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Biochar

ORIGINAL RESEARCH

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# Biomass residue to carbon dioxide removal: quantifying the global impact of biochar

David Lefebvre[1], Samer Fawzy[2,3], Camila A. Aquije[4], Ahmed I. Osman[2], Kathleen T. Draper[4] and Thomas A. Trabold[5*]

**Abstract**

The Climate Change Conference of Parties (COP) 21 in December 2015 established Nationally Determined Contributions toward reduction of greenhouse gas emissions. In the years since COP21, it has become increasingly evident that carbon dioxide removal (CDR) technologies must be deployed immediately to stabilize concentration of atmospheric greenhouse gases and avoid major climate change impacts. Biochar is a carbon-rich material formed by high-temperature conversion of biomass under reduced oxygen conditions, and its production is one of few established CDR methods that can be deployed at a scale large enough to counteract effects of climate change within the next decade. Here we provide a generalized framework for quantifying the potential contribution biochar can make toward achieving national carbon emissions reduction goals, assuming use of only sustainably supplied biomass, i.e., residues from existing agricultural, livestock, forestry and wastewater treatment operations. Our results illustrate the significant role biochar can play in world-wide CDR strategies, with carbon dioxide removal potential of $6.23 \pm 0.24\%$ of total GHG emissions in the 155 countries covered based on 2020 data over a 100-year timeframe, and more than 10% of national emissions in 28 countries. Concentrated regions of high biochar carbon dioxide removal potential relative to national emissions were identified in South America, northwestern Africa and eastern Europe.

**Highlights**

- Biochar production via biomass pyrolysis is one of few carbon dioxide removal (CDR) technologies that can be deployed at scale.
- Modeled biochar CDR potential of nearly every country, based on available biomass residues and national average soil temperature.
- Biochar can offset over 10% of national emissions in many countries, with concentrated impacts in three global regions.

**Keywords** Pyrolysis, Biochar, Waste biomass, Carbon sequestration, Negative emissions technologies (NETs), Nationally Determined Contributions (NDCs)

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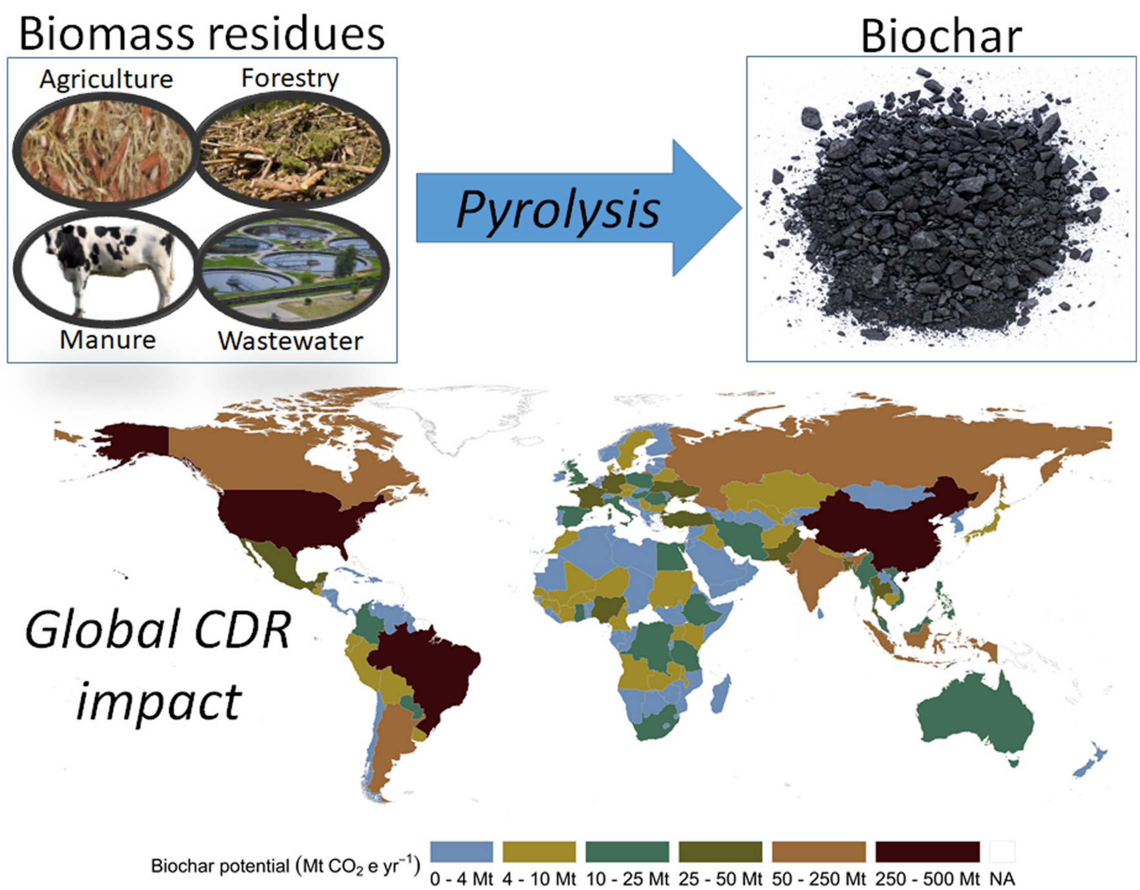
*Correspondence:
Thomas A. Trabold
tatasp@rit.edu
Full list of author information is available at the end of the article

**Graphical abstract**




## 1 Introduction

There is clear scientific evidence of the correlation between anthropogenic carbon emissions and rising global temperatures, resulting in increased incidence of severe weather events and other climate-related impacts (Pörtner et al. 2022). It is now well understood that counteracting the rapidly rising concentration of atmospheric carbon dioxide, reaching a global average of nearly 415 parts per million in 2021 (Friedlingstein et al. 2022), will require integrated efforts in mitigation of emissions from fossil fuel combustion and deployment of carbon dioxide removal (CDR) technologies. In fact, in its April 2022 report on mitigating climate change, the United Nations Intergovernmental Panel on Climate Change (IPCC) stated that CDR is "…an essential element of scenarios that limit warming to 1.5 °C or below 2 °C by 2100, regardless of whether global emissions reach near zero, net zero or net negative levels." (Pathak et al. 2022).

Within the sphere of $CO_2$ emission reduction, a number of technologies have already been developed to displace fossil fuel combustion, including solar panels, wind turbines, battery electric vehicles and fuel cells, and many nations have applied policies to incentivize their commercialization (Schuman and Lin 2012; Mundaca and Richter 2015; Nicolini and Tavoli 2017). However, CDR technologies are currently far less common in the marketplace, and therefore systematic technical assessments are required to support future decision making at national and regional levels. Among the CDR technologies identified by Pathak et al. (2022), eight are at a Technology Readiness Level (TRL) of 6 or higher, meaning they have been demonstrated in an industrially relevant environment: afforestation/reforestation, soil carbon sequestration in croplands and grasslands, peatland and coastal wetland restoration, agroforestry, improved forest management, biochar, direct air carbon capture and storage (DACCS), and bioenergy with carbon capture and storage (BECCS). In the past several years, there has been growing interest in biochar, a persistent form of solid carbon produced by high-temperature biomass conversion under reduced oxygen conditions (Jiao et al. 2021). Unlike many other CDR technologies, there is a wide variety of co-benefits associated with biochar application beyond sequestration of atmospheric carbon, including displacing fossil thermal and electrical energy generation, providing nutrients for agriculture, additives for manufactured products, water treatment and other industrial processes, etc. (Azzi et al. 2021). Biochar is also gaining interest because the underlying pyrolysis process is well known and has been refined over the course of more than a century, and production is scalable from batch systems suitable for small farms or communities up to large industrial processes capable of converting hundreds of tonnes per day.

A number of studies have demonstrated that biochar can provide a meaningful contribution to CDR targets, with life-cycle climate change impacts of net emission reduction in the range of 0.4–1.2 Mg $CO_2$ equivalent $Mg^{-1}$ dry feedstock, through carbon persistence and avoided non-$CO_2$ emissions (Cowie et al. 2015). Other benefits, such as decreased native soil organic carbon mineralization after biochar application (negative priming; Weng et al. 2022) may further elevate its role in an integrated CDR strategy. Prior research has also demonstrated that biochar can provide appreciable benefits within a single industry, and at regional or national scales by converting a broad variety of available biomass resources. For example, recent papers have described the significant negative emissions impact of biochar production from sugarcane bagasse in Brazil (Lefebvre et al. 2020), olive tree trimmings in Spain (Fawzy et al. 2022) and forest residues in Norway (Hagenbo et al. 2022). Breunig et al. (2019) showed the potential of a hypothetical bioenergy infrastructure in California, combining application of digestate from anaerobic digestion and biochar from gasification that could produce a greenhouse gas (GHG) offset of 80–350% of the state's annual emissions. Yang et al. (2021a) explored the potential of utilizing crop residues in China as feedstock for slow pyrolysis, and found that a 4.5% reduction of annual national carbon emissions can be achieved by producing biochar, bio-oil and syngas from the seven most common crops. Noting that pyrolysis "poly-generation" of these multiple co-products is a near-term alternative to BECCS, Yang et al. (2021b) analyzed the cumulative GHG reduction achievable by converting 73% of China's national crop residues from 2020 to 2030. Feng et al. (2020) also analyzed the emission reduction effectiveness of biochar at a national scale in China, but considered a broader variety of feedstocks that included four main biomass sources: crop straw, firewood and forest residue, livestock manure and urban organic waste. They concluded that biochar's GHG mitigation potential is equivalent to about 15% of China's total greenhouse gas emissions.

Although the significant CDR potential of biochar has been widely reported, much of the prior work has focused on major global emitters or regions and industries where significant data exist regarding available feedstocks, energy emission factors, etc. The present study was undertaken to expand the scope of prior research by considering, for the first time, the potential CDR benefit of deploying biochar technology in every country across all global regions, by analyzing the net avoided GHG emissions from biochar production at a national scale. This objective has been achieved by developing a generalized framework for computing the carbon sequestration potential of biochar based on the model of Woolf et al. (2021), covering major sources of biomass residue that are available as the output of existing agricultural, livestock, forestry and wastewater treatment operations. As described in the Methods section, we also quantified for each country the mean soil temperature that determines biochar permanence, as well as country-level emissions associated with biochar production and application. This effort has provided an initial quantification of the carbon sequestration benefits of biochar production in all countries to support policy decisions regarding their country-specific greenhouse gas emission reduction goals. Many countries formalized their emission reduction goals as part of the so-called Paris Agreement, a legally binding international treaty on climate change adopted at the Climate Change Conference of Parties (COP) 21 in December 2015. One of the major outcomes of this historic event was the establishment of Nationally Determined Contributions (NDCs) that represent the commitments of each country to reduce greenhouse gas emissions and adapt to climate change. The results presented below illustrate the significant role biochar can play in meeting NDCs, especially in countries with diverse agricultural industries and relatively low national emissions levels. For major emitters such as China and the United States, biochar production must be deployed in concert with a broad array of other GHG emission reduction and CDR technologies at a scale beyond NDC levels if we are to keep global warming below 2 °C by the end of the century (Liu and Raftery 2021). Of course, relative cost of different CDR systems is a major consideration in such decision-making (Bednar et al. 2019), but the cost of deploying biochar production at scale is beyond the scope of this initial study.

## 2 Methods

### 2.1 Generalized framework for biochar carbon dioxide removal model

The framework described in this section starts with the greenhouse gas inventory model proposed by Woolf et al. (2021) for biochar added to soil, and extends it to enable computation of biochar CDR potential for every country. The major assumptions made in formulating a generalized framework for biochar carbon sequestration are provided below. We've attempted to be generally conservative in our approach to yield realistic and achievable projections of the potential for biochar carbon sequestration, without considering the potential benefits of other co-products, beyond assuming that the biochar process is self-sufficient in terms of electricity production and that it produces enough heat to dry the biomass feedstock. Several key simplifications have also been made in the spirit of constructing a reasonably straightforward framework that facilitates broad application across all countries in different global regions:

1. We consider the use of only biomass residue feedstocks; thus, GHG emissions associated with biomass production are not included in the analysis. However, as described below, we do consider emissions from feedstock transport and pre-treatment, pyrolysis plant construction and operational energy needs, biochar post-treatment and application, and loading and truck transport to and from the pyrolysis plant.
2. For biomass residues obtained from harvesting agricultural crops, 30% of the total available residue is retained in the field to maintain long-term soil health, based on recommendations provided for a variety of large-volume commodity crops (Puro Earth 2022; Battaglia et al. 2021). It is, however, assumed that all residues generated in food crop processing are available for conversion to biochar.
3. Biochar's impact on soil organic carbon (SOC) mineralization rate (priming) is inconclusive, with conflicting results (Blanco-Canqui et al. 2020; Ding et al. 2018). High-temperature biochar on temperate soils may reduce SOC mineralization rate, but further research is needed (Chen et al. 2021; Weng et al. 2022; Yang et al. 2022). Given these uncertainties, this study assumes no effect from biochar addition on SOC mineralization rate, consistent with Woolf et al. (2021) who conservatively did not include this factor in their GHG accounting methodology.
4. Other GHG emissions associated with nitrous oxide and methane are not included in the analysis because these effects are expected to be small relative to biochar carbon sequestration.
5. The majority of biochar produced will be added to soil, and thus we use the permanence factors provided by Woolf et al. (2021). Biochar used in other long-term industrial applications is assumed to be shielded from decomposition, yielding equal or greater permanence than the same biochar added to soil (Winters et al. 2022).
6. All biochar is produced under anaerobic (i.e., pyrolysis) conditions at temperature ≥ 600 °C. The biochar permanence factor ($F_{perm}$) over a 100-year timeframe is maximized when biochar is produced at "high" temperature, defined as ≥ 600 °C by Woolf et al. (2021), whose model was the basis for our biochar carbon sequestration framework. The primary objective of this work is to quantify the potential carbon dioxide removal (CDR) by converting all of a nation's available waste biomass resources to biochar. Because of the sheer volume of feedstock material involved at such a scale, it is necessary to think in terms of deploying continuously fed industrial-scale systems and not kilns or similar systems that are much smaller and operate in batch mode. Many continuous industrial-scale systems can reasonably control pyrolysis temperature at 600 °C or higher.
7. Biochar is the sole product of the pyrolysis process, with heat generated from combustion of syngas and higher hydrocarbons sufficient to dry the incoming feedstock and produce enough energy to sustain operation of the pyrolysis system itself.
8. For T ≥ 600 °C, the mean mass yield on a dry basis ($Y_m$) for biochar made from all crop residues considered is assumed to be 25% (Weber and Quicker 2018).
9. For T ≥ 600 °C and a 100-year GHG inventory period as recommended by Woolf et al. (2021), the biochar permanence factor ($F_{perm}$) is a function of only soil temperature ($T_s$). As illustrated in Fig. 1, the data are reasonably well represented by a 2nd-order polynomial:

$$F_{perm} = 0.0003 \times T_s^2 - 0.0167 \times T_s + 1.018 \tag{1}$$

Based on these assumptions, the Woolf et al. model may be generalized into the following form:

$$GHG_{bs} = \left[\Sigma_i \left(M_{fs,i} \times Y_i \times F_{c,i}\right) \times F_{perm} \times 44/12\right] - GHG_{bp} \tag{2}$$

where: $GHG_{bs}$ = net avoided GHG emissions from biochar carbon sequestration in units of tonne $CO_2$-equivalent ($CO_2$e) per year [t $CO_2$e year$^{-1}$]; $M_{fs,i}$ = dry mass of feedstock $i$ available for conversion to biochar [t year$^{-1}$]; $Y_i$ = dry basis mass yield of biochar derived from feedstock $i$; $F_{c,i}$ = dry basis organic carbon fraction of biochar derived from feedstock $i$; $F_{perm}$ = biochar permanence factor, a function of only national average soil temperature ($T_s$); Fig. 1. 44/12 = conversion factor from carbon to $CO_2$e. $GHG_{bp}$ = GHG emissions from biochar production [t $CO_2$e year$^{-1}$].

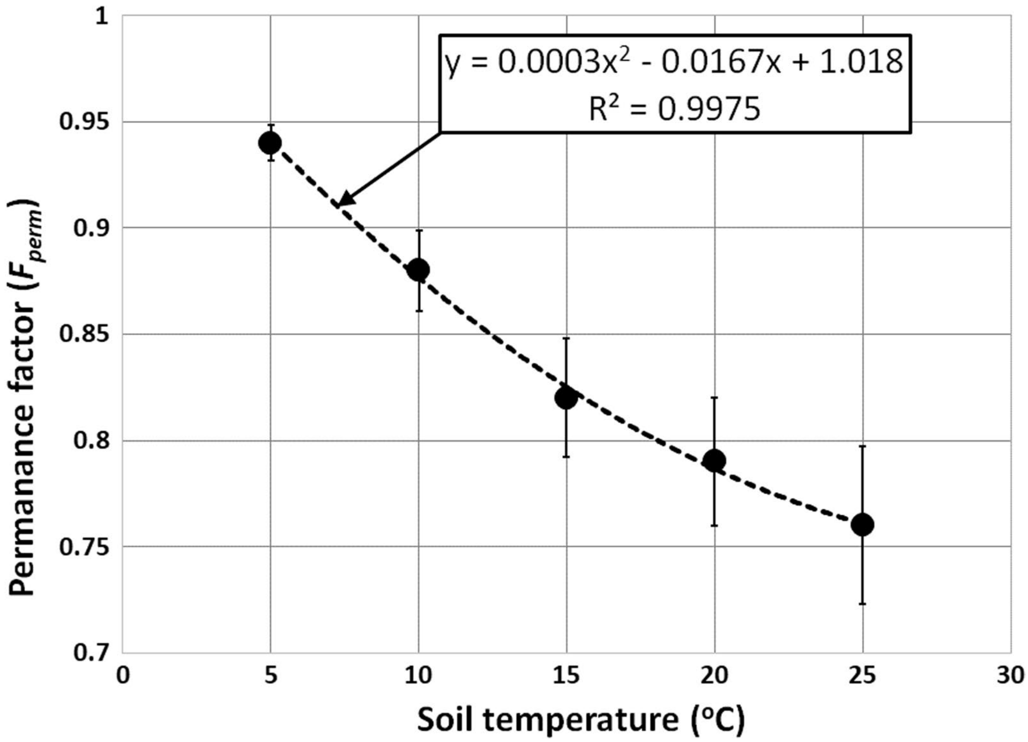



**Fig. 1** 100-year biochar permanence factor as a function of soil temperature, assuming biochar production via pyrolysis at high temperature (≥ 600 °C); based on data from Woolf et al. (2021). The bars indicate the standard errors reported in Table 5 of the same publication

### 2.2 Quantifying biomass residue resources

The collection of primary biomass residue data was carried out according to four broad categories: crop residues, animal manure, forestry wood residues, and wastewater biosolids.

#### 2.2.1 *Crop residues*

Crop production statistics were retrieved from the website of the Food and Agriculture Organization of the United Nations (FAOSTAT). All countries were selected, with the exception of Hong Kong, Macao, Taiwan and Mainland China, since such data were already aggregated under China. The same approach was used for China in the animal manure and forestry wood residue categories. From the items menu, "primary crops" was selected, and from the elements menu, "area harvested" and "production quantity" were specified. Data were obtained for 2020, as this was the most comprehensive and updated dataset available. The dataset included 148 crops produced globally, representing ~ 9.34 billion tonnes of global crop production. Based on the available crop residue generation data available in the scientific literature, we selected 44 crops, totaling ~ 7.72 billion tonnes, or 82.6% of global crop production. Biomass residue quantification was then carried out based on the residue-to-product ratio (RPR) or areal residue production (ARP) ratios listed in Additional file 1: Tables S1 and S2, considering the moisture content presented. In cases where both RPR and ARP values were available, we used the former because these values are directly correlated to crop production and thus comprehend temporal variations in residue generation. Field and process residues were quantified on a dry basis, where applicable. Collection factors of 70% and 100% were assumed for field and process residues, respectively. It is assumed that 30% of field residue mass needs to be retained to maintain soil health and crop levels (Puro Earth 2022; Battaglia et al. 2021).

#### 2.2.2 *Animal manure*

Livestock statistics were also retrieved from the FAOSTAT website (Crops and livestock products), following the same approach as crop production data. From the items menu "live animals" was selected and only buffalo, cattle, chickens, goats, horses, sheep and swine were specified, since we only had reliable manure generation data for these animals. Under "elements" section, "stocks" was selected to obtain data for 2020. Factors for manure generation rates (kg $d^{-1}$ $hd^{-1}$), collection factors, solids content and biochar yield, as listed in Additional file 1: Table S3, were used to quantify the total amount of dry manure available per type of livestock. In every case, we assumed a biochar organic carbon content of 39% on a dry basis (Woolf et al. 2021).

#### 2.2.3 Forestry wood residues

Forestry statistics were retrieved from the FAOSTAT website (Forestry production and trade). From the items menu, "wood residues" and "wood chips and particles" were selected. Under elements section, "production quantity" was specified to obtain data for 2020. As indicated in Additional file 1: Table S4, dry bulk density of 0.16 t $m^{-3}$ (Gendek et al. 2016) and collection factor of 100% (i.e., all residue materials generated from industrial wood processes) were used to quantify residue generation. We also assumed dry basis biochar yield and organic carbon content of 25% (Weber and Quicker 2018) and 81% (Woolf et al. 2021), respectively. We did not include forestry wood residues used for fuel and other applications.

#### 2.2.4 Waste water biosolids

To quantify biosolids generation, country level sanitation data were obtained from the WHO UNICEF JMP website. All countries were selected, representing 130 nations. The service type selected was "sanitation", and the safely managed element specified was "sewage treated". The data retrieved was in the form of population with access to treated sewage systems. Furthermore, the biosolids generation factor of 25.6 kg $year^{-1}$ $person^{-1}$ (dry basis; DiGiacomo and Romano 2022) and a collection factor of 100%, as indicated in Additional file 1: Table S5, were used to quantify dry biosolids generation mass per country. We assumed dry basis biochar yield and organic carbon content of 55.2% (Hossain et al. 2011) and 38% (Woolf et al. 2021), respectively.

### 2.3 Emissions from biochar production and application

The GHG emissions associated with the production, transport, and application of the biochar account for the building materials necessary for the pyrolysis plant construction and the energy required for pyrolysis preheating (natural gas), feedstock size reduction (electricity), biochar pelletizing (electricity), and pyrolysis plant auxiliary systems (electricity). The system boundary also includes the fuel used during the loading operations of the feedstock and biochar (diesel), the truck transportation of the feedstock and biochar, respectively, to and from the pyrolysis plant (diesel), and the biochar spreading on the field using an agricultural spreader (diesel).

The modeled system, with main input parameters summarized in Table 1, assumes that the pyrolysis plant produces enough electricity and heat to sustain itself and dry the receiving feedstock. Although crop and forest residues likely have higher energy and lower moisture content than livestock manure and wastewater biosolids, we assume there is sufficient waste heat available to bring all feedstocks to a moisture content level for optimal pyrolysis. The emissions associated with the production, transportation, and utilization of one tonne of biochar (in kg $CO_2$e per oven dry tonne of biochar) are calculated following Eq. 3:

$$\begin{aligned} CO_2Emission = & \left[Diesel_{Spread+Load} \times Ef_{Diesel}\right] \\ & + \left[\left(Ef_{transport} + \frac{Ef_{transport}}{Biochar_{yield}}\right) \times Dist\right] \\ & + \left[Elec \times Ef_{electricity}\right] + [NG \times Ef_{NG}] \\ & + Construction \end{aligned} \tag{3}$$

Modeling results are shown in Additional file 1: Figure S1 and Table S6.

### 2.4 National average soil temperatures

Using QGIS software version 3.24 (QGIS Association 2023), worldwide yearly average air temperatures were extracted from the Chelsa Climate Website (Chelsa 2022) and cropped to the combined pasture and cropland areas from Ramankutty et al. (2008). Air temperatures were then converted to soil temperature using the equations from Jian et al. (2022) and averaged by country to provide a national yearly average soil temperature on cropland and grassland. Results are shown in Fig. 2 and as numerical data in Additional file 1: Table S7.

### 2.5 Uncertainty analysis

The uncertainty analysis was performed using Monte Carlo simulations in R software version 4.2.2 (R Core Team 2022). The Monte Carlo simulations for assessing the GHG emissions associated with the production, transport, and application of biochar included 10,000 iterations from the distributions and values presented in Table 1. Mean and standard deviation of GHG emissions associated with the production of biochar per country are shown in Additional file 1: Figure S1, with mean values only listed in Additional file 1: Table S6. The Monte Carlo simulations for the assessment of total biochar potential (Fig. 3) and biochar potential as share of country's emissions (Fig. 5) further included additional uncertainty factors on the total mass of available feedstock (20% SD), feedstock-to-biochar conversion yield on a dry basis (5% SD), biochar permanence factor (10% SD), and organic carbon fraction of biochar (5% SD). These additional uncertainty parameters were assumed to be normally distributed.

**Table 1** Main input parameters for computation of GHG emissions from biochar production, transportation, and application

| Parameter | Definition | Value | Assumed distribution | Unit | Source |
|---|---|---|---|---|---|
| $Diesel_{Spread+Load}$ | Energy requirement for biochar spreading and loading | 2.21 ± 1.39 (mean ± SD) | Gamma | l diesel $t_{BC}^{-1}$ * | Koga et al. (2003); Grisso et al. (2010); Handler and Nadlinger (2012); Bühle (2014) |
| $Biochar_{Yield}$ | Biochar yield (w/w) | 0.25 ± 0.0125 (mean ± SD) | Normal; Assumed SD (5%) | – | Conservative assumption |
| Elec | Biochar plant electricity consumption | 400, 550, 700 (min, mode, max) | Triangular | kWh $t_{BC}^{-1}$ | Roberts et al. (2010); Bartocci et al. (2016); Wernet et al. (2016); Yang et al. (2016); Brassard et al. (2018); AMISY (2020a, 2020b); Tisserant et al. (2022) |
| NG | Natural gas combustion | 5.39 ± 0.539 (mean ± SD) | Gamma; Assumed SD (10%) | $m^3\ t_{BC}^{-1}$ | Roberts et al. (2010); MET-Group (2021) |
| Construction | Emissions associated with biochar plant construction | 29.65 to 185.51 (min, max) | Uniform | kg $CO_2$e $t_{BC}^{-1}$ | Roberts et al. (2010); Wernet et al. (2016); Yang et al. (2016) |
| Distance | Combined distance (to and from the pyrolysis plant) | Country—dependent | Gamma; Assumed SD (20%) | km | Estimated** |
| $Ef_{Diesel}$ | Emission factor for diesel combustion | 1.93 | – | kg $CO_2$e $l^{-1}$ | Our World in Data (2017) |
| $Ef_{Transport}$ | Emission factor for transportation | 0.2 | – | kg $CO_2$e $tkm^{-1}$ | Poore and Nemecek (2018) |
| $Ef_{NG}$ | Emission factor for natural gas combustion | 1.46 | – | kg $CO_2$e $m^{-3}$ | Our World in Data (2017) |
| $Ef_{Electricity}$ | Emission factor for electricity production | Country—dependent | Gamma | kg $CO_2$e $kWh^{-1}$ | Our World in Data (2022) |

*$t_{BC}$: metric tonne of biochar

**Interpolated using the function [distance = – 56.43*ln (pop_density_factor) + 50] based on minimal combined distance of 50 km and a baseline combined distance of 150 km for population density of Belgium (World Bank & FAO 2022). Pop_density_factor is a 0 to 1 scale representing the country's population density

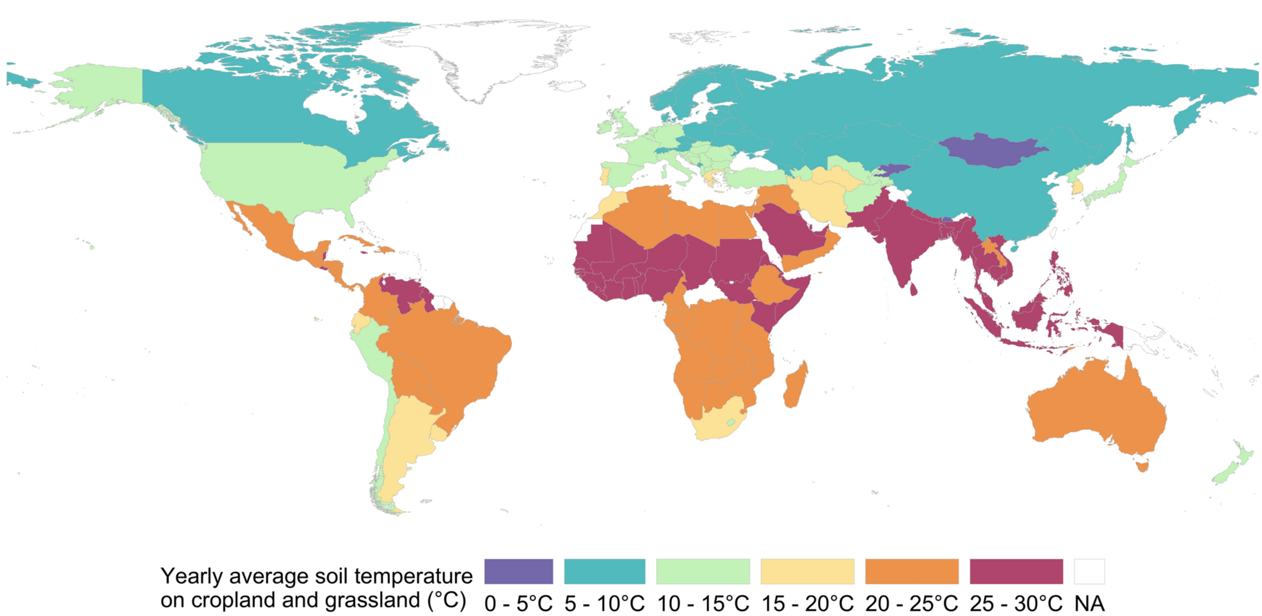



**Fig. 2** National average soil temperature on croplands and grasslands for computation of biochar permanence factor

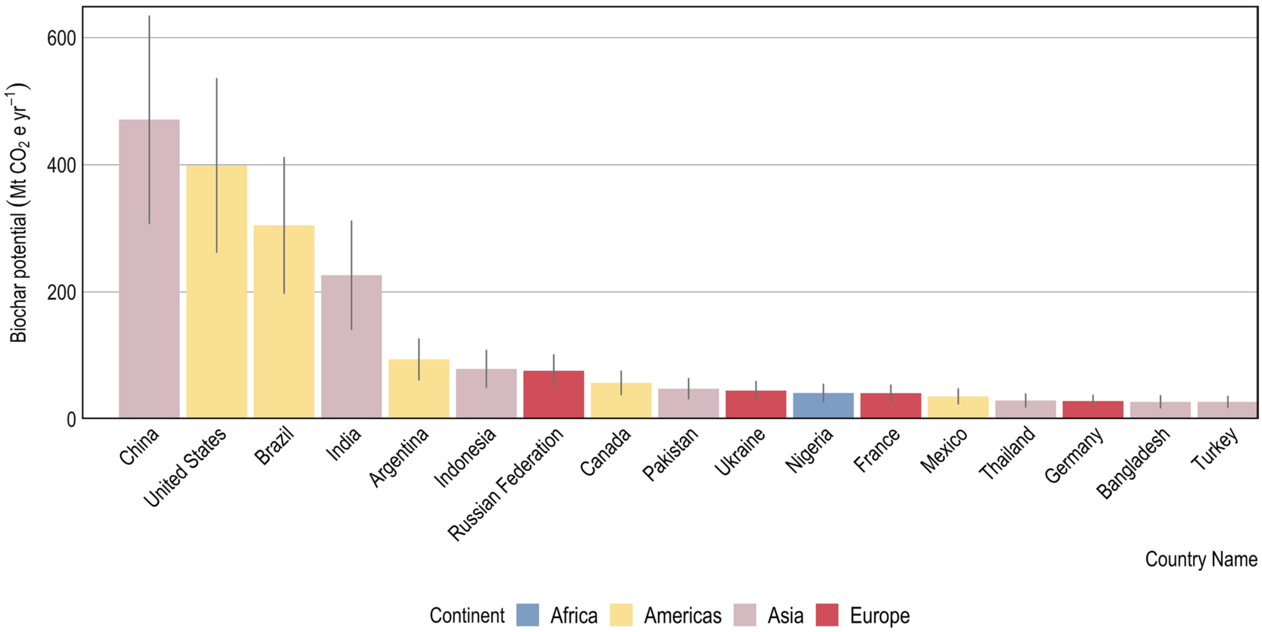



**Fig. 3** Countries with the largest biochar carbon dioxide removal potential (Mt $CO_2$e year$^{-1}$). Presented data are for the 17 countries with biochar carbon dioxide removal potential > 25 Mt $CO_2$e year$^{-1}$. Error bars represent standard deviation computed via Monte Carlo simulation (Methods section and Additional file 2)

## 3 Results and discussion

### 3.1 Global view of biochar's potential for carbon dioxide removal

As described in detail in the Methods section, our analysis approach was designed to be as inclusive as possible to enable assessment of biochar carbon sequestration potential in all global regions. We therefore relied on primary data for agricultural production, livestock production and wood/forestry residues from the Food and Agriculture Organization (FAO) of the United Nations, and wastewater biosolids data from the World Health Organization (WHO). We intentionally excluded the organic fraction of municipal solid waste (MSW) because consistent and accurate global data are not available. This global approach, however, required that we also be conservative in quantifying the benefits of biochar and focus solely on its role in sequestering atmospheric carbon dioxide in the form of recalcitrant solid carbon that can be added to soil or used in long-term industrial applications. Adequately computing other biochar production benefits related to minimizing $CH_4$ and $N_2O$ emissions, enhancing crop yields, displacing fossil fuels, etc. would require detailed information that is simply not available for most developing countries, or would require making many assumptions contributing to unreasonable uncertainty in the final results. Therefore, our approach is necessarily conservative but yields a useful global picture of where biochar can have the largest immediate impact, and what biomass residue feedstocks should be fully utilized to provide the greatest carbon dioxide removal benefits.

In Fig. 3 we present the results for the countries with the greatest biochar carbon potential in absolute terms, with the unit of million tonnes (Mt) $CO_2$e year$^{-1}$. As expected, countries with large populations, land areas and agriculture production dominate the list, with potential biochar carbon dioxide removal for China, the U.S., Brazil and India at 468, 398, 303 and 225 Mt $CO_2$e year$^{-1}$, respectively. The remaining countries, from Argentina to Turkey, all have biochar potentials between 25 and 100 Mt $CO_2$e year$^{-1}$. Generally, the group of 17 countries in Fig. 3 represent those with larger populations and thus significant domestic food production industries, with seven countries in Asia, five in the Americas and four in Europe. Nigeria is the only African country among those with the largest biochar potential in absolute terms. The map in Fig. 4 provides a global snapshot of biochar carbon dioxide removal potential, and in this view, several general observations emerge. A significant proportion of the land mass of North and South America is comprised of countries that have large biochar potentials, in excess of 25 Mt $CO_2$e year$^{-1}$. Conversely, bands of relatively low biochar potential extend across North Africa into the Middle East, and are also present across smaller regions of Europe and southern Africa.

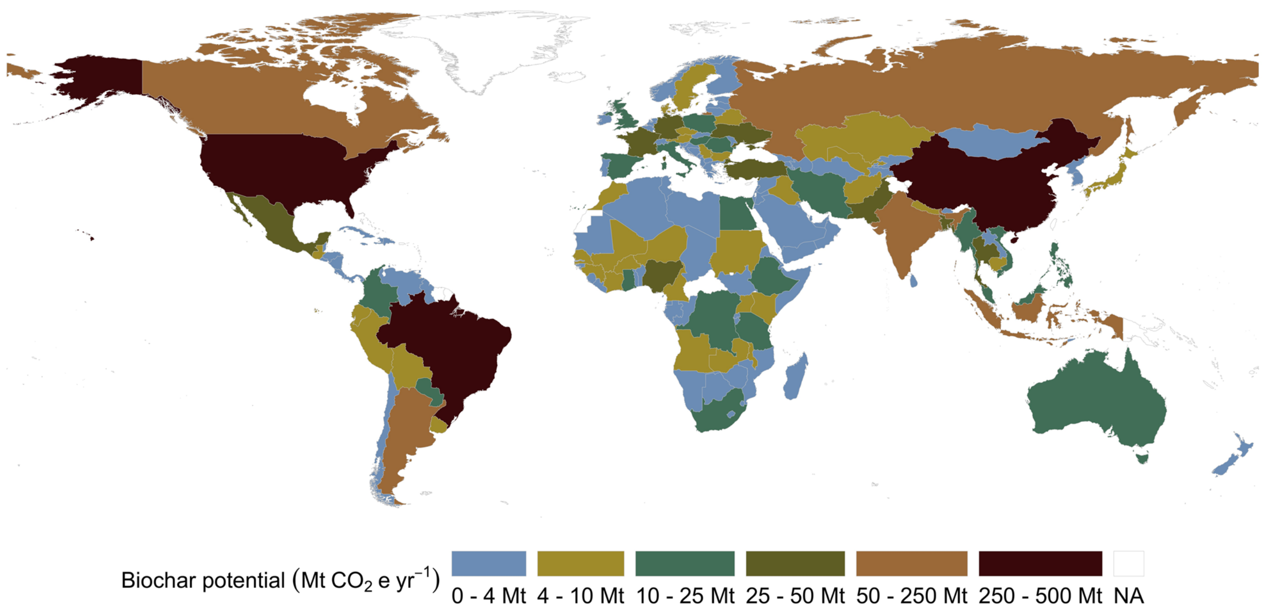



**Fig. 4** Global biochar carbon dioxide removal potential map (Mt $CO_2$e year$^{-1}$)

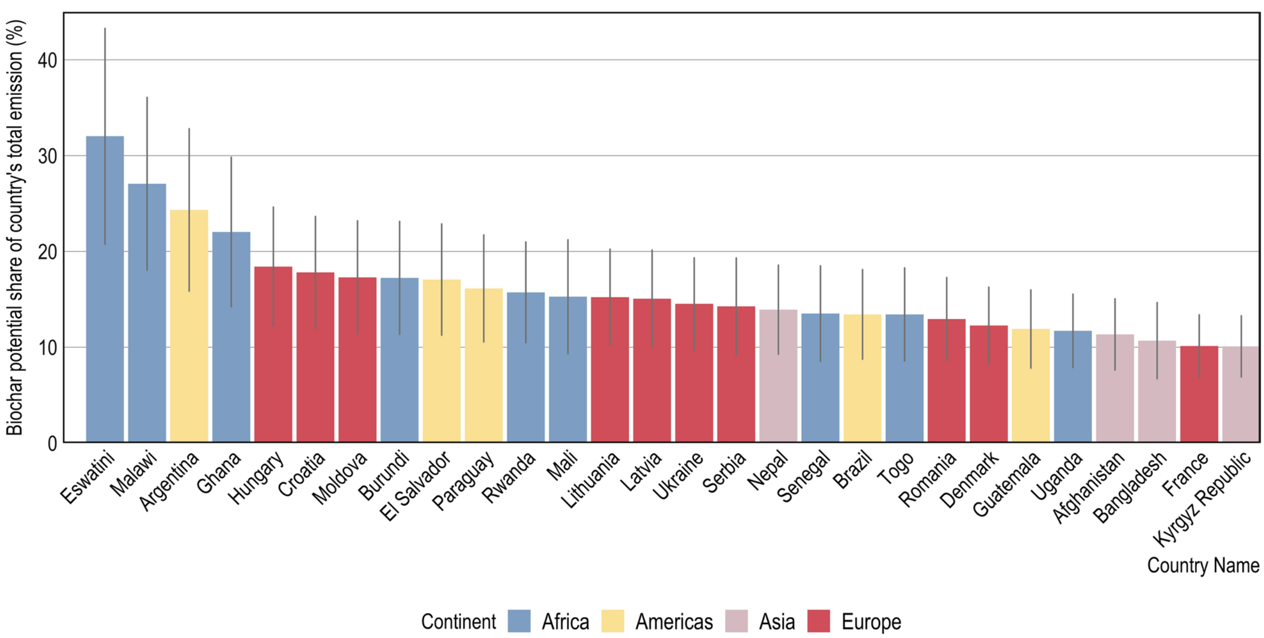



**Fig. 5** Countries with the largest biochar carbon dioxide removal potential as percentage of total GHG emissions. Presented data are for the 28 countries with biochar carbon dioxide removal > 10% of total national emissions. Error bars represent standard deviation computed via Monte Carlo simulation (Methods section and Additional file 2)

Figures 5 and 6 present the biochar carbon dioxide removal potential as a percentage of total national emissions in 2020, as reported by Jones et al. (2023). The bar chart in Fig. 5 displays the results for 28 countries with biochar potential in excess of 10% of emissions, with Eswatini (formerly Swaziland) showing the greatest impact at 32% of national emissions, and three other countries with impacts exceeding 20% of national emissions: Malawi (27%), Argentina (24%) and Ghana (22%). The largest number of countries presented in Fig. 5 are in Europe, but Africa, the Americas and Asia are also represented by four or more countries.

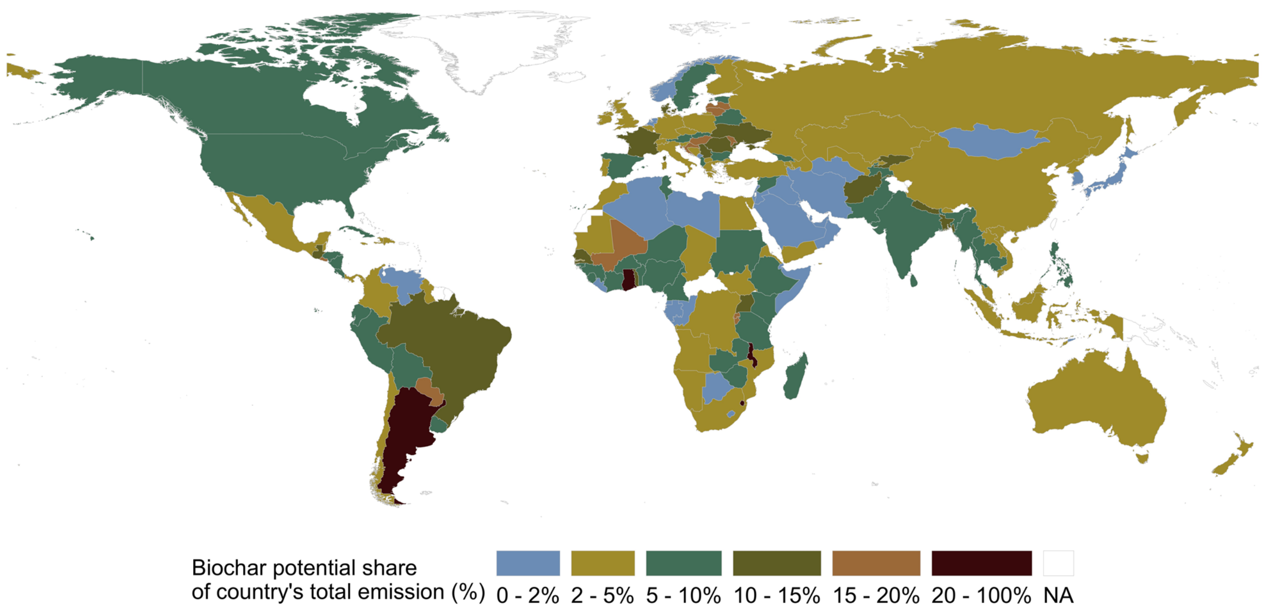



**Fig. 6** Global biochar carbon dioxide removal potential map as a percentage of total national GHG emissions

In comparing the bars charts in Figs. 3 and 5, we find that only five nations are among those with the greatest biochar carbon dioxide removal potential in absolute terms, as well as having the potential to offset at least 10% of national emissions via biochar production: Brazil, Argentina, Ukraine, France and Bangladesh. The global map in Fig. 6 also reveals some interesting general trends. Similar to Fig. 4, a band of low biochar impact as a percentage of national emissions is concentrated across North Africa and the Middle East, and extending to Kazakhstan and Mongolia, presumably due to the arid climate that places natural constraints on agricultural production that yields the major source of biomass residue for biochar production. However, some pockets of concentrated low biochar impact exist in areas that would seem to be better suited for efficient

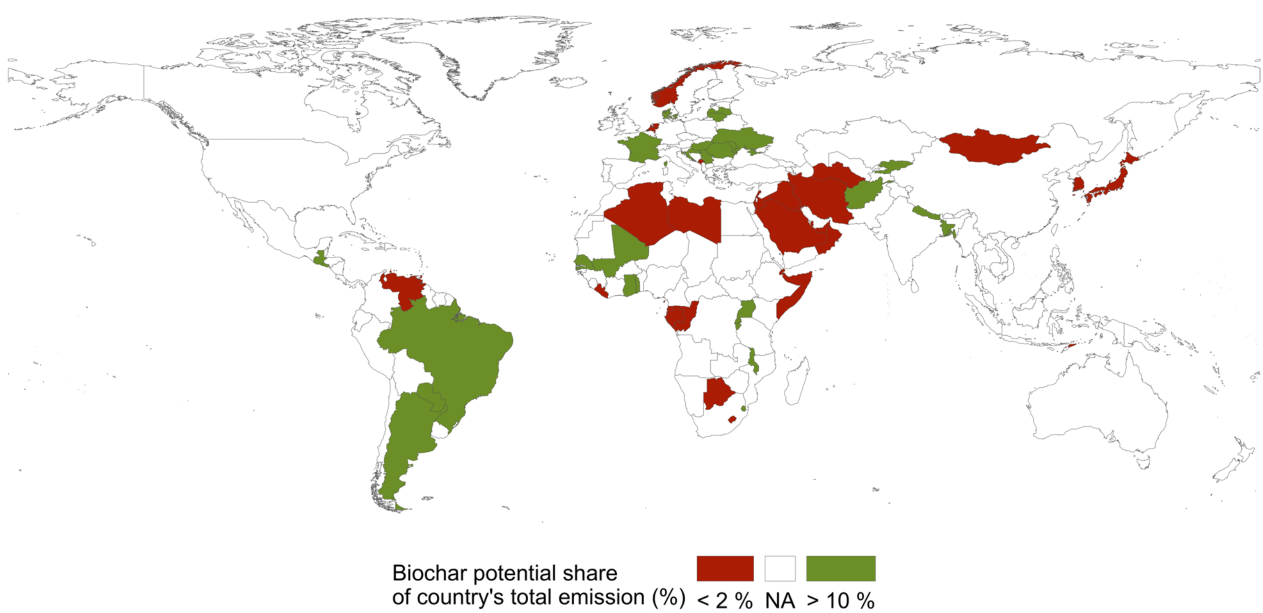



**Fig. 7** Global map of countries with highest potential biochar impact (> 10% of national emissions; green) and lowest potential biochar impact (< 2% of national emissions; red)

and diverse crop production, but current agricultural output may be adversely impacted by economic and/or political factors. These impacts are likely at play in Venezuela, which shows a relatively low potential biochar impact (~1.8% of national GHG emissions) despite having favorable climate conditions for agricultural production and bordering Brazil, one of the highest biochar potential countries in the world. Brazil belongs to one of the three global regions notable for having concentrations of countries with high biochar carbon impact. The contiguous region comprised of Argentina, Brazil and Paraguay, with biochar impacts of about 24%, 16% and 13% of national emissions, respectively, accounts for over 65% of the total land area of South America. Two other global regions are also important to highlight because of their concentrated potential for significant biochar carbon dioxide removal, albeit covering much smaller land areas. In northwestern Africa, four countries in close proximity stand out: Ghana (22% of national emissions), Mali (15%), Senegal (13%) and Togo (14%). In eastern Europe, six contiguous countries have biochar potential exceeding 10% of current national emissions: Hungary (18%), Croatia (18%), Moldova (17%), Ukraine (15%), Serbia (14%) and Romania (13%). The clear distinction between regions of highest (>10% of national emissions) and lowest (<2%) potential biochar impact is further illustrated in Fig. 7.

### 3.2 Comparison of high biochar impact countries

Deploying biochar production at scale requires detailed knowledge at a national level of specific feedstock production locations, volumes and seasonality, as well as myriad economic and policy factors that would influence the decision-making process across all facets of an industrial biomass-to-biochar infrastructure. The first step in developing this foundational knowledge is identifying and quantifying the most significant sources of biomass residue available for conversion to biochar. In Fig. 8, we present the sources of agricultural residues that provide the greatest contributions to biochar organic carbon for the first seven countries presented in Fig. 3 with the largest absolute biochar potentials in Mt $CO_2$e year$^{-1}$. Each of the major biochar impact countries has a small number of agricultural residue resources that dominate the potential for biochar production, in terms of total organic carbon percentage. In India, China, the Russian Federation and the United States, a single crop dominates the biochar production potential, with rice, maize, wheat and maize providing about 28%, 44%, 53% and 63%, respectively, of each country's share of biochar carbon production. In Brazil, two crops stand out as providing the majority of the biochar impact, with soya beans and sugar cane residues each contributing about 34% of total organic carbon potential. Similarly, in Argentina, soya beans and maize each contribute about 42% of the total potential biochar carbon. This combined impact of 84% of national emissions is important to highlight because the residues from just these two crops are sufficient to position Argentina as the country with the fifth highest biochar potential in absolute terms (Fig. 3), but also #3 in regards to the contribution biochar can make toward reducing net national GHG emissions (Fig. 5). Although some countries, including China, India, Indonesia and the Russian Federation have a greater variety of crops that can make significant contributions to biochar production, in every case presented in Fig. 8, the residue from only one to three crops is sufficient to achieve over 50% of the total national biochar potential. It's therefore evident that initial deployment of any national biochar production strategy should focus on the most widely produced crops, strategically applying policy instruments to encourage growers to invest in crop residue collection and pre-treatment technologies, thereby making their material readily available and suitable for downstream transport, pyrolysis, post-treatment and distribution as a biochar product for agricultural, horticultural and industrial applications.

The dominant impact of various agricultural residues illustrated in Fig. 8 leads one to question why the non-crop biomass resources have relatively minor influences on national biochar carbon dioxide removal potential, at least for the countries with largest absolute biochar potential. As shown in Additional file 1: Figure S2 for the same countries covered in Fig. 8, crop residues contribute by far the largest fraction of biochar organic carbon with animal manure the next largest contributor, approaching about 20% of the total in Indonesia. The primary challenge to manure as a major biochar feedstock source is the low collection factor, assumed to be 11–12% for all animals except chickens with a collection factor of 48% (Additional file 1: Table S3). Improved manure management systems, especially in situations where livestock are housed in barns or similar structures, could significantly improve collection efficiency as has been demonstrated for anaerobic digesters deployed at large farms that maintain hundreds or thousands of cows (Adghim et al. 2020). However, other limitations to the biochar potential of animal manure and biosolids from wastewater treatment are their relatively high moisture and low biochar organic carbon content (Additional file 1: Tables S3 and S5). Regarding forestry residue, we intentionally limited our methodology to consider only wood residues, wood chips/particles and recoverable wood products (Additional file 1: Table S4) to avoid any potential conflicts with resources used in other existing applications, such as fuel for heating and cooking. However, detailed

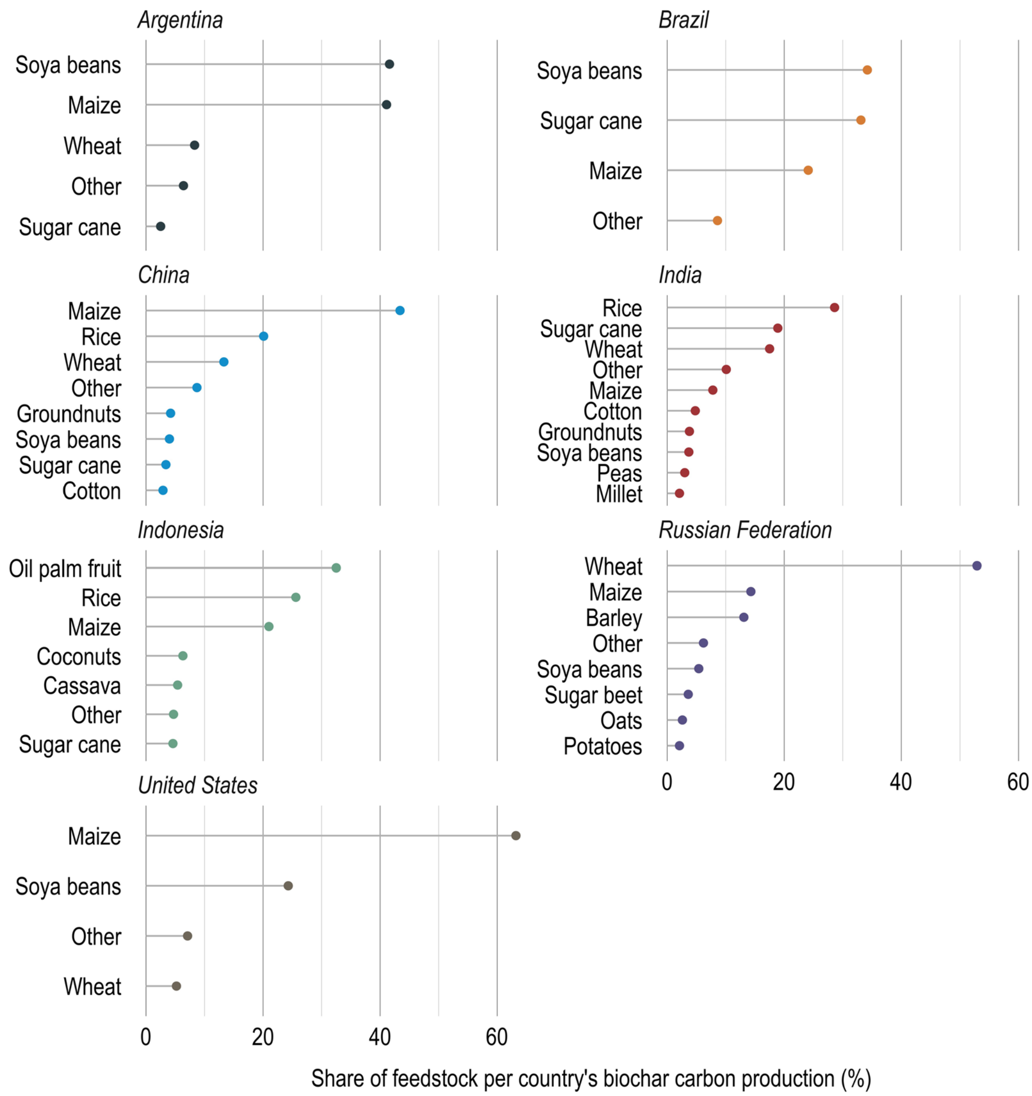



**Fig. 8** Major sources of crop residues in high biochar potential countries, based on the percentage of biochar carbon production

assessment at a national level may reveal greater potential for forest residues as reported in the study by Feng et al. (2020), who attributed 18.52% of the total biochar carbon sequestration potential in China to "firewood and forest trees".

### 3.3 Discussion

It is instructive to compare the results of the present analysis to prior studies that have considered the carbon dioxide removal potential of biochar at global or national scales. The widely cited study by Woolf et al. (2010) demonstrated that biochar can offset a maximum of 12% of annual global anthropogenic $CO_2e$ emissions when utilizing biomass resources harvested without impacting food security, habitat or soil health. They included major sources of crop residues (sugar cane, rice and other cereals), animal manure (cattle, pigs, poultry) and forestry residue, but is also considered biomass crops, green wood waste and agroforestry waste which the present analysis did not. Woolf et al. also assumed biochar benefits beyond carbon sequestration alone, including avoided methane and nitrous oxide emissions, and fossil fuel offsets from excess energy production. Our analysis is more inclusive regarding crop residues, to account for all major sources of biomass in addition to sugar cane and cereal crops, but also conservative in the sense that biochar's benefit was limited to only carbon dioxide removal in the form of recalcitrant carbon with permanence factor based solely on national average soil temperature. Because of our generally more conservative approach, we computed an annual biochar carbon dioxide removal potential of 6.23 ± 0.24% of total GHG emissions of the 155 countries covered; national-level emissions were reported by Jones et al. (2023) and have been tabulated in the Additional file 2 in column "total_ghg". In other words, averaged over all countries assessed, biochar production can effectively sequester 62.3 ± 2.4 kg of $CO_2$e per tonne of total $CO_2$e emitted. It is important to emphasize that the total GHG emissions in the Jones et al. (2023) paper include not only $CO_2$ from fossil fuel combustion, but also fossil fuel-related $CH_4$ and $N_2O$ emissions, as well as emissions of all three gases associated with land use, land use change and forestry (LULUCF). The primary reasons for our biochar potential relative to total GHG emissions being significantly smaller than that predicted by Woolf et al. (2010) is the much broader variety of biochar benefits included in the Woolf analysis, as well as their inclusion of additional feedstocks such as woody and herbaceous biomass crops that were not considered in our model. It should also be noted that our results may be influenced somewhat by the impacts of COVID-19 on both biomass residue production and global emissions, but we believe the overall effect on the percentage of $CO_2$e removal would be small, based on the relatively minor dip in global $CO_2$ emissions in 2020 reported by Liu et al. (2023).

Because of China's current position as the largest global GHG emitter (IEA 2022) and its enormous production of biomass residues (Fig. 3), there is significant interest in the role biochar can play in meeting the country's aggressive de-carbonization goals. Several recent papers have quantified the potential for biochar carbon dioxide removal, albeit with quite different approaches. Feng et al. (2020) considered four major biomass resources in China: crop straw, firewood and forest trees, livestock manure and municipal organic waste, the latter including industrial solid waste and household garbage. They concluded that crop residues yielded less than one-third (31.4%) of the carbon sequestration benefit among the wide variety of biomass resources considered. This is in contrast to our results that show about 85% of the global biochar carbon sequestration potential is associated with crop residues, because we considered a wider variety of crop residue resources in every country (not just crop straw) and also did not include firewood, forest trees and municipal organic waste as feedstocks for biochar production. As stated in Sect. 2.2, we considered forestry waste residues comprised of only "wood residues" and "wood chips and particles" from the FAOSTAT database, and intentionally did not include forestry wood residues used for fuel and other applications. Moreover, Feng et al. included many biochar benefits that we did not: displacing coal-fired electricity generation, improved crop yields, avoided emissions from reduced fertilizer use, reduced soil $N_2O$ emissions, suppression of soil organic carbon (SOC) decomposition, and avoided methane emissions from landfill diversion of some feedstocks. Combining their much broader range of included biochar feedstocks and considering all the additional biochar benefits (in aggregate greater than the biochar carbon sequestration benefit alone), they concluded that it is possible to offset 15.23% of China's total GHG emissions, nearly four times greater than our estimate of 3.9% of emissions.

Another recent study by Yang et al. (2021b) posed a somewhat narrower research question more closely aligned with the present study: "if all of a country's crop residues were used to produce biochar for soil storage and biofuel for energy recovery without endangering food security, what's the maximum amount of carbon that could be sequestered?". Considering only crop residues as biochar feedstocks, but including some of the same non-sequestration benefits analyzed by Feng et al. (2020), Yang et al. concluded that a national biochar system in China could offset 4.5% of total GHG emissions, based on 2014 data. This result is in much closer agreement to that from the present framework, and again emphasizes that our analysis is conservative by design to enable consistent biochar impact assessment for all countries. Other recent studies of biochar potential in China by Xia and co-workers have focused on carbon−neutral crop production (Xia et al. 2023a) and broader climate mitigation potential by considering biomass residues similar to those of Feng et al. (2020): crop residues, forest residues, livestock manure, food waste, and sewage sludge (Xia et al. 2023b). The latter publication reported an average GHG mitigation potential of 455.7 Mt $CO_2$e $year^{-1}$ based on 2018 residue data, equivalent to 3.8% of China's national GHG emissions in 2020. This result is quite consistent with our calculation for China (469.8 Mt $CO_2$e $year^{-1}$, 3.9% of national emissions); however these nearly equivalent values were arrived at by applying different methods. Xia et al. (2023b) added fossil fuel offsets, reduced soil $CH_4$ and $N_2O$ emissions and avoided GHG emissions from higher rice yields to the direct carbon sequestration benefit of biochar, but they constrained biomass residue availability to account for current agricultural and industrial uses. For example, Xia et al. assumed only 10.3% of collectable crop residues are available for conversion to biochar (equivalent to use for energy recovery), while excluding materials currently used for bio-fertilizer (47%) and animal feed (19%).

A recent Canadian paper highlights many important logistical and economic issues to consider when developing country-level estimates of the potential impact in 2030 of so-called natural climate solutions, including $CO_2$ sequestration from crop residue derived biochar (Drever et al. 2021). As in the current study, these researchers limited their analysis to crop residues that can be sustainably harvested, while assuming 100-year persistence and no effect on $N_2O$ or $CH_4$ emissions from soil. However, they adjusted their residue projections by considering bale yields after rotary combine harvesting of oats, barley, wheat, and corn, and computed effective residue-to-product ratios (RPR) in the range of 0.4–0.6, with moisture contents of 15% and 25% for small grains and corn stover, respectively. These values compare to much larger RPR values for the same field residues in our analysis, based on the study by Koopmans & Koppejan (1998): 1.75 for oats, barley and wheat straw, and 2.0 for corn stalks (Additional file 1: Tables S1 and S2). This apparent discrepancy may relate to differences in harvesting technology that impact the fraction of recoverable residues. The Drever et al. study based their analysis on data for heavy automated machinery, whereas the primary data in Koopmans and Koppejan are more than 25 years old and likely involved lower-technology mechanical harvesting methods, or perhaps manual harvesting in many cases. Following their generally conservative methodology, Drever et al. also reduced the amount of crop residues available for biochar production to account for livestock feeding, and also accounted for emissions from additional nitrogen fertilizer needed to replace lost soil nutrients and loss of soil organic carbon (SOC) from reduced inputs of crop residues. The total amount of biomass feedstock available for conversion to biochar from the four main crops listed above was estimated as 16.1 Mt year$^{-1}$, providing a net biochar carbon sequestration benefit of 6.9 Mt $CO_2$e year$^{-1}$, with total uncertainty range of 3.2 to 10.6 Mt $CO_2$e year$^{-1}$. Our estimate for residues generated from these same four crops, based on 2020 data, is about 69 Mt year$^{-1}$, over four times greater as expected from our much higher assumed RPR value. Based on the total 2020 crop residue generation rate estimated from 25 crops, combined with the associated biochar carbon dioxide removal potential, we computed a net biochar benefit for Canada of 0.44 t $CO_2$e t$^{-1}$ residue, about 63% greater than the value of 0.27 t $CO_2$e t$^{-1}$ reported by Drever et al. (2021). When aggregating all the global biomass residue feedstocks available and the associated biochar carbon dioxide removal potentials listed in Additional file 2 (7.37 billion t and 2.65 billion t $CO_2$e, respectively), we arrived at a global biochar benefit factor of 0.36 t $CO_2$e t$^{-1}$ dry feedstock, 10% less than the lower end of the range 0.4–1.2 cited by Cowie et al. (2015).

As mentioned throughout the foregoing discussion, the primary objective of this study was to develop a global view of biochar's potential as a carbon dioxide removal strategy. In using data resources that offered consistent biomass residue information for all countries, we necessarily compromised on the level of detail and granularity in the data, and thus likely left out important information that will be critical in deploying pyrolysis and biochar systems as part of a sustainable economic enterprise. Thus, we consider this initial study as a starting point for researchers who will pursue the opportunity for biomass residue-to-biochar production in individual countries. In this spirit, we offer several recommendations for further refining the findings from our biochar carbon impact framework. We relied heavily on the data from Koopmans and Koppejan (1998) for residue-to-product ratio (RPR), areal residue production (ARP) factor and moisture content for many crops, but this publication focused specifically on Asia and reported primary data that are now at least 25 years old. Crops grown in other global regions may vary due to differences in farming practices, ambient and soil conditions, etc., and therefore current country-level data for these various parameters should be obtained, as nicely illustrated for Canada in the paper by Drever et al. (2021). Even papers published within the last five years report very wide ranges of RPR values for various crops grown in different global regions, further emphasizing the need to acquire reliable local RPR data. For example, Avcıoğlu et al. (2019) analyzed a large body of literature to determine RPRs for estimating biomass residue resources in Turkey, and reported values for maize (corn) stalks that varied from 1.50 to 2.25, with an overall average of 1.88, 6% less than our value of 2.0 (Additional file 1: Table S1). It should also be recognized that RPR is a function of crop yield, with higher yields that result from more advanced farming practices generally leading to lower RPR (Scarlat et al. 2010). To more accurately quantify available organic biomass residues at the national level, data should be updated with locally derived values to the extent possible. For example, Ferreira-Leitão et al. (2010) reported detailed residue data for production of maize, cassava, wheat, coconut and citrus crops in Brazil, and similar analysis would be required for any country with aspirations to build a viable biochar industry. Lastly, our results clearly show the dominant contribution of agricultural residues in biochar production, but in many regions animal manure and forest residues can play much larger roles if the logistics associated with raw biomass collection, pre-treatment, transport, etc. can be addressed and systems designed to make these materials economically viable feedstocks.

## 4 Conclusions

A framework has been developed and applied for quantifying the carbon dioxide removal (CDR) potential of biochar for nearly every country, assuming use of only biomass residue materials generated from existing agriculture, livestock, forestry and wastewater treatment operations. This effort has included determination of national average soil temperature that dictates biochar permanence, and also considered the emissions generated at a national level in the production and application of biochar. The results demonstrate that biochar can play a meaningful role in worldwide CDR efforts, with the potential to offset at least $6.23 \pm 0.24\%$ of total GHG emissions of the 155 countries covered based on our conservative set of assumptions. However, far greater impacts can be realized in a number of countries, with regions of especially high carbon dioxide removal potential relative to national emissions identified in South America, northwest Africa and eastern Europe. To facilitate rapid expansion of the biochar industry to a scale needed to counteract continuously rising atmospheric $CO_2$ levels, further research is urgently needed at the scale of individual countries to obtain reliable data for biomass residue generation rates, residue-to-product ratio (RPR), etc. Country-level data are also needed to fully quantify biochar's carbon dioxide removal potential, including benefits of displacing fossil electrical energy generation, improved crop yields, reduced use of synthetic fertilizers, etc. that were not included in the present analysis, but in aggregate could conceivably result in much larger CDR benefits. Future research should also focus on development of detailed roadmaps at a national level for high-impact feedstocks that may have not been considered in this study, prioritized based upon both techno-economic analysis and co-benefits such as climate change adaptation and resilience in different cropping and growing scenarios.

## Supplementary Information

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**Additional file 1.** Supplementary tables and figures.

**Additional file 2.** Supplementary data.

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**Author contributions**

DL: Modeling and data presentation, writing—original draft. SF: Feedstock analysis, data curation, writing—original draft. CAA: Feedstock analysis, data curation, writing—original draft. AIO: Feedstock analysis, writing—original draft. KTD: Conceptualization, funding acquisition. TAT: Conceptualization, project administration, writing—original draft. All authors read and approved the final manuscript.

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**Availability of data and materials**

The datasets used or analyzed during the current study are available from the corresponding author on reasonable request.

## Declarations

**Competing interests**

The authors have no financial or proprietary interests in any material discussed in this article.

**Author details**

[1]University of British Columbia, Vancouver, BC V6T 1Z4, Canada. [2]School of Chemistry and Chemical Engineering, Queen's University, Belfast BT9 5AG, Northern Ireland. [3]Trinity Biocarbon, Masdar City, P.O. Box 135098, Abu Dhabi, UAE. [4]International Biochar Initiative (IBI), Longmont, CO 80501, USA. [5]Golisano Institute for Sustainability, Rochester Institute of Technology, Rochester, NY 14623, USA.

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