the capacities. For the Optimal, Even, and Worst-Case scenarios, this problem has been solved using the network simplex algorithm (Király and Kovács 2012), whereas the Random scenario does not require any optimization and has been solved by generating random assignments from forests to plants, and then from plants to fields.

The attributes were computed the following way: the forest capacities were calculated based on their area and expected residues production ratio per quantity harvested (see Section 2.1). The transportation emission/cost of each route is its length multiplied by a transport emission/cost factor depending on the transportation leg (forest to biochar plant or biochar plant to field) accounting for the mass of either wet residue or biochar transported and including an empty return ([Supporting Information](#)). Route lengths have been computed as the shortest itinerary between the start and end location through the actual road network, using the OpenStreetMap API. The climate change mitigation capacities for each field were calculated based on the modeling described in (Lefebvre et al. 2024), by assuming a maximum biochar application rate of 10 tonnes per hectare. In-depth description of the model and implementation details can be found in the [Supporting Information](#).

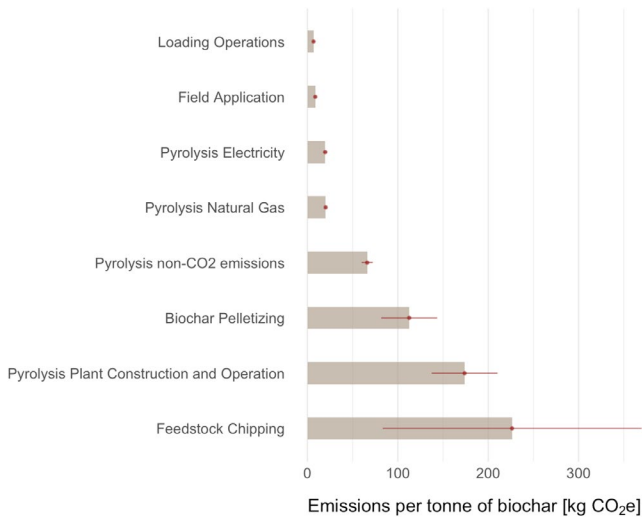


FIGURE 3 | Contribution analysis. Average impact of each process group in kg CO₂e per tonne of biochar produced and applied. The whiskers result from the Monte Carlo analysis and represent ± 1 SD.

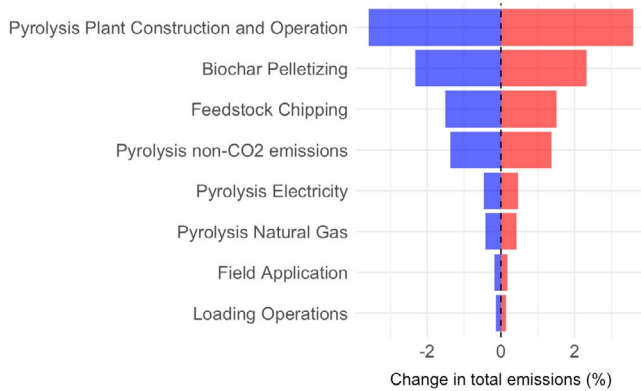


FIGURE 4 | Sensitivity analysis. Impact on total emission of a 10% increase (red) or a 10% decrease (blue) on the activity data of each process included in the production and application of biochar (except transportations legs).

2.5 | Software

EcoInvent 3.9.1 (Wernet et al. 2016) database was accessed through the OpenLCA software (version 2.1.1) (Ciroth et al. 2020). The Monte Carlo analysis, figures, and graphs were made using R software (version 4.3.1) (R Core Team 2023) and the package “ggplot2” (Wickham 2016). Access to the British Columbian road network was done using OpenStreetMap data through the “OSRM” R package (Giraud 2022). The transport optimization was done in Python (version 3.8.17), using the NetworkX package (version 3.1).

3 | Results

3.1 | Life Cycle Assessment

Our baseline assumptions consist of the open-air combustion of 4.55 tonnes of forest harvest residues (amount required to produce 1 tonne of biochar) which emits 2257 ± 465 kg CO₂e considering methane and nitrous oxide emissions only (Wernet et al. 2016).

Excluding transportation, our theoretical pyrolysis plant emits 634 ± 151 kg CO₂e per tonne of biochar produced and applied to the field. The contribution of each process to the final carbon footprint is shown in Figure 3.

Sensitivity analysis of our hypothetical biochar producing chain shows that the plant construction and operation is the most sensitive process, followed by the biochar pelletizing and feedstock chipping process (Figure 4).

3.2 | Optimization Effect

Each scenario leads to different total distance traveled, thus different transportation emissions. Figure 5 presents the average distance and average transport related GHG emissions of each scenario for the two transportation legs. Optimal and Even scenarios both optimize transportation and, as such, minimize the distances of the first transportation leg (from forest to biochar production hub) as this leg needs to transport 7.6 tonnes of feedstock per tonne of biochar (accounting for biochar yield and feedstock moisture content) and rely on smaller trucks than that for biochar transport (hence higher emission factors) to drive on forestry roads.

Similarly, each scenario leads to different field application strategies; hence, different climate change mitigation potentials. In the Optimal scenario, transportation distance of the forestry harvest residues to the biochar production site is minimized which leads to each biochar production hub being put to use while biochar application is focused (up to 10 tonnes per hectare) on the southwestern corner of the province, where the fields show the highest climate change mitigation potential in the province due to a combination of relatively high temperature, high precipitation, and crops with high nitrogen requirement (Lefebvre et al. 2024) (Figure 6). In the Even and Random scenario, every field receives an equal amount of biochar (around 1.16 tonne per hectare), but in the Even scenario, transportation is optimized leading to minimum transportation distances between forest, biochar production hub, and fields, while the Random scenario selected the production hub and field randomly (figures in Supporting Information—section 3). In the Worst-Case scenario, transportation distances are maximized to a couple of production hubs while biochar application is focused on fields in the northeastern part of the province where fields show the lowest climate change mitigation potential in the province (Lefebvre et al. 2024) (figures in Supporting Information—section 3).

3.3 | Climate Change Mitigation Potential

Including the process and transport emissions and considering the assumptions made in this study (Section 2.1), the optimal scenario leads to the average yearly climate change mitigation potential of 2662 ± 153 kg CO₂e per tonne of biochar or 2.29 ± 0.134 Mt. CO₂e over the entire province over a 20-year period (Figure 7). This corresponds to 3.9% of the total emissions of the province in 2021 or 100% of the emissions attributed to agriculture in BC the same year (Environment and Climate Change Canada 2023). These results are lowered to 3.3% and 1.7% of the total emissions of the province for the Even and Random scenario, respectively.

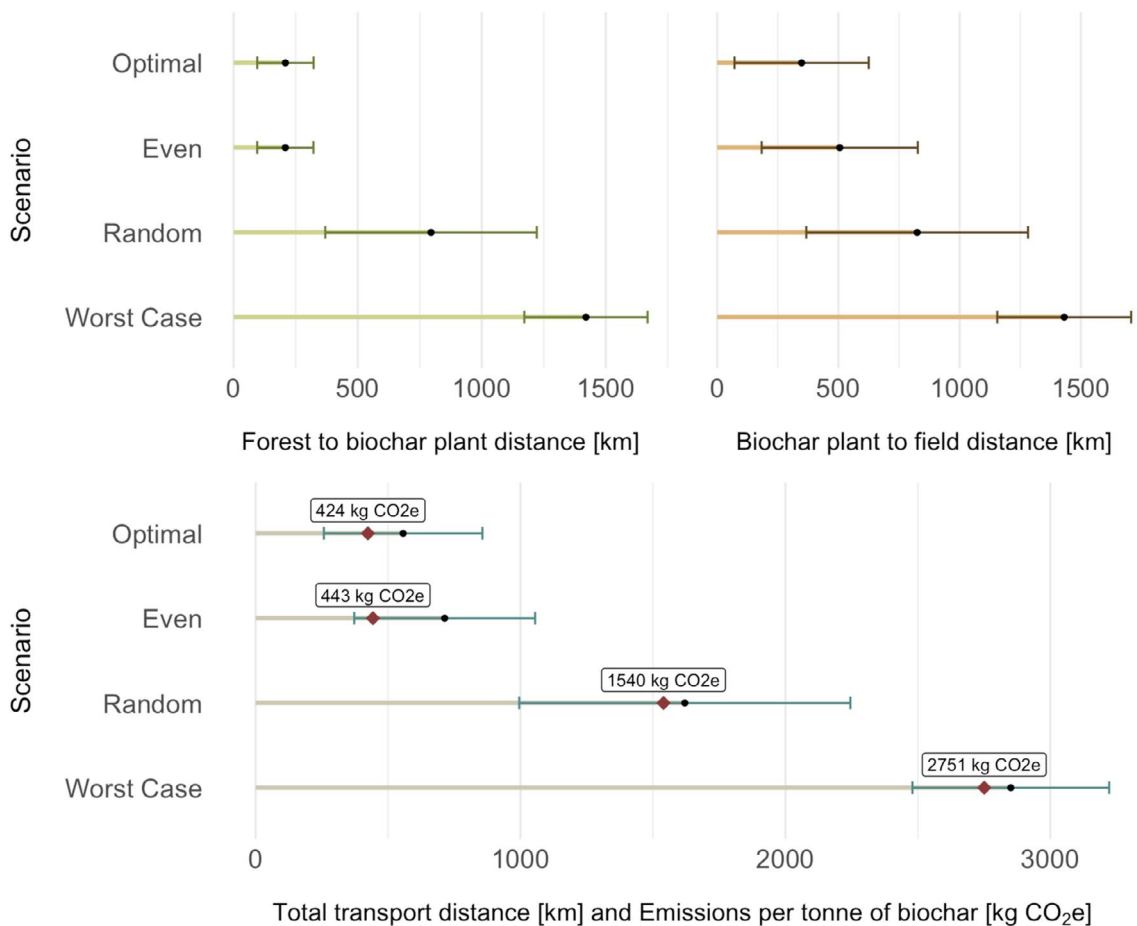


FIGURE 5 | Average transport distance (km) and associated emissions (kg CO₂e per tonne of biochar—red diamond and labels) for each of the scenario modeled in this study. Description of each transportation scenario is made in Section 2.2. The whiskers represent ±1 SD.

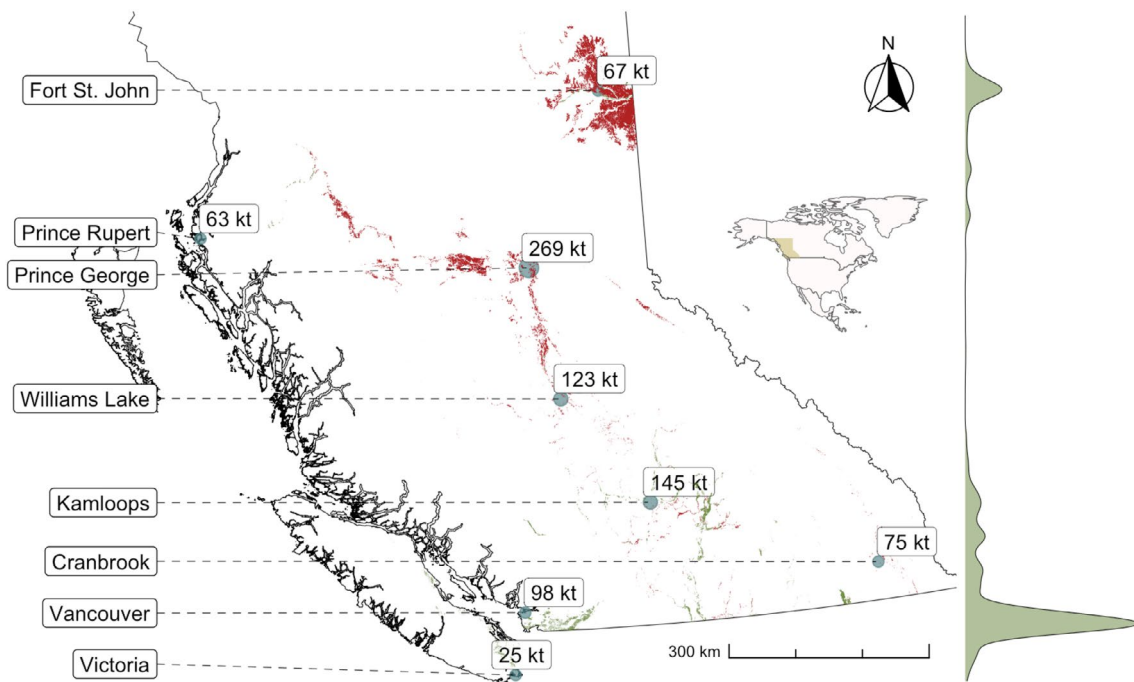


FIGURE 6 | Biochar application strategy for the optimal scenario. Green polygons depict agricultural fields receiving biochar. Red polygons indicate untreated fields. The green density plot aids in identifying latitudes of fields with biochar application. Left aligned labels represent biochar production hubs. Point size and label value reflect the annual biochar production requirements of each hub in kilo tonne for processing the incoming feedstock.

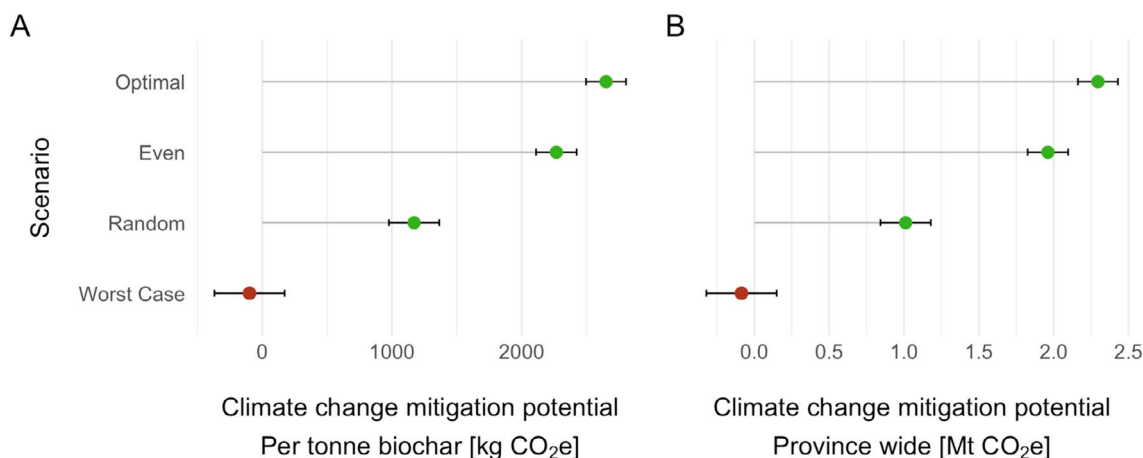


FIGURE 7 | Yearly climate change mitigation potential over a 20-year period of the different scenario, including process and transport emissions, averaged per tonne of biochar produced (A) and over the entire province (B). The red points signify that the scenario's mitigation potential is below 0 and therefore is a net emitter of CO₂e. The whiskers result from the Monte Carlo analysis and represent ±1 SD.

Including the avoided emissions from preventing the open-air burning of the pile residues, these climate change mitigation potentials become 4919 ± 489 kg CO₂e, 4535 ± 490 kg CO₂e, 3438 ± 504 kg CO₂e, and 2166 ± 538 kg CO₂e per tonne of biochar for the Optimal, Even, Random, and Worst-Case scenario, respectively.

4 | Discussion

4.1 | An Improved Assessment of CDR Potential of Biochar

Our Optimal climate mitigation potential scenario includes biochar impact on organic carbon stocks, plant biomass, nitrous oxide emissions from soils, and lime requirement (Lefebvre et al. 2024) and accounts for the emissions to produce, transport, and apply the biochar to fields. Although results from biochar LCA studies cannot be reliably compared as both biochar's climate change mitigation potential and associated emissions are location, method, and boundary specific, our "Optimal" net (including all emissions to setup the practice) emissions reduction results are in line with the literature (Figure 8A) (Cowie and Cowie 2023; Lefebvre et al. 2023; Matuščík et al. 2021). It is important to note that previous LCAs in this comparison use GWP100, whereas our analysis employs GWP20, which places greater emphasis on short-lived greenhouse gases such as methane and nitrous oxide. This therefore does not allow for a direct comparison of the net emission reduction potential of our scenarios with the existing literature. Nevertheless, we consider this comparison a reasonable representation that our net emission reduction assessments align with the range reported in existing biochar LCAs.

However, most biochar potential assessments focus on well-defined systems within specific geographical areas. This is evidenced by the typically short transportation distances reported in these studies (e.g., ranging of 32–190 km in (Ayer and Dias 2018; Brassard et al. 2018; Hammond et al. 2011; Lugato et al. 2013; Marzeddu et al. 2021; Rajabi Hamedani et al. 2019; Sahoo et al. 2021)) (Figure 8B). While those studies have

significantly supported the understanding of biochar's CDR potential, their claims of net climate negativity may not hold true as the practice scales beyond their system boundaries due to transportation-related emissions.

Our provincial scale assessment, taking into account the reality of BC's eco-cultural context, reveals transportation distances orders of magnitude larger than system-scale assessments, significantly impacting the net CDR potential of the practice. With the number of biochar projects growing rapidly and more CDR projects emerging (Geden et al. 2024), the search for available feedstock will become broader, and transportation distances will increase. It is crucial to start updating CDR potential models at a wider geographical scale to maximize their mitigation potential while revealing any limitations and potential challenges, thus emphasizing the need for ex-ante modeling and optimization of CDR practices and transportation routes.

4.2 | Opportunities for Improvement

4.2.1 | Including Biogenic Emissions

Carbon dioxide is emitted during pyrolysis or open combustion of forest residues. Those emissions are considered biogenic (of biological origin) and are usually excluded from LCA calculations because the CO₂ emitted from combustion of organic feedstocks is assumed to be captured back as the biomass regrows. This assumption may be an elegant shortcut for annual feedstocks, but marketable forest plots in BC have a lifecycle of 25 to 90 years (Watts and Tolland 2005) hence, assuming all the CO₂ emitted during pyrolysis is offset by the growing tree is an unrealistic claim when accounting for the 20-year timeframe climate change mitigation potential of the practice (Matuščík et al. 2021).

The emitted biogenic CO₂ fraction of pyrolysis was computed using the model described in Kane and Miller (2024) and reached 7599 ± 1615 kg CO₂ per tonne of biochar produced, using biomass composition from Moriana et al. (2015) and setting the pyrolysis efficiency to 75%, as a conservative assumption for large-scale

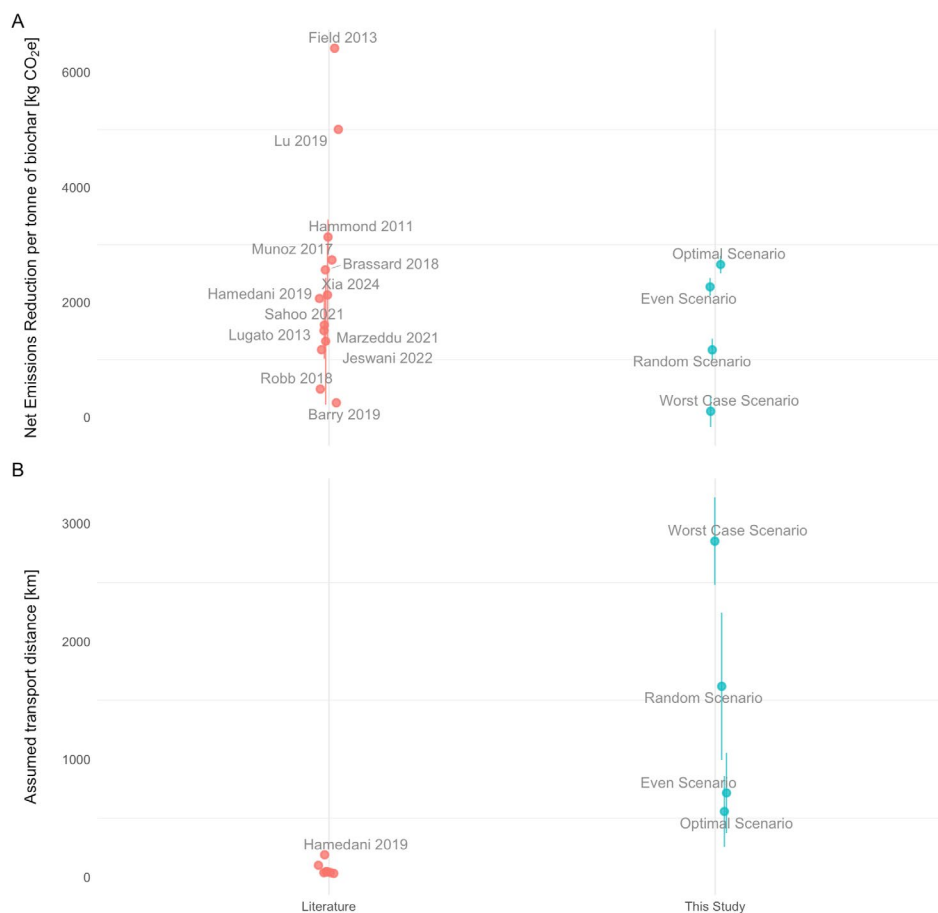


FIGURE 8 | Comparison of net emissions reduction results (A) and assumed transportation distances (B) between this study and values found in the literature (Ayer and Dias 2018; Barry et al. 2019; Brassard et al. 2018; Field et al. 2013; Hammond et al. 2011; Jeswani et al. 2022; Lu and El Hanandeh 2019; Lugato et al. 2013; Marzeddu et al. 2021; Muñoz et al. 2017; Rajabi Hamedani et al. 2019; Robb and Dargusch 2018; Sahoo et al. 2021; Xia et al. 2024). The whiskers represent \pm one standard deviation (when available).

industrial pyrolysis systems. This puts our optimal scenario as an overall net emitter of 4944 ± 1622 kg CO₂e per tonne of biochar. The biogenic emissions associated with the open-air burning of the forestry residues amount to 6249 ± 1091 kg CO₂ per tonne of biochar (Wernet et al. 2016). When methane and nitrous oxide emissions are included, this results in a total of 8506 ± 1186 kg CO₂e per tonne of biochar. Therefore, when incorporating biogenic emissions, our optimal scenario remains carbon negative, with a net climate change mitigation potential of 907 ± 2003 kg CO₂e sequestered per tonne of biochar. Ideally, this value needs to be subtracted from the average CO₂e captured in the first 20 years of a growing BC forest plot to truthfully represent the emissions associated with biochar production. Since including biogenic emissions into LCAs is not yet the norm, it does not allow for comparison with other systems. The LCA community as a whole needs to change this approach and start including biogenic CO₂ in their calculations to more truthfully represent process-associated GHG emissions.

4.2.2 | Consider On-Site Biochar Production

Utilizing forestry harvest residues poses a significant challenge due to their widespread and remote distribution throughout the province (Wilson et al. 2024). Consequently, on-site biochar

production is often considered the optimal method for managing those residues and avoiding transportation legs (Wilson et al. 2024). In addition, converting forest slash to biochar on-site has many ecological advantages over the current practice of slash disposal by open burning (accounting for 4.6% of the provinces total CO₂e emissions (Environment and Climate Change Canada 2023)), including reduced soil heating, gas and particulate emissions, along with multiple benefits of the biochar to forest soil health and water-holding capacity when left in place (Wilson et al. 2024). Additionally, on-site production and application of biochar are less extractive, maintaining carbon pools in forest ecosystems.

However, on-site production necessitates mobile pyrolysis systems, which are typically less efficient and lack afterburners and filters, leading to lower efficiency and higher GHG emissions. Lowering feedstock moisture content has been shown to significantly reduce methane emissions from low-tech pyrolyzers (Cornelissen et al. 2023), but on-site moisture management and drying are much more challenging compared to industrial drying systems, especially given the wet nature of BC's climate.

Although, on-site biochar production is more ecologically advantageous than slash burn piles, it is more logistically difficult and currently lacks economic incentive. Due to the aforementioned

inefficiencies of mobile systems, those methods have gained few accreditations for verified carbon removal; therefore, the emissions reduction is not currently valued by the marketplace. Additionally, the yield and market access of remote, mobile biochar production will be less than that of a centralized facility.

With that said, we welcome the continued innovation of future mobile systems which may address those concerns. Considering the remote and diverse landscape of BC, there may be instances when mobile production is the most fitting solution. Additionally, mobile production provides opportunity for in situ biochar application to amend degraded forest soils. Although spreading and incorporating biochar into forest soils presents its own set of logistical and ecological challenges, applying it in easily accessible areas, such as forestry landings, could be an interesting solution for further exploration.

4.3 | Optimization Impact

Based on our case-study context, the Optimal scenario for climate change mitigation potential (optimizing transportation routes and field selection) is, on average, 17% higher than the Even (optimizing transportation routes only) scenario. This means that maximizing biochar application in geographical areas with high expected biochar climate change mitigation potential (Lefebvre et al. 2024) can have an important impact on the potential of the practice.

Similarly, the Even scenario's climate change mitigation potential is almost double the Random scenario's potential (random selection of production hub and fields), highlighting the importance of optimizing transportation routes to maximize the climate change mitigation potential of the practice.

However, BC is a relatively large territory, and the optimization results from this case study should not be directly extrapolated to regions with significantly different spatial scale and geographical contexts. As modeled transportation distances decrease (while all other parameters remain constant), the relative benefits of optimization in terms of net CO₂ sequestration potential (when comparing the Optimal and Random scenarios) decline significantly (Figure 9). This suggests that while our approach may be particularly beneficial in regions with long transportation routes, its impact may be less pronounced in regions where transportation distances are inherently shorter.

Similarly, advancements in transportation technologies, particularly the shift from diesel to electric vehicles and renewable fuels, will have significant implications for the results presented here. These developments will reduce the overall greenhouse gas emissions associated with transportation, diminishing the benefits of optimization. Nevertheless, resource use and operational efficiency will remain critical. By minimizing transportation distances and maximizing carbon mitigation potential per tonne of biochar, the Optimal scenario remains relevant, offering both environmental and financial advantages to non-optimized scenarios. Indeed, the total transportation distance in the Optimal scenario is, on average, one-third of that in the Random scenario (Figure 5), leading to lower transportation costs, while the average mitigation potential per tonne of biochar

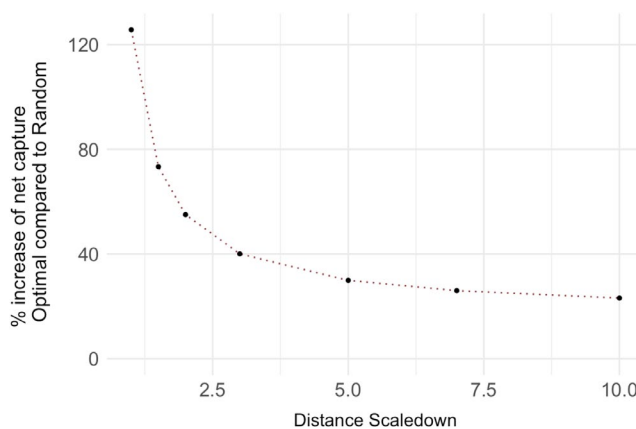


FIGURE 9 | Progression of optimization benefits, expressed as the percentage increase in net CO₂ captured in the Optimal scenario relative to the Random scenario, as modeled transportation distances are scaled down by factors from 1 to 10, with all other parameters held constant.

in the Optimal scenario is more than double that of the Random scenario (Figure 7), thereby enhancing potential revenue from carbon credits. By simultaneously minimizing costs and maximizing financial returns, the Optimal scenario is expected to be the most economically viable among the alternatives. However, implementing the Optimal scenario across BC would require province-wide transportation logistics oversight, which may not be fully feasible in practice. Nevertheless, our approach can serve as a guideline or be applied to aggregated forest and field areas rather than being constrained to the specific granularity examined in this study.

The Worst-Case scenario is a net emitter of CO₂e and, although unlikely, must serve as a reminder that CDR practices' potential should not be taken for granted but that each application should be contextualized and assessed ahead of implementation.

5 | Conclusion

This study shows that planning and optimizing the implementation of biochar systems can have an important impact on its climate mitigation benefits. In the context of British Columbia, considering biochar derived from forestry residues, its application in agricultural settings, and current transportation technologies, ex-ante modeling of biochar climate change mitigation potential along with optimization of field selection and transportation logistics can enhance biochar's net potential by 126%.

We argue that this approach should be applied to all transport-dependent CDR practices and that project funding should not only be approved by proof of carbon negativity (usually incumbent for CDR practices) but also through comparison of CDR application scenarios to ensure maximization of its climate change mitigation potential.

Author Contributions

David Lefebvre: conceptualization, data curation, methodology, software, writing – original draft, writing – review and editing. **Mathieu**

Heitz: data curation, formal analysis, methodology, software, visualization, writing – original draft, writing – review and editing. **Jack Edgar:** conceptualization, project administration, writing – original draft, writing – review and editing. **Xiaotao Bi:** conceptualization, methodology, project administration, supervision, writing – original draft, writing – review and editing. **Jeroen Meersmans:** data curation, software, writing – review and editing. **Jean-Thomas Cornelis:** conceptualization, methodology, project administration, supervision, writing – original draft, writing – review and editing.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are openly available in Borealis at <https://doi.org/10.5683/SP3/FCWUUK>. Code Availability Statement: The code used to generate the results of this study is openly available in Borealis at <https://doi.org/10.5683/SP3/FCWUUK>.

References

- Ahuja, R. K., T. L. Magnanti, and J. B. Orlin. 1993. “Network Flows: Theory, Algorithms, and Applications.” <https://api.semanticscholar.org/CorpusID:12577796>.
- Ayer, N. W., and G. Dias. 2018. “Supplying Renewable Energy for Canadian Cement Production: Life Cycle Assessment of Bioenergy From Forest Harvest Residues Using Mobile Fast Pyrolysis Units.” *Journal of Cleaner Production* 175: 237–250. <https://doi.org/10.1016/j.jclepro.2017.12.040>.
- Barry, D., C. Barbiero, C. Briens, and F. Berruti. 2019. “Pyrolysis as an Economical and Ecological Treatment Option for Municipal Sewage Sludge.” *Biomass and Bioenergy* 122: 472–480. <https://doi.org/10.1016/j.biombioe.2019.01.041>.
- BC Hydro & Industrial Forestry Service Ltd. 2018. “Wood Based Biomass in British Columbia and Its Potential for New Electricity Generation Prepared for BC Hydro’s Long Term Planning Process.” March, 1–56. <https://www.bchydro.com/content/dam/BCHydro/customer-portal/documents/corporate/regulatory-planning-documents/integrated-resource-plans/current-plan/rou-characterization-wood-based-biomass-report-201507-industrial-forestry-service.pdf>.
- Blackburn, K. 2017. “Bulkley Timber Supply Area Biomass Availability Estimation (Vol. 52, Issue 52).” <https://www2.gov.bc.ca/assets/gov/farming-natural-resources-and-industry/forestry/timber-tenures/fibre-recovery/tr2017n52.pdf>.
- Brassard, P., S. Godbout, F. Pelletier, V. Raghavan, and J. H. Palacios. 2018. “Pyrolysis of Switchgrass in an Auger Reactor for Biochar Production: A Greenhouse Gas and Energy Impacts Assessment.” *Biomass and Bioenergy* 116: 99–105. <https://doi.org/10.1016/j.biombioe.2018.06.007>.
- Ciroth, A., C. Noi, T. Lohse, and M. Srocka. 2020. “openLCA 1.10 – Comprehensive User Manual. V 1.10.2, 127.” <https://www.openlca.org/learning/>.
- Cornelissen, G., E. Sørmo, R. K. A. de la Rosa, and B. Ladd. 2023. “Flame Curtain Kilns Produce Biochar From Dry Biomass With Minimal Methane Emissions.” *Science of the Total Environment* 903: 166547. <https://doi.org/10.1016/j.scitotenv.2023.166547>.
- Cowie, A. L. 2023. “Biochar as a Fast Track to Net Zero.” *Nature Food* 4: 203–204. <https://doi.org/10.1038/s43016-023-00714-z>.
- Cowie, A. L., and A. J. Cowie. 2023. “Life Cycle Assessment of Greenhouse Gas Mitigation Benefits of Biochar Case Study Report.” (Issue March). <https://doi.org/10.13140/RG.2.2.34348.13442>.
- Environment and Climate Change Canada. 2023. “National Inventory Report 1990–2021: Greenhouse Gas Sources and Sinks in Canada.” <https://publications.gc.ca/site/eng/9.506002/publication.html>.
- Field, J. L., C. M. H. Keske, G. L. Birch, M. W. Defoort, and M. Francesca Cotrufo. 2013. “Distributed Biochar and Bioenergy Coproduction: A Regionally Specific Case Study of Environmental Benefits and Economic Impacts.” *GCB Bioenergy* 5, no. 2: 177–191. <https://doi.org/10.1111/gcbb.12032>.
- Friedlingstein, P., M. O’Sullivan, M. W. Jones, et al. 2023. “Global Carbon Budget 2023.” *Earth System Science Data* 15, no. 12: 5301–5369. <https://doi.org/10.5194/essd-15-5301-2023>.
- Geden, O., M. J. Gidden, W. F. Lamb, J. C. Minx, and S. M. Smith. 2024. “The State of Carbon Dioxide Removal 2024 – 2nd Edition.” <https://doi.org/10.17605/OSF.IO/F85QJ>.
- Giraud, T. 2022. “Osm: Interface Between R and the OpenStreetMap-Based Routing Service OSRM.” *Journal of Open Source Software* 7, no. 78: 4574. <https://doi.org/10.21105/joss.04574>.
- Government of Canada. 2023. “Vegetation Resource Inventory (2002–2022). VRI.” <https://catalogue.data.gov.bc.ca/dataset>.
- Hammond, J., S. Shackley, S. Sohi, and P. Brownsort. 2011. “Prospective Life Cycle Carbon Abatement for Pyrolysis Biochar Systems in the UK.” *Energy Policy* 39, no. 5: 2646–2655. <https://doi.org/10.1016/j.enpol.2011.02.033>.
- Höglund, R., K. Niparko, Q. Servais-Laval, et al. 2024. “Trending on Track? – CDR.fyi 2023 Year in Review.” CDR.fyi.
- Jacobson, R., S. Sokhansanj, D. Roeser, J. Hansen, B. Gopaluni, and X. Bi. 2021. “A Cost Analysis of Mobile and Stationary Pellet Mills for Mitigating Wildfire Costs.” *Journal of Sustainable Bioenergy Systems* 11, no. 3: 131–143. <https://doi.org/10.4236/jsbs.2021.113010>.
- Jeswani, H. K., D. M. Saharudin, and A. Azapagic. 2022. “Environmental Sustainability of Negative Emissions Technologies: A Review.” *Sustainable Production and Consumption* 33: 608–635. <https://doi.org/10.1016/j.spc.2022.06.028>.
- Kane, S., and S. A. Miller. 2024. “Predicting Biochar Properties and Pyrolysis Life-Cycle Inventories With Compositional Modeling.” *Bioresour Technol* 399: 130551. <https://doi.org/10.1016/j.biortech.2024.130551>.
- Király, Z., and P. Kovács. 2012. “Efficient Implementations of Minimum-Cost Flow Algorithms.” <https://doi.org/10.48550/arXiv.1207.6381>.
- Lefebvre, D., J. T. Cornelis, J. Meersmans, J. Edgar, M. Hamilton, and X. Bi. 2024. “Environmental Factors Controlling Biochar Climate Change Mitigation Potential in British Columbia’s Agricultural Soils.” *GCB Bioenergy* 16, no. 1: 13109. <https://doi.org/10.1111/gcbb.13109>.
- Lefebvre, D., S. Fawzy, C. A. Aquije, A. I. Osman, K. T. Draper, and T. A. Trabold. 2023. “Biomass Residue to Carbon Dioxide Removal: Quantifying the Global Impact of Biochar.” *Biochar* 5, no. 1: 65. <https://doi.org/10.1007/s42773-023-00258-2>.
- Lefebvre, D., P. Goglio, A. Williams, et al. 2019. “Assessing the Potential of Soil Carbonation and Enhanced Weathering Through Life Cycle Assessment: A Case Study for Sao Paulo State, Brazil.” *Journal of Cleaner Production* 233: 468–481. <https://doi.org/10.1016/j.jclepro.2019.06.099>.
- Lehmann, J., A. Cowie, C. A. Masiello, et al. 2021. “Biochar in Climate Change Mitigation.” *Nature Geoscience* 14, no. 12: 883–892. <https://doi.org/10.1038/s41561-021-00852-8>.

- Leme, M. M. V., O. J. Venturini, E. E. S. Lora, et al. 2018. "Electricity Generation From Pyrolysis Gas Produced in Charcoal Manufacture: Technical and Economic Analysis." *Journal of Cleaner Production* 194: 219–242. <https://doi.org/10.1016/j.jclepro.2018.05.101>.
- Lu, H. R., and A. El Hanandeh. 2019. "Life Cycle Perspective of Bio-Oil and Biochar Production From Hardwood Biomass; What Is the Optimum Mix and What to Do With It?" *Journal of Cleaner Production* 212: 173–189. <https://doi.org/10.1016/j.jclepro.2018.12.025>.
- Lugato, E., F. P. Vaccari, L. Genesio, et al. 2013. "An Energy-Biochar Chain Involving Biomass Gasification and Rice Cultivation in Northern Italy." *GCB Bioenergy* 5, no. 2: 192–201. <https://doi.org/10.1111/gcbb.12028>.
- Marzeddu, S., A. Cappelli, A. Ambrosio, M. A. Décima, P. Viotti, and M. R. Boni. 2021. "A Life Cycle Assessment of an Energy-Biochar Chain Involving a Gasification Plant in Italy." *Land* 10, no. 11: 1256. <https://doi.org/10.3390/land10111256>.
- Matušík, J., M. Pohořelý, and V. Kočí. 2021. "Is Application of Biochar to Soil Really Carbon Negative? The Effect of Methodological Decisions in Life Cycle Assessment." *Science of the Total Environment* 807: 151058. <https://doi.org/10.1016/j.scitotenv.2021.151058>.
- Moriana, R., F. Vilaplana, and M. Ek. 2015. "Forest Residues as Renewable Resources for Bio-Based Polymeric Materials and Bioenergy: Chemical Composition, Structure and Thermal Properties." *Cellulose* 22, no. 5: 3409–3423. <https://doi.org/10.1007/s10570-015-0738-4>.
- Muñoz, E., G. Curaqueo, M. Cea, L. Vera, and R. Navia. 2017. "Environmental Hotspots in the Life Cycle of a Biochar-Soil System." *Journal of Cleaner Production* 158: 1–7. <https://doi.org/10.1016/j.jclepro.2017.04.163>.
- Quirk, R. G., L. Van Zwieten, S. Kimber, A. Downie, S. Morris, and J. Rust. 2012. "Utilization of Biochar in Sugarcane and Sugar-Industry Management." *Sugar Tech* 14, no. 4: 321–326. <https://doi.org/10.1007/s12355-012-0158-9>.
- R Core Team. 2023. *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing.
- Rajabi Hamedani, S., T. Kuppens, R. Malina, E. Bocci, A. Colantoni, and M. Villarini. 2019. "Life Cycle Assessment and Environmental Valuation of Biochar Production: Two Case Studies in Belgium." *Energies* 12, no. 11: 2166. <https://doi.org/10.3390/en12112166>.
- Robb, S., and P. Dargusch. 2018. "A Financial Analysis and Life-Cycle Carbon Emissions Assessment of Oil Palm Waste Biochar Exports From Indonesia for Use in Australian Broad-Acre Agriculture." *Carbon Management* 9, no. 2: 105–114. <https://doi.org/10.1080/17583004.2018.1435958>.
- Sahoo, K., A. Upadhyay, T. Runge, R. Bergman, M. Puettmann, and E. Bilek. 2021. "Life-Cycle Assessment and Techno-Economic Analysis of Biochar Produced From Forest Residues Using Portable Systems." *International Journal of Life Cycle Assessment* 26, no. 1: 189–213. <https://doi.org/10.1007/s11367-020-01830-9>.
- Smyth, C. E., Z. Xu, T. C. Lemprière, and W. A. Kurz. 2020. "Climate Change Mitigation in British Columbia's Forest Sector: GHG Reductions, Costs, and Environmental Impacts." *Carbon Balance and Management* 15, no. 1: 21. <https://doi.org/10.1186/s13021-020-00155-2>.
- Veksha, A., H. McLaughlin, D. B. Layzell, and J. M. Hill. 2014. "Pyrolysis of Wood to Biochar: Increasing Yield While Maintaining Microporosity." *Bioresour Technol* 153: 173–179. <https://doi.org/10.1016/j.biortech.2013.11.082>.
- Wang, H., R. Clift, and X. Bi. 2022. "Part II Clean Energy Strategies for Mitigating Greenhouse Gas Emissions in British Columbia (Issue January)." <https://cerc.sites.olt.ubc.ca/files/2022/01/22-01-30-White-paper-Part-II.pdf>.
- Wang, H., S. Zhang, X. Bi, and R. Clift. 2020. "Greenhouse Gas Emission Reduction Potential and Cost of Bioenergy in British Columbia, Canada." *Energy Policy* 138: 111285. <https://doi.org/10.1016/j.enpol.2020.111285>.
- Watts, S. B., and L. Tolland. 2005. *Forestry Handbook for British Columbia Forestry Undergraduate Society*. University of British Columbia.
- Wernet, G., C. Bauer, B. Steubing, J. Reinhard, E. Moreno-Ruiz, and B. B. Weidema. 2016. "The Ecoinvent Database Version 3 (Part I): Overview and Methodology." *International Journal of Life Cycle Assessment* 21, no. 9: 1218–1230. <https://doi.org/10.1007/s11367-016-1087-8>.
- Wickham, H. 2016. *ggplot2: Elegant Graphics for Data Analysis*. Springer-V.
- Wilson, K. J., W. Bekker, and S. I. Feher. 2024. "Producing, Characterizing and Quantifying Biochar in the Woods Using Portable Flame Cap Kilns." *Journal of Visualized Experiments* 2024, no. 203: 1–14. <https://doi.org/10.3791/65543>.
- Xia, F., Z. Zhang, Q. Zhang, H. Huang, and X. Zhao. 2024. "Life Cycle Assessment of Greenhouse Gas Emissions for Various Feedstocks-Based Biochars as Soil Amendment." *Science of the Total Environment* 911: 168734. <https://doi.org/10.1016/j.scitotenv.2023.168734>.

Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Figure S1:** Life cycle assessment system boundary. Blue represents the different processes with their associated input source in yellow. The boundary account for the non-CO₂ emissions associated with the open combustion and pyrolysis process. **Figure S2:** We show the graphs used for each scenario, in a simplified case with 4 forests (FO-*), 3 pyrolysis plants (FC-*), and 6 fields (FI-*). Numbers in black indicate the cost of each edge (in gCO₂e/kgBC). We introduced artificial forest and field nodes (FO-COM, FI-COM) and artificial edges to each forest/field, which let us specify: the forest production capacities and field application capacities (in red, in kgBC), the field capture potentials (in black, in gCO₂e/kgBC) that are specified as negative costs, and finally the total supply and demand at the artificial nodes (in green, in kgBC). The edge attributes in green (in kgBC) indicate the solution found for that specific scenario, that is, how much feedstock must travel through each edge to satisfy the constraints and objective of the scenario. In this example, an arbitrary amount of 2500kgBC is transported through the network. (a) Optimal scenario: the biochar is transported along the route with the minimum cost, while respecting field capacities. (b) Even scenario: here, we didn't need an artificial field node, as we had to specify demand (in green) on individual field nodes to ensure an even distribution proportional to field areas. (c) Random scenario: no optimization is performed. (d) Worst-Case scenario: here the goal is to maximize cost, therefore, we simply specified the negative of the actual costs, so that the minimization turns into a maximization. **Figure S3:** Equal scenario biochar application strategy. Green polygons depict agricultural fields receiving biochar. Red polygons indicate untreated fields. The green density plot aids in identifying latitudes of fields with biochar application. Left aligned labels represent biochar production hubs. Points size and label value reflect the annual biochar production requirements of each hub in kilo tonne for processing the incoming feedstock. **Figure S4:** Worst-Case scenario biochar application strategy. Green polygons depict agricultural fields receiving biochar. Red polygons indicate untreated fields. The green density plot aids in identifying latitudes of fields with biochar application. Left aligned labels represent biochar production hubs. Points size and label value reflect the annual biochar production requirements of each hub in kilo tonne for processing the incoming feedstock. **Figure S5:** Random scenario biochar application strategy. Green polygons depict agricultural fields receiving biochar. Red polygons indicate untreated fields. The green density plot aids in identifying latitudes of fields with biochar application. Left aligned labels represent biochar production hubs. Points size and label value reflect the annual biochar production requirements of each hub in kilo tonne for processing the incoming feedstock.