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Environmental factors controlling biochar climate change mitigation potential in British Columbia's agricultural soils

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Abstract

To combat climate change, carbon dioxide must be prevented from entering the atmosphere or even removed from it. Biochar is one potential practice to sequester carbon, but its climate change mitigation potential depends on a multitude of parameters. Differentiating areas of low and high climate change mitigation through biochar addition is key to maximize its potential and effectively use the available feedstock for its production. This study models the realistic application of 1 metric tonne (t) per hectare (ha) of forest harvest residue derived biochar over the climatically and pedologically diverse agricultural area of British Columbia, Canada, and provides a framework and assumptions for reproducibility in other parts of the world. The model accounts for the direct (input of organic carbon) and indirect (enhanced plant biomass) effects of biochar on soil organic carbon stock, its impact on nitrous oxide emissions from soils, and the avoided emissions from the reduced lime requirement due to biochar's alkalinization potential. Impacts are modelled over 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 and conform to the IPCC GWP 20-year time horizon reporting. The results show that a single application of 1 t of biochar per ha^{-1} can mitigate between 3 and 5 t CO_2e ha^{-1} over a 20-year time frame. Applied to the 746,000 ha of agricultural land of British Columbia this translate to the mitigation of a total of 2.5 million metric tonnes (Mt) CO_2e over a 20-year time frame. Further, the results identify agricultural areas in the Lower Mainland region (the southwestern corner of British Columbia) as the area maximizing climate change mitigation potential through biochar addition due to a combination of relative high temperature, high precipitation, and crops with high nitrogen requirement.

KEYWORDS

Canada, carbon dioxide, climate change, greenhouse gas removal, nature-based solution, negative emissions technologies, NET, nitrous oxide, RothC, soil model

1 | INTRODUCTION

Carbon dioxide removal (CDR) practices are critical to meet the temperature goal of the Paris Agreement (Smith et al., 2016). Novel CDR practices (defined as all practices except afforestation/reforestation; soil carbon in croplands and grasslands; peatland and wetland restoration; agroforestry; improved forest management; and durable harvested wood products) currently only capture 2 Mt CO_2 per year worldwide, and compose 0.1% of the existing CDR portfolio (Smith et al., 2023). As most of the 196 countries that signed the Paris agreement are running behind their Nationally Determined Contributions (information on target, policies and measures to reduce their emissions and adapt to climate change), not only will the dependence on CDRs rises but it will be essential to maximize their efficacy to ensure optimal carbon (C) capture (Chiquier et al., 2022; Climate Analytics and New Climate Institute, 2023).

Biochar has been increasingly studied for both its CDR and soil fertility enhancing abilities (IPCC, 2020; Li et al., 2018; Wu et al., 2023). Despite the enthusiasm, biochar effect on soil and plant systems can also be neutral or detrimental, depending on a manifold of local and production parameters such as feedstock type, pyrolysis conditions, application rate and method (e.g., alone or charged with fertilizers), and pedological and climatic contexts (Chagas et al., 2022; Joseph et al., 2021). Additional limits to adoption may include sustainable feedstock sourcing and management, price, and biochar toxicity (mainly due to polycyclic aromatic hydrocarbons, dioxins, and heavy metals) (Das et al., 2023; Fridahl et al., 2021; Pourhashem et al., 2018).

The province of British Columbia (BC), in Canada, is home to a vast forestry industry, and while some harvest residues are used, the majority are burnt on site following provincial requirement to reduce fuel loads for potential wildfire (BC Hydro and Industrial Forestry Service Ltd., 2018; Wang et al., 2022). Meanwhile, some of BC agricultural systems are characterized by a "yield gap" (crop yields do not reach their full potential), "moderate" to "severe" limitations in agricultural capability, and a continued loss of soil organic carbon (SOC) mainly explained by agricultural practices (e.g., high biomass exportation and low cover crops) (Agriculture and Agri-Food Canada, 2016; Jing, Qian, et al., 2017; Jing, Shang, et al., 2017; Paul et al., 2020; Province of British Columbia, 2018; Subedi & Ma, 2009). Despite limited yield benefits associated with biochar addition in temperate climates (Lévesque et al., 2022), the combination of available feedstock and agricultural constraints offers an opportunity for biochar production and use throughout the province to: (i) sequester carbon (IPCC, 2020); (ii) support food security via improved soil physical properties (Blanco-Canqui, 2017) and increased nutrient availability (Bilias et al., 2023; Hardy et al., 2016), and (iii) enhance BC agroecosystem resilience (Cornelis et al., 2022; Kumar et al., 2022).

BC's landscape and diversity of biogeoclimatic zones make the province an idea candidate to test the influence of variable ecological contexts on climate change mitigation potential through the production and use of biochar in agricultural settings. BC's agricultural area spans over 9 degrees of latitude, with yearly precipitation between 250 and 2600 mm, yearly average temperature between 0.9°C and 10.7°C, and soil texture class ranging from clay to sandy loam (USDA classification) (Poggio et al., 2021; Wang, Hamann, et al., 2016). The large diversity of crop type, soil type, and climatic conditions is expected to affect biochar potential over the province, as the capacity of storing C in soils is highly controlled by climatic variables and their influence on decomposition rates together with the formation of organo-mineral associations and aggregates (Lal, 2004; Six et al., 2002). Therefore, we propose to assess the climate change mitigation potential of forestry harvest residue derived biochar, applied on agricultural fields of contrasting ecological regions over BC. In particular, we are testing biochar soil amendments with realistic application rates ($1\,t\,ha^{-1}$) according to harvest residue availability and accessibility in BC (Section 2.2). The results account for the agricultural, climatic, and pedologic diversity of the province and include biochar effect on nitrous oxide (N_2O) emissions from soil, the reduction in agricultural lime consumption due to biochar alkalinization potential, and biochar effect on biomass production and subsequent influence on soil C stock. This is a modelling exercise and, as such, we recognize that it does not encompass the full complexity of living systems. It is, however, to our knowledge, the most precise large-scale assessment of the climate mitigation potential of biochar to date. This case study is important as it sets a framework and showcases model use and assumptions that can be replicated to other regions globally to help differentiate areas of high climate change mitigation potential from low climate change mitigation potential at the field scale.

The manuscript does not include the emissions associated with the production, transport, and application of biochar, nor does it account for the effects associated with potential on-site decay and open-air combustion of forestry harvest residues. Therefore, the values presented here are not net mitigation potential values and should not be considered as such.

2 | METHOD

2.1 | British Columbia's agricultural state

The total georeferenced agricultural area, including cropland, pastures and fallows, amount to around 746,000 ha (Illert & Afflerbach, 2022), which is in line with the value reported from the Government of British Columbia (2022). Aggregated crop categories from the georeferenced dataset (e.g., "Agriculture Undifferentiated") were compared against un-georeferenced additional datasets for added differentiation (Government of Canada, 2021). The complete list of crop groups and sub-groups included in this study are presented in the supplementary information (Table S1, Table S2, and Figure S1). Economic regions were used to separate the province into shares of agricultural land. Main characteristics of each region are shown in Figure 1, Figure 2, and Table 1.

2.2 | Forestry harvest residues

Forestry harvest residues are defined as tree biomass that remain in situ after the harvesting of the main merchantable tree biomass. The harvest residues considered in this study consist of softwood tree branches, tops, and small diameter trees piled along the forestry roads or in the cutblock. Although part of these residues are either used within the forestry industry or to produce energy (BC Hydro and Industrial Forestry Service Ltd., 2018), the majority of residues are left to dry during the summer season

FIGURE 1 Province of British Columbia divided into economic regions with main cities (red dots) and agricultural fields (white polygons).

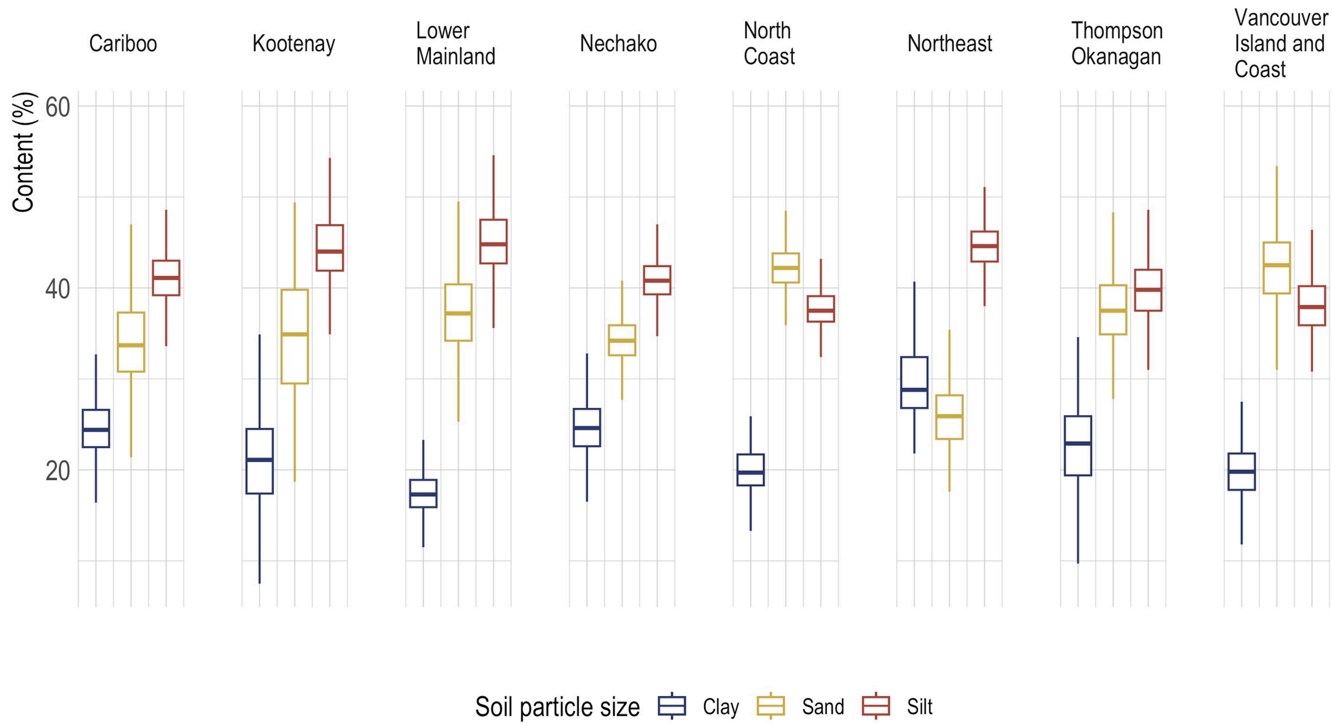

FIGURE 2 Soil particle size content (%) range in the different regions of British Columbia.

TABLE 1 Region's agricultural area main parameter.

Region name	Yearly average precipitation (mm)	Yearly average temperature (°C)	Three most represented crop group	Agricultural area (ha)
Cariboo	597.5	4.55	Pasture Forages > Agriculture Undifferentiated > Barley	79,495
Kootenay	483.8	6.63	Agriculture Undifferentiated > Orchard > Vineyards	14,043
Lower Mainland	1503.5	10.27	Berry > Pasture Forages > Agriculture Undifferentiated	26,201
Nechako	523.7	3.19	Agriculture Undifferentiated > Pasture Forages > Vegetables	104,050
North Coast	722.0	5.46	Pasture Forages > Vegetables > Oats	4958
Northeast	476.5	1.93	Agriculture Undifferentiated	457,494
Thompson-Okanagan	394.1	7.77	Agriculture Undifferentiated > Orchards > Vineyards	52,193
Vancouver Island and Coast	1145.1	9.89	Agriculture Undifferentiated > Vineyards > Orchards	7732

and then burnt on site once wildfire risk decreases in the fall (BC Hydro and Industrial Forestry Service Ltd., 2018; Wang et al., 2022). In 2019, 55 million m^3 of wood was harvested and 0.77 million m^3 of the harvest residues were used in the pulp, chip and pellet industry (Canadian Council of Forest Ministers, 2020; Ministry of Forests Lands and Natural Resource Operations, 2019). Assuming a chipped harvest residues to timber ratio of 11%, a wood density of 0.41 oven dry $t\,m^{-3}$, and the residue utilization, the quantity of available forestry harvest residue in 2019 amounts to 2.16 million oven dry t (MacDonald et al., 2012). Accounting for additional sources or calculation methods, estimates range between 0.6 million and 4.7 million oven dry $t\,year^{-1}$ of unused residue (residues that would otherwise be burnt) potentially available for biochar production (BC Hydro and Industrial Forestry Service Ltd., 2018; Blackburn, 2017; Canadian Council of Forest Ministers, 2020; MacDonald et al., 2012; Wang et al., 2020). Assuming a biochar yield of softwood at 650°C to be around 22% (Veksha et al., 2014), BC's total agricultural area could be amended with between 0.18 t and 1.38 t of oven dry biochar $ha^{-1}year^{-1}$. To represent this low potential application rate, this study focused on assessing the benefit of a single application of 1 t of biochar ha^{-1}.

2.3 | Biochar carbon

The biochar modelled in this study is produced from various tree species harvest residues at around 600°C. A recent thesis studied the characteristics of BC's forestry harvest residue derived biochar made at similar temperature and reported a C content of 92% (de Ruiter, 2018). We further divided the biochar C between a 4% labile fraction and a 96% recalcitrant fraction according to recent literature (Pulcher et al., 2022; Wang, Xiong, et al., 2016). The mean residence time of the labile fraction was set at 0.287 years according to the existing literature (Pulcher et al., 2022; Wang, Xiong, et al., 2016), while the mean residence time of the recalcitrant fraction was calculated as a function of soil temperature following the approach described in Woolf et al. (2021) and deriving soil temperatures from air temperature according to Jian et al. (2022).

2.4 | Biochar impact on agricultural biomass production

The impact of biochar on crop yield depends on its intrinsic characteristics, soil type, climate, and application rate (Schmidt et al., 2021). According to a field experiment meta-analysis, combined biochar and fertilizer addition increases crop yield by an average of 15% (Ye et al., 2020). Other meta-analysis, considering both pristine and charged biochar application, reported an average impact of biochar addition on crop yield between 13% and 25% (Bai et al., 2022; Schmidt et al., 2021). As this study exclusively takes place on temperate soils and models low application rate, we used the average effect of biochar on crop yield of 3.59% as reported for low application rate of woody biochar on temperate soils by Liu et al. (2019).

This study assumes the expected yield increase following biochar application to extend to aboveground biomass (crop residues) and belowground biomass (root mass). This increase in above and belowground biomass is further expected to impact SOC dynamics as it increases the amount of C input to soils compared to a non-biochar-amended soil. To model this impact, we assumed that the field SOC stock, as gathered from the ISRIC database, represents the SOC stock at equilibrium (Poggio et al., 2021). Using the RothC soil C model (Coleman & Jenkinson, 2014), and its inverse approach detailed in Meersmans et al. (2013), we derived the C inputs (Cin) required to maintain the SOC stock to its equilibrium value. The modeled Cin values per ha were then increased by 3.59% per t of biochar added following Liu et al. (2019), and inputted back into RothC to model the SOC change over time after biochar addition. The biochar effect on biomass production is assumed to increase the first year after application, reach its maximum within 2 years after application, and to drop to zero at year three (Bai et al., 2022). To account for this temporal significance of a single application of biochar, the effect of the modelled single doses of biochar on SOC was integrated over 20 years. Additional information on the integration approach is available in the supplementary material (Figure S3, Figure S5).

2.5 | Biochar impact on nitrous oxide emissions

Nitrogen mineral fertilizer application rate was considered crop specific, and the recommended application rate for each crop type assessed in this study was derived from Huffman et al. (2008), Kissel and Harris (2015), and Ludemann et al. (2022). The application rate for the considered crop group can be found in the supplementary information (Table S1). Fertilization regime is considered unchanged after biochar amendment. The assessment of the direct emissions of N_2O from mineral fertilizer application on agricultural soils was made following the equations and suite of factors provided in Poore and Nemecek (2018) building on Stehfest and Bouwman (2006) and Smeets et al. (2009). The direct emissions equation factors include crop type, soil pH, soil texture, climate, SOC content, bulk density, and nitrogen application rate (Smeets et al., 2009). The indirect emissions (volatilization, leaching, and runoff) were calculated according to IPCC methodology (Hergoualc'h et al., 2019) as prescribed by Poore and Nemecek (2018) when lack of data prevented a more precise assessment. According to a recent meta-analysis, biochar application reduces N_2O emissions from soil by 38.8% on average (Kaur et al., 2022). Other analysis set this values between 22% and 50% (Borchard et al., 2019; He et al., 2017; Tisserant et al., 2022). Our analysis follow the conservative assumption from Liu et al. (2019) that low application of woody biochar on temperate soils reduces the N_2O emissions by an average of 13.04%. We assumed the effect of biochar on N_2O emission at its maximum the year of its application and decreasing to zero the following year, in line with existing experimental evidences on the topic (Borchard et al., 2019; Kaur et al., 2022). To account for this temporal significance of a single application of biochar, the effect of the modelled single doses of biochar on N_2O was integrated over 20 years. Additional information on the integration approach is available in the supplementary material (Figure S4, Figure S6).

2.6 | Biochar liming potential

The high concentration of carbonates and oxides (K_2O, CaO and MgO) in biochar ashes explain the alkaline nature of most biochars. It is therefore assumed that biochar addition could offset agricultural lime (Singh et al., 2017). The biochar liming potential used in this study is based on Tisserant et al. (2022), where all the calcium present in the forest residual biomass is expected to persist in the produced biochar as calcium carbonate. The alkalinity from other bases potentially present in the biochar are not included in their liming potential calculation. Following their approach, and since their biochar feedstock and production conditions are similar to the one modeled in this study, we assumed every t of biochar to be equivalent to 56.81 kg of agricultural lime (Tisserant et al., 2022). This value is comparable to the 5% by weight lime equivalent measured in Singh et al. (2017) for biochar made from pine chips at 550°C. The amount of lime required to elevate soil pH of one unit was extracted from (Vossen, 2006) and depend on the initial soil pH value and soil texture. The emission factor of limestone was set at 439 g CO_2e per kg of agricultural lime applied, following Canadian inventory values (ECCC, 2022b). Official national statistics report 977 farms around BC using lime on a total of 8039 ha (Statistics Canada, 2022). Our modelling activity sets the total area requiring lime to 6225 ha, hence a more conservative assumption than the official values but of similar order of magnitude.

2.7 | Biochar priming effect

Whether biochar increases native SOC mineralization rate (positive priming) or decreases it (negative priming) is still under debate. While Blanco-Canqui et al. (2020) reported a negative priming effect, others seemed to report an overall positive priming effect, with potential changes in direction over time (Ding et al., 2018). The most recent published data tended toward a negative priming effect of biochar addition, particularly when produced at high temperature and applied on temperate soils (Chen et al., 2021; Weng et al., 2022; Yang et al., 2022). Overall, most authors warranted further studies to understand the causes and parameters driving the impact (Blanco-Canqui et al., 2020; Ding et al., 2018; Maestrini et al., 2015; Wang, Xiong, et al., 2016). Therefore, this study assumes no priming effect of biochar addition. A potentially conservative approach followed and suggested by Woolf et al. (2021).

2.8 | Software and data

The geolocated cultivated area of BC was extracted from the 2021 annual crop inventory (Illert & Afflerbach, 2022). SOC stock, bulk density, pH, as well as sand, clay, and silt content were obtained through ISRIC database (Poggio et al., 2021). Soils were classified based on their texture using the R software 'Soil texture' package (Moeys, 2018) through the USDA soil texture categorization system and the EU HYPRESS soil texture classification system depending on the requirement of the different model in use. Soil texture category data and geographical extend can be found in the supplementary material (Table S3, Figure S2). Potential evapotranspiration for use in RothC was calculated using the R software 'SPEI' package (Beguería & Vicente-Serrano, 2017) following the Thornthwaite method. Precipitation and temperature data were extracted from ClimateBC version 5.03 (Wang, Hamann, et al., 2016). RothC was run in the R software version 4.2.2 using the package 'SoilR' (Sierra et al., 2012). Mapping requirements were made using QGIS software version 3.24 (QGIS Association, 2023). Modeling, data wrangling, and figures were made using R software version 4.2.2 (R Core Team, 2022).

3 | RESULTS

3.1 | Biochar potential for climate change mitigation

The climate change mitigation potential of a single 1 t biochar application ranges between 3.3 and 5.1 t CO_2e ha^{-1} when integrated over a 20-year time frame. Fields located in the Lower Mainland region (Figure 1) show the highest potential for climate change mitigation through biochar application while fields located in the Northeast region (Figure 1) show the lowest potential (Figures 3 and 4).

According to the methodology applied in this study, the single application of 1 t ha^{-1} of forestry harvest residue derived biochar over the 746,000 ha of agricultural land of BC would mitigate climate change by a total of 2.5 Mt CO_2e over a 20-year time frame.

The C content of the biochar itself has the major role in the emissions reduction, totalling 94% of the modelled provincial average climate change mitigation potential with very low variability (Figure 5).

The impact of biochar on biomass growth and subsequent impact on SOC has a significant impact on the total reduction potential of biochar averaging 5% of the total CO_2 emission reduction potential (Figure 5). Variability throughout the province is high and spans three orders of magnitude. Its effect depends mainly on climate and soil type, with the highest potential shown in climates characterized by high precipitation and temperature and soil types characterized with a higher sand content.

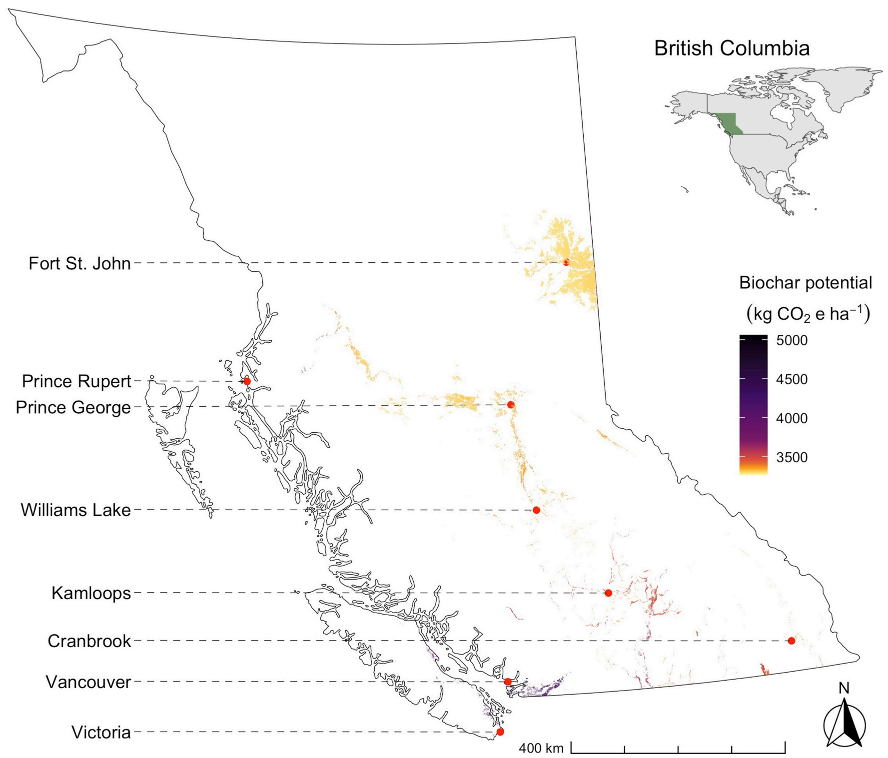

FIGURE 3 Agricultural field localization over the province of British Columbia and their climate change mitigation potential through biochar application as modelled in this study.

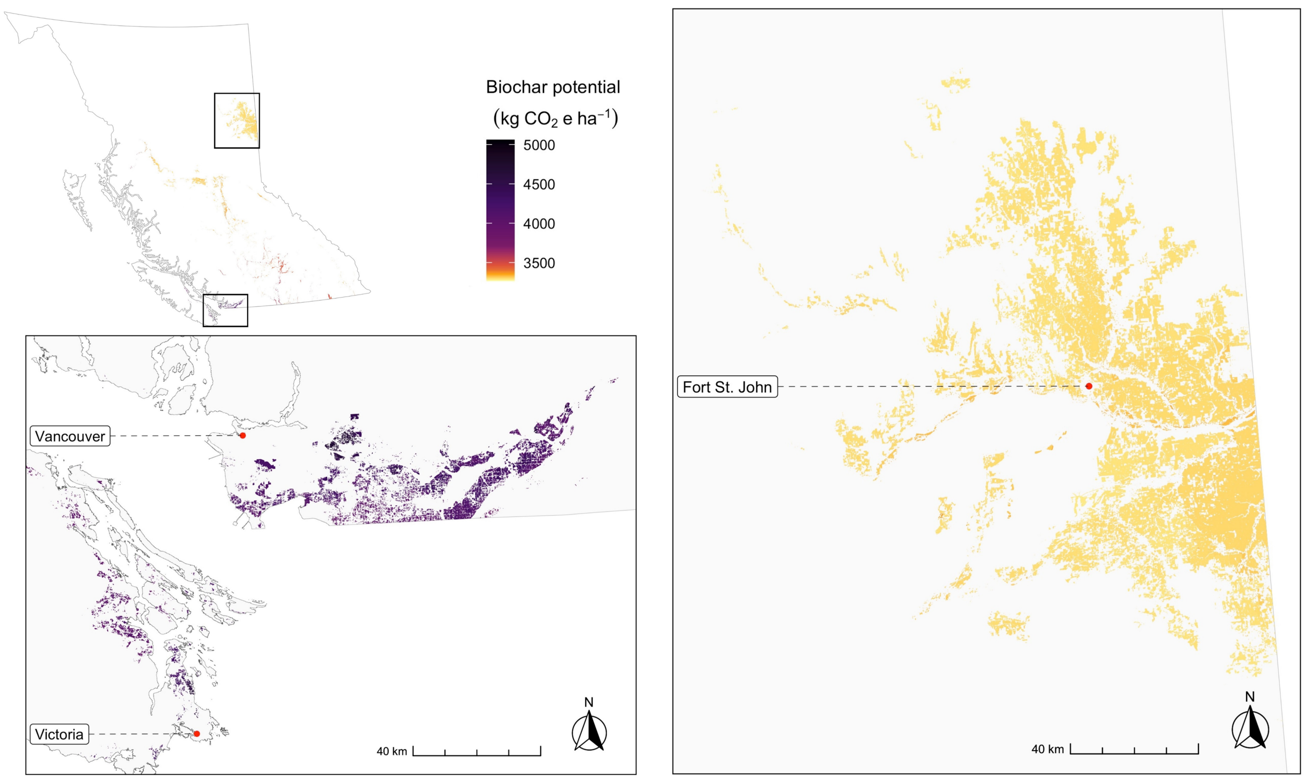

FIGURE 4 Enhanced view of the province's agricultural area with the highest and lowest biochar CO_2e mitigation potential.

The avoided N_2O emissions from soils following biochar application account for 0.03% of the province's average climate change mitigation potential of biochar application (Figure 5). Although the average value is low, its variability is also high throughout the province and its contribution can reach up to 18.9% of the total climate change mitigation potential of the practice for some crop and soil type combinations (i.e., vegetable on clay soils – Figure 6).

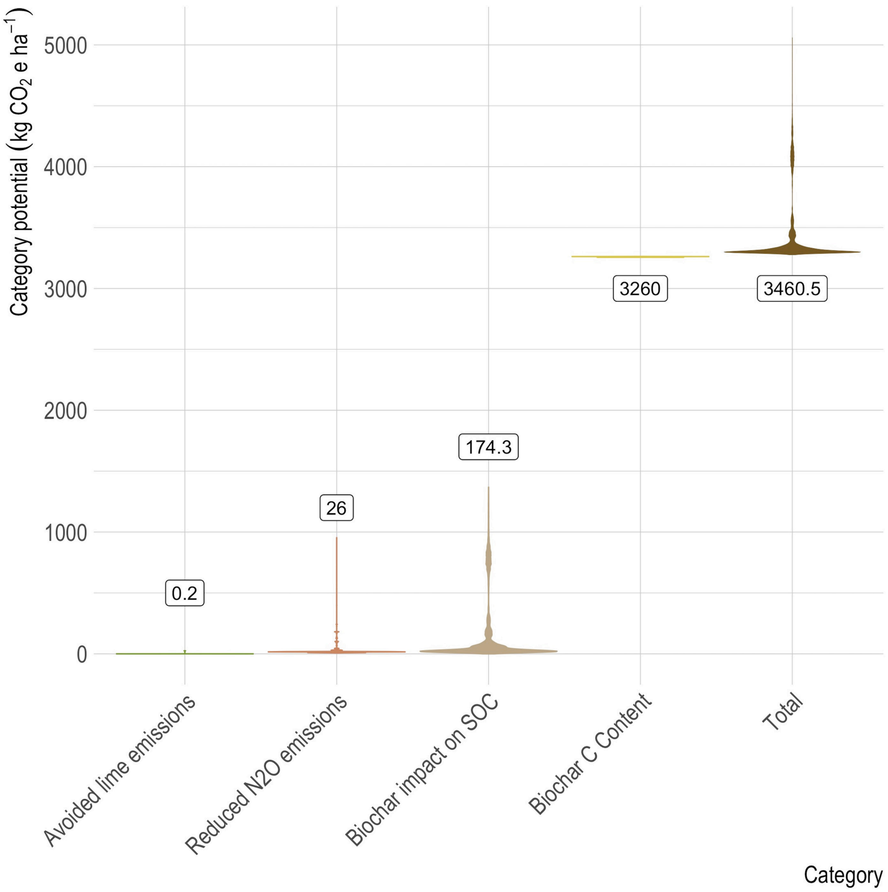

FIGURE 5 Violin plot representing the contribution of each category to the total mitigation potential of the single biochar application modelled in this study. A violin plot was chosen over a box plot to effectively depict the distribution and structure of the data. Labels are mean value over the totality of the province's fields in kg CO_2e ha^{-1}.

The climate change mitigation potential related to biochar alkaline nature and the resulting reduced application of lime is very limited over the province. On fields where lime is required, the liming effect of biochar averages 0.6% of the total reduction potential. This low value is mainly due to the single low biochar application rate modelled (1 t ha^{-1}), offsetting only 2.5% of the total lime required in the province, based on the modelled lime requiring area and assumed biochar liming potential (Section 2.6).

4 | DISCUSSION

4.1 | Geographical range of biochar potential for climate change mitigation

The climate change mitigation potential of biochar in BC is higher when applied on fields located in the Lower Mainland region (Figure 1). Biochar C degradation rate is negatively correlated with soil temperature, hence areas located in the northern part of the province show a slightly higher C removal potential from biochar C content but the variation throughout the province is small (Figure 5). However, biochar impact on SOC stock induced by changes in biomass production is highly and positively correlated with soil temperature, precipitation, and proportion of sand-size minerals in soil; explaining why the fields located in the southern part of province are susceptible to higher SOC stock increase after biochar amendment. The magnitude of the increase in aboveground and belowground biomass after biochar application is the greatest where temperature and precipitation are the highest in the province. The proportion of sand-size minerals also play a key role to get the best compromise in terms of soil water dynamics (optimal SOC stock increase reached with sand content between 35% and 45%), avoiding soil water saturation when proportion of clay-size minerals is too high (above 35%) or poor water retention when proportion of sand-size minerals is too high (above 45%). In addition avoided N_2O emissions from soils following biochar application is highly and positively correlated with the nitrogen fertilizer application rate, and hence crop type, but also with soil texture and moisture regimes which drives the N_2O emissions from N fertilizer application (Smeets et al., 2009). As crop type requiring high nitrogen fertilizer (e.g., vegetables, berries, potatoes) are mainly located in the south of the province, avoided N_2O emissions are higher there as well. Therefore, the higher mitigation potential of biochar addition in the southern part of the province is mainly due to a combination of high temperature, high precipitation, and crops with high N requirement, maximizing the effect of biochar on SOC stock and N_2O emissions.

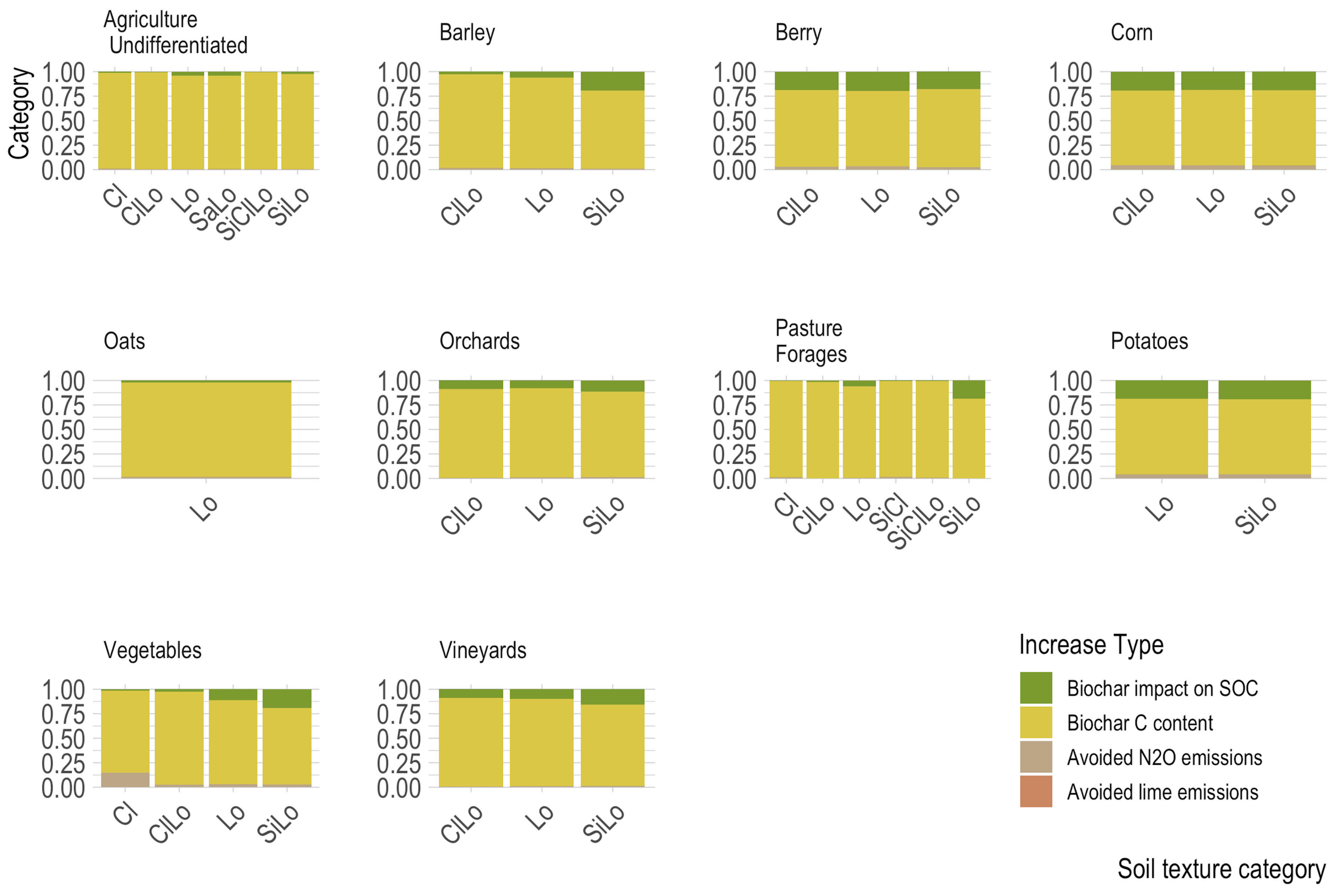

FIGURE 6 Contribution of the different categories (i.e., increase type) assessed on the total mitigation potential of biochar addition. The different land uses, and soil textures are separated. Soil texture acronyms are defined in the supplementary material.

4.2 | Time scale and implication

Biochar C is generally assumed to be highly stable in soils, with a mean residence time ranging from centuries to millennia (Chiquier et al., 2022; Petersen et al., 2023; Schmidt et al., 2022). Similarly, the effect of biochar on lime upstream emissions and N_2O emissions from soils is considered permanent since its application directly avoids the emissions of GHGs in the atmosphere, and hence, has no risks of reversal. However, biochar effect on biomass production and its consequence on SOC stock (biochar C aside) is temporary as it will, in time, return to its equilibrium value. Hence, understanding the duration of the effect of biochar on crop biomass and C input to soil is capital and has important implications on the climate change mitigation potential of biochar addition, but also provides meaningful information on the interval between applications. Indeed, foreseeing biochar's impact and duration on biomass production and consequential effect on SOC stock could provide important insights to optimize application rates and frequency to maximize the mitigation impact of the practice.

4.3 | Low resource leads to careful application location

Assuming that 740,000 t of harvest residue biochar can be produced annually (cf. Section 2.2), homogeneously spreading it at 1 t ha^{-1} over the entire agricultural area results in the mitigation of 2.5 Mt CO_2e over a 20-year time horizon. Focusing biochar application to 10 t ha^{-1} on the 10% most efficient fields can increase the mitigation potential to 2.82 Mt CO_2e over 20 years. Conversely, applying 10 t ha^{-1} of biochar on the 10% least efficient fields decreases the mitigation potential to 2.46 Mt CO_2e over 20 years. This value is close to the homogeneous application value due to the small climate mitigation potential difference between the least efficient fields and average ones (Figure 5). Nevertheless, attempting to predict the effect of biochar application and maximizing its potential in BC considering an application rate up to 10 t ha^{-1} in regions with the highest climate change mitigation potential could improve its potential by 311,000 t CO_2e, or a 12.5% increase compared to its homogeneous application.

4.4 | Limitations of the analysis

The emissions associated with the production, transport, and application of the biochar, as well as the effects associated with potential on-site decay and open-air combustion of forestry harvest residues, should be considered following a life cycle assessment approach to comprehensively represent biochar climate change mitigation potential. Localization of forest harvest residue biomass accessible for collection and biochar production sites are crucial as they will determine the transportation legs and emissions associated with them.

This study makes a single conservative assumption of the impact of biochar on biomass growth (i.e., +3.59%; Section 2.4). Similarly, it considers a single avoided emissions potential for the impact of biochar on N_2O emissions from soils (i.e., −13.04%; Section 2.5). Refining these values based on soil type, crop type, and climates combinations would provide much finer results and potentially further segregate areas of high from low potential.

We do not consider potential crop rotations which would affect the N fertilizer requirements, the associated N_2O emissions, and, hence, the overall biochar mitigation potential. In addition, this study considers the field carbon content prior to biochar addition to be at equilibrium, while this may be true for some areas, others are already experiencing change as a result of changes in agricultural practices (Government of Canada, 2022).

In addition, this study does not account for the potential charging or co-composting of the biochar prior to its application. These practices are known to increase the beneficial impact of biochar on biomass growth (Joseph et al., 2021; Schmidt et al., 2017) and thus its SOC stock increase potential. Similarly, this study does not encompass the potential co-benefits associated with biochar application such as increase nutrient use efficiency (Bilias et al., 2023; Joseph et al., 2021) or climate change resiliency (Kumar et al., 2022) that, in addition of their inherent benefices, may indirectly impact its climate change mitigation potential as well.

Finally, as accounting for the 20-year impact of biochar on N_2O emissions from soils and biomass growth has a significant impact on the results, improvements to our understanding of biochar's temporal effect on N_2O emissions from soils and biomass growth is essential to properly estimate its climate change mitigation potential.

4.5 | Potential for British Columbia and Canada

The 20-year time horizon 2.5 Mt CO_2e abatement potential from the single 1 t ha^{-1} biochar application modelled in this study (production and transportation emissions aside) could lower the annual 61.7 Mt CO_2e emissions released in BC in 2020 by 4%. This contribution fully negates the 2.2 Mt CO_2e attributed to the agricultural sector in 2020 (ECCC, 2022c). Please note that these mitigation values do not include the emissions associated with the establishment of the practice. Therefore, these figures should not be regarded as net mitigation potentials.

According to the 2022 National Inventory Report, 300,000 t of CO_2e were emitted from the combined direct and indirect emissions of N_2O from agricultural soils in BC (ECCC, 2022c). Considering our modelling activities, the homogenous single application of 1 t of biochar over the agricultural area of BC could reduce the N_2O emissions from agricultural soil in the province by 14,270 t of CO_2e, or around 5% of its N_2O emissions in 2020, thus participating to the national pledge to reduce fertilizer's emissions by 30% for the year 2020 (ECCC, 2022a).

5 | CONCLUSION

The addition of 1 t of forest harvest residue biochar can offset between 3.3 and 5.1 t CO_2e ha^{-1} over a 20-year time frame when applied on a given agricultural field in BC. While most of the climate change mitigation potential is driven by the carbon content of the biochar, the variability within the province is primarily led by biochar impact on N_2O emissions, and biomass growth and subsequent impact on soil C stocks. Our modelling activity shows that locations characterized by high temperature, high precipitation, and crops with high N requirement, maximizes the effect of biochar on increase SOC stock and reduced N_2O emissions and hence, maximize biochar climate change mitigation potential.

Our analysis shows that, considering a limited amount of biomass, focusing biochar application onto areas of maximum biochar CDR potential greatly improves the climate change mitigation potential of the practice over the province. We discuss additional considerations that would enhance the precision and reliability of the assessment such as increasing our knowledge on the duration of biochar's impact on N_2O emissions and plant C input, accounting for the emissions associated with producing and applying the biochar, and refining biochar impact on soil nitrous oxide emissions and biomass growth according to specific crop, soil type, and climate combinations.

Identifying areas with high biochar mitigation potential from low ones over a broad region is fundamental to maximize its CDR potential. Although this study focuses on the Canadian province of British Columbia, it presents a modelling framework and potential assumptions, and constitutes, to date, the most precise large-scale assessment of biochar's climate change mitigation potential.

AUTHOR CONTRIBUTIONS

Conceptualization: David Lefebvre, Jean-Thomas Cornelis, and Xiaotao Bi. Data curation: David Lefebvre, Jeroen Meersmans, and Morgan Hamilton. Formal analysis: David Lefebvre. Methodology: David Lefebvre, Jean-Thomas Cornelis, and Xiaotao Bi. Project administration: Jean-Thomas Cornelis, Jack Edgar, and Xiaotao Bi. Software: David Lefebvre and Jeroen Meersmans. Supervision: Jean-Thomas Cornelis and Xiaotao Bi. Validation: Jack Edgar, Morgan Hamilton, and Jeroen Meersmans. Writing and original draft: David Lefebvre, Jean-Thomas Cornelis, and Xiaotao Bi. Writing—review & editing: David Lefebvre, Jean-Thomas Cornelis, Jeroen Meersmans, Jack Edgar, Morgan Hamilton, and Xiaotao Bi.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict 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/SOQDJU

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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