Received: 15 June 2023 | Revised: 25 August 2023 | Accepted: 28 August 2023

DOI: 10.1111/gcbb.13102

GCB-BIOENERGY Bioproducts for a sustainable bioeconomy Open Access WILEY

RESEARCH ARTICLE

Potential for biochar carbon sequestration from crop residues: A global spatially explicit assessment

Shivesh Kishore Karan[1,2] | Dominic Woolf[3,4,5] | Elias Sebastian Azzi[1] | Cecilia Sundberg[1] | Stephen A. Wood[6,7]

[1]Department of Energy and Technology, Swedish University of Agricultural Sciences, Uppsala, Sweden

[2]Department of Geomatics, Norwegian Institute of Bioeconomy Research, Ås, Norway

[3]School of Integrative Plant Sciences, Cornell University, Ithaca, New York, USA

[4]Atkinson Center for Sustainability, Cornell University, Ithaca, New York, USA

[5]Institute of Digital Agriculture, Cornell University, Ithaca, New York, USA

[6]The Nature Conservancy, Arlington, Virginia, USA

[7]Yale School of the Environment, New Haven, Connecticut, USA

Correspondence
Dominic Woolf, School of Integrative Plant Sciences, Cornell University, Ithaca, NY, USA.
Email: d.woolf@cornell.edu

Funding information
Bezos Earth Fund

Abstract

Global warming necessitates urgent action to reduce carbon dioxide (CO_2) emissions and remove CO_2 from the atmosphere. Biochar, a type of carbonized biomass which can be produced from crop residues (CRs), offers a promising solution for carbon dioxide removal (CDR) when it is used to sequester photosynthetically fixed carbon that would otherwise have been returned to atmospheric CO_2 through respiration or combustion. However, high-resolution spatially explicit maps of CR resources and their capacity for climate change mitigation through biochar production are currently lacking, with previous global studies relying on coarse (mostly country scale) aggregated statistics. By developing a comprehensive high spatial resolution global dataset of CR production, we show that, globally, CRs generate around 2.4 Pg C annually. If 100% of these residues were utilized, the maximum theoretical technical potential for biochar production from CRs amounts to 1.0 Pg C year^{-1} (3.7 Pg CO_2e year^{-1}). The permanence of biochar differs across regions, with the fraction of initial carbon that remains after 100 years ranging from 60% in warm climates to nearly 100% in cryosols. Assuming that biochar is sequestered in soils close to point of production, approximately 0.72 Pg C year^{-1} (2.6 Pg CO_2e year^{-1}) of the technical potential would remain sequestered after 100 years. However, when considering limitations on sustainable residue harvesting and competing livestock usage, the global biochar production potential decreases to 0.51 Pg C year^{-1} (1.9 Pg CO_2e year^{-1}), with 0.36 Pg C year^{-1} (1.3 Pg CO_2e year^{-1}) remaining sequestered after a century. Twelve countries have the technical potential to sequester over one fifth of their current emissions as biochar from CRs, with Bhutan (68%) and India (53%) having the largest ratios. The high-resolution maps of CR production and biochar sequestration potential provided here will provide valuable insights and support decision-making related to biochar production and investment in biochar production capacity.

Dominic Woolf and Shivesh Karan should be considered joint first author.

KEYWORDS

biochar, carbon sequestration, crop residues, geospatial information science, global maps, negative emissions

1 | INTRODUCTION

To limit global warming to below 2°C compared to pre-industrial levels, it is essential to both reduce net greenhouse gas (GHG) emissions, and also to remove excess carbon dioxide (CO_2) from the atmosphere through carbon dioxide removal (CDR) strategies (Griscom et al., 2017; Liu & Raftery, 2021). Resources and techniques for land-based climate change mitigation, including storing CO_2 in land-based pools are gaining attention (Baruch-Mordo et al., 2019; Roe et al., 2021). Efforts aimed at land-based mitigation, such as afforestation, reforestation, or soil carbon sequestration, require significant amounts of finite resources, including land, and biomass (Smith, 2018). These resources may be scarce in some regions and face competition from other uses, which can limit their availability for these efforts and make implementation more challenging, expensive, and unsustainable. However, crop residues (CRs) offer a promising solution to counter these challenges. Unlike other biomass resources, CRs do not require additional land and provide a variety of uses without driving demand for land. One potential use for CRs is their conversion to biochar, which can be added to soil, or otherwise sequestered, as a strategy for CDR (Woolf et al., 2010). Biochar as a land-based mitigation strategy has several co-benefits, making it a potentially more cost-effective method of CDR than bioenergy with carbon capture and storage (BECCS) technologies whereby biochar could become economically viable at a lower carbon price than BECCS (Woolf et al., 2016).

Biochar, a type of charcoal produced from the thermal decomposition of organic materials has been proposed as a potential tool for climate mitigation (Lehmann et al., 2021). When added to soil, biochar can sequester carbon because the carbon in biochar is relatively stable and remains in the soil for long periods, rather than being released into the atmosphere as CO_2 (Lehmann et al., 2021; Wang et al., 2016; Woolf et al., 2021). The conversion of photosynthetically fixed carbon into persistent biochar that would otherwise be returned to atmospheric CO_2 through respiration or combustion, thus constitutes a net CDR from the atmosphere (Lehmann et al., 2021). Maintaining a safe climate will require some CDR to offset hard to eliminate emissions, and to recover from any overshoot in safe CO_2 concentrations (IPCC, 2022). This article provides a spatially explicit assessment of the potential for carbon sequestration in biochar from CRs. Most life-cycle assessments indicate that carbon sequestration is the largest contribution to net GHG impacts of biochar systems, contributing to more than half of the net GHG emission reductions (Lehmann et al., 2021; Tisserant & Cherubini, 2019).

In addition to directly sequestering carbon, biochar production and application to soils can contribute to a range of other impacts on net GHG fluxes. For example, biochar can modify (typically reduce) soil N_2O (Borchard et al., 2019) and CH_4 (Jeffery et al., 2016) emissions. Emissions of N_2O and CH_4 that would have arisen from the decomposition or combustion of the feedstock are avoided (Woolf et al., 2010). Biochar can alter (typically reduce in the long term) the decomposition rate of native soil organic carbon (SOC; Maestrini et al., 2015). Reduced fertilizer requirements avoid GHGs from fertilizer production and transport (Woolf et al., 2010). Co-production of bioenergy with biochar can offset fossil-fuel emissions (Woolf et al., 2016). Biomass pyrolysis can entail emissions of volatile and gaseous organic compounds, particularly if simple low-cost technologies are utilized that fail to fully combust the pyrolysis gases (Cornelissen et al., 2016). There are emissions associated with harvesting and transport. Biochar can also improve soil quality, leading to increased phytomass production that may be utilized for further carbon sequestration (Schmidt et al., 2021; Woolf et al., 2010). A complete inventory of emissions and avoided emissions would form part of a life-cycle assessment for individual biochar projects that goes beyond the carbon sequestration potential provided in this article. However, life-cycle assessments must be related to specific conversions of specific feedstocks applied in specific locations, and are not readily generalizable to global maps. While the specific climate change mitigation potential of biochar depends on various factors, such as the feedstock used and the production method (Joseph et al., 2021; Woolf et al., 2021), it has the potential to make a significant contribution to efforts to address global warming (Matustik et al., 2020; Tisserant & Cherubini, 2019; Woolf et al., 2010).

There are estimates of the potential of biochar to contribute to climate change mitigation at global and national scales (Griscom et al., 2017; Roe et al., 2021). While these estimates are useful for actions at these scales, there is a need for refined estimates to guide planning of actions at finer scales, such as agriculture and conservation projects that operate at regional and landscape levels. Providing tools to guide planning of biochar at these scales can help provide a sustainable use for currently unused CRs (Monforti et al., 2013, 2015). To effectively quantify the potential for biochar to contribute to climate change mitigation at regional and landscape scales, it is necessary to quantify the biomass input to biochar production at this scale. Additionally, spatially explicit assessment can help identify areas where CR production may be limited or where there are opportunities to increase production, potentially leading to more efficient and sustainable resource management (Scarlat et al., 2019).

The aims of this study are twofold. First, to provide a global, high spatial resolution (5×5 min of arc) dataset of CR production that can be used for biotechnology and organic resource assessments. Second, we use this CR dataset to estimate the potential for biochar production from CRs, and the associated carbon sequestration, at the same high spatial resolution and global extent. The spatially explicit CR datasets can be reused for assessing the potential of other bio-technologies and, ultimately, for comparative assessments that are useful for policy development. The work can also lead to more refined national or local assessments, with more detailed information on current CR uses, supporting investment decisions in pyrolysis plants, for example.

2 | MATERIALS AND METHODS

We first used gridded crop production data and well-acknowledged estimation approaches based on residue-to-product ratios (RPRs) to estimate CR production. Then we applied previously developed empirical models to estimate biochar yields, biochar carbon content, and permanence of biochar. The CDR potential was estimated using a two-factor model based on the pyrolysis temperature and local soil temperature. Both maximum technical and constrained potentials were calculated, taking into account the fraction of residues that can be sustainably harvested, or that would compete with use as livestock fodder, thereby potentially reducing food security.

2.1 | Crop production data and crop selection

One approach to assessing CR potential is through the use of the RPRs, which are dimensionless factors used to estimate the amount of CR relative to the harvested yield of a particular crop. For large-scale assessments of CR potentials, RPRs can be estimated by functions considering crop yield variations and accounting for them (Bentsen et al., 2014; Ronzon & Piotrowski, 2017; Scarlat et al., 2019). This is useful for scaling up CR potential assessments to regional, national, or global levels. Previous assessments of CR potentials at a larger scale have often relied on crop production statistics that are either downscaled to a spatial grid cell based on land cover data (Scarlat et al., 2019) or simply applied uniformly to regions from which the statistics are derived (Bentsen et al., 2014; Karan & Hamelin, 2021). However, these approaches limit the level and accuracy of spatial disaggregation, which is important for mapping and visualizing the spatial variation in CR potential. Visualizing and mapping the spatial variation of CR enables a more accurate and detailed understanding of the distribution of CR potential, which can be crucial for making informed decisions in various areas, such as siting of biochar production units, carbon sequestration estimation, land management strategies, resource allocation, and assessing the economic viability of bioenergy or biochar projects. Recent developments have greatly improved the spatial downscaling of crop production statistics to be directly associated with cropland (Lu et al., 2020; Yu et al., 2020) using a more comprehensive set of covariate predictors. This allows for more detailed assessments of CR potential, and the development of tools to identify areas where CR production is likely to be highest, and to inform management decisions related to the use of CRs for various purposes, such as biochar production.

Our spatially explicit CR potential was built upon the MapSPAM crop production dataset (SPAM 2010 v2.0 Global Data, Yu et al., 2020). This dataset contains production statistics for 42 different crops at a resolution of 5-arc min (approximately 10×10 km) ca 2010. SPAM 2010 v2.0 accounts for interannual variability by averaging over the period 2009–2011, with averages over the period 2005–2015 used for gap-filling where necessary. The MapSPAM dataset analyses various crop production parameters across four distinct production systems for each crop (Yu et al., 2020). For this study, we used the dataset that integrates all four production systems into one, thereby providing a comprehensive representation of the overall crop production. For each crop, two layers were used, namely the crop yield Y_i (in Mg ha^{-1} at harvest moisture content) and the harvested area (A) in hectares (ha). The crop yield data were converted to dry weight using the dry weight conversion factors from Yu et al. (2020; Table S1).

Of the 42 MapSPAM crops, the analysis was limited to 34 crops. Crops were excluded based on the non-existence of residues for these crops (e.g., flaxseed and hemp for which both the seed and the straw are used), aggregated crop categories with low potential for residue harvesting (vegetables and "other crops"), or their unsuitability for biochar production and other thermochemical treatments (see Table S2, presenting all crops and their residues). It is worth noting that some crops have multiple residue types and that residues can be generated in-field or during processing of the harvest (Table S2). For instance, coconut is associated with in-field frond, post-processing husk, and post-processing shell. Rice is associated with in-field straw and post-processing husk. Both primary (in-field) and secondary (processing) residues are included in this study.

2.2 | Crop residue production

For each residue type t and crop i, the annual CR production per pixel in Megagram (Mg) of dry weight $R_{t,i}$ was calculated using Equation (1).

$$R_{t,i} = \lambda_{t,i} Y_i A_i \tag{1}$$

where Y_i is the crop yield in Mg ha^{-1} (dry weight), $\lambda_{t,i}$ the residue-to-product ratio (RPR), and A_i the harvested area in ha, which accounts for multiple harvests of a crop within a year (and can be larger than the physical area of a pixel). Where energy content of these residues is reported, these were calculated on a lower heating value (LHV) basis (see Table S13a).

2.2.1 | Residue-to-product ratio

Lists of functional and constant RPRs for some major agricultural crops have been previously compiled (Karan & Hamelin, 2021; Ronzon & Piotrowski, 2017). In this study, we built upon these efforts by compiling an expanded list of published RPR models for the selected crops (Tables S3–S6). Where multiple RPR models were available for a specific crop, we compared those models according to several criteria (year of publication, number of observations, availability of uncertainty, R^2, and empirical yield range, see Section 4.1 and Table S7). This resulted in the selection of RPR models from the most recent publications, which usually correlated with larger datasets and higher R^2.

For the 14 crops with an exponential RPR function, the modeled residue yield increased with crop yield up to a certain point before asymptotically approaching zero (Figure S1), indicating that such models cannot be safely extrapolated outside their calibrated range. Bentsen et al. (2014) found a similar trend, and recommended using a piecewise continuous model to correct CR potentials for wheat, rice, maize, barley, and soybean. Following this recommendation, we applied the piecewise continuous model correction shown in Equation (2) for the nine other crop classes with an exponential RPR function. These included other cereal straw, sorghum, potato, bean, sunflower, rapeseed, other oil crops, sugarbeet, and cotton.

$$\lambda_{t,i} = \begin{cases} a_{t,i} e^{b_{t,i} Y_i}, & \text{if } Y_i \leq \dfrac{-1}{b_{t,i}} \\ \dfrac{-a}{b_{t,i} e} \dfrac{1}{Y_i}, & \text{otherwise} \end{cases} \tag{2}$$

where, a and b are the crop- and residue-specific functional parameters compiled by Bentsen et al. (2014) and Ronzon and Piotrowski (2017) and shown in Table S6.

The maximum yields for many of the selected crops in the MapSPAM database were observed to be unrealistically high in a small proportion of map pixels. For example, 32 Mg ha^{-1} (28 Mg ha^{-1} dry mass) for wheat and 76 Mg ha^{-1} (68 Mg ha^{-1} dry mass) for rice (see Table S8). In contrast, the highest reported crop yield for wheat of which we are aware is 17.4 Mg ha^{-1}. To correct for this, we constrained yield for all crops to be no greater than the 99.95th percentile. None of the factorial combinations of (1) truncating the yield distribution to the 99.95th percentile, (2) excluding pixels with yields greater than the 99.95th percentile, or (3) applying the piecewise model correction according to Ronzon and Piotrowski (2017) altered the total global residue production by more than 0.1%. On this basis, we included both the RPR model correction and crop yield threshold for the calculation of residue production to ensure that realistic CR values are obtained for all map pixels—even those in the highest percentiles for crop yields (see Section 5, Table S9 and Figure S2).

Mass of dry biomass predicted by the above RPR functions was converted to a mass of carbon using the carbon contents from Table S1.

2.3 | Crop residue availability

The CR production from the RPR model above provides a theoretical technical potential scenario for the maximum quantity of biomass that could be provided if all residues were utilized (i.e., it is equivalent to the full amount of above-ground residues that are grown, without any accommodation for losses in harvesting, fire, decomposition, or competing uses). However, there are environmental, social, and economic constraints on the fraction of this biomass that could realistically be available for any specific application such as biochar production. Although 100% utilization of residues is unfeasible, we provide results for the full technical potential both to provide the upper bound on what is achievable, and to allow other researchers and stakeholders to apply their own scalar multipliers to the technical potential estimates to reflect utilization constraints.

Here, we developed a constrained potential scenario that recognizes two of the most important constraints on

CR utilization: the fraction of residues that can be harvested without increasing soil degradation, and the fraction of residues that are already used in food production as livestock fodder and bedding. Reliance on CRs in livestock production is particularly prevalent in South Asia and Sub-Saharan Africa, where many subsistence farmers are dependent on this resource for food security. Crop-specific harvest factors for the fraction of residues that can be sustainably removed were derived from the literature (Herrero et al., 2013; Lal, 2005; Proville et al., 2020; Scarlat et al., 2010; Woolf et al., 2010; Table S10). Most secondary residues that are routinely removed at harvest, and tree prunings were assumed to have a maximum availability of 90% after losses, because their utilization would not adversely affect soil conservation. Exceptions to this rule were pineapple tops and fruit peels and pith, large fractions of which are discarded in household waste, with a maximum availability factor of 10% assumed for these. Regionally specific fractions of residues used in livestock production were from Herrero et al. (2013).

2.4 | Biochar yields and permanence

Biochar yield (Y_{ch}, defined as mass of dry ash-free biochar per unit mass of dry ash-free biomass feedstock) was calculated using Equation (3; Woolf et al., 2014).

$$Y_{ch} = 0.126 + 0.273L + 0.539e^{-0.004T}, \quad (3)$$

where L is the lignin fraction of the biomass on a dry ash-free basis (Table S1), and T the pyrolysis temperature in °C. The carbon fraction of the biochar (C_{ch}, defined as mass of carbon per unit mass of dry ash-free biochar) was calculated using Equation (4; Neves et al., 2011).

$$C_{ch} = 0.93 - 0.92e^{-0.0042T}, \quad (4)$$

with a medium pyrolysis temperature of 550°C (Woolf et al., 2021) assumed for both these calculation steps.

The yield (Y_{c_ch}) of biochar carbon (i.e., the mass of biochar C per unit dry mass of biomass feedstock) is then calculated according to Equation (5).

$$Y_{c\_ch} = Y_{ch} \times C_{ch} / C_{bm}, \quad (5)$$

where C_{bm} is the carbon fraction of biomass on a dry ash-free basis (Table S1).

In addition to reporting the quantity of biochar that may be produced from the CR resource, we also calculated the amount of this biochar carbon that would remain sequestered after 100 years of decomposition. This "permanence" fraction (F_{perm}) was calculated according to Woolf et al. (2021), based on medium pyrolysis temperatures and adjusted for soil temperature. Soil temperatures were from Lembrechts et al. (2022), with the assumption that biochar would be returned to soils at or near to the location the residues were generated.

3 | RESULTS

3.1 | Crop residue production

Globally, 2.4 Pg C (8.8 Pg CO_2) is generated in CRs each year. This is approximately one quarter of the total global C emissions from fossil fuels and cement production for 2021 (Friedlingstein et al., 2022). The top five residue-producing countries are China (0.41 Pg C), the United States (0.33 Pg C), India (0.30 Pg C), Brazil (0.17 Pg C), and Argentina (0.08 Pg C). The combined potential of CR production for EU 27 is estimated at 0.18 Pg C, equivalent to 16% of EU 27's fossil C emissions for the year 2021 (Table S11, and Eurostat, 2022). Figure 1 shows the spatial distribution of CR production in Mg C ha^{-1} year^{-1}.

Residues (both primary and secondary) from cereal crops had the highest share of the overall potential at 1.62 Pg C year^{-1} (67.4% of the total), followed by oil/pulse crops (both field and tree), and fruits/nuts at 0.45 Pg C year^{-1}, 18.7% (Figure 2). Among cereals, maize (straw and cobs) had the highest share of CR potential at 0.58 Pg C year^{-1}, followed by rice (straw and husks) at 0.49 Pg C year^{-1} (Table S12).

3.2 | Biochar carbon sequestration potential

The technical potential (i.e., with 100% utilization of CRs) for biochar production from residues is 1.0 Pg C year^{-1}. The fraction of biochar, F_{perm}, that would remain unmineralized one century after addition to soils varies globally from 60% in hot climates to close to 100% in cryosols (Figure 3). Within cropland locations with residue production, F_{perm} ranges from 0.62 to 0.92 (95% CI). Accounting for this decomposition, 0.72 Pg C year^{-1} of the technical potential would remain sequestered after 100 years. This is equivalent to 45% of the global GHG emissions from the agricultural sector in 2019 (Ritchie et al., 2020). The top 10 countries account for approximately 65% of this total global potential (Figure S3, and Table S14). China has the largest biochar carbon sequestration potential at 128 Tg C year^{-1} followed by the United States (104 Tg C year^{-1}), India (82 Tg C year^{-1}), and Brazil (47 Tg C year^{-1}).

Once we consider limits on the fraction of residues that can be sustainably harvested and the fraction of residues

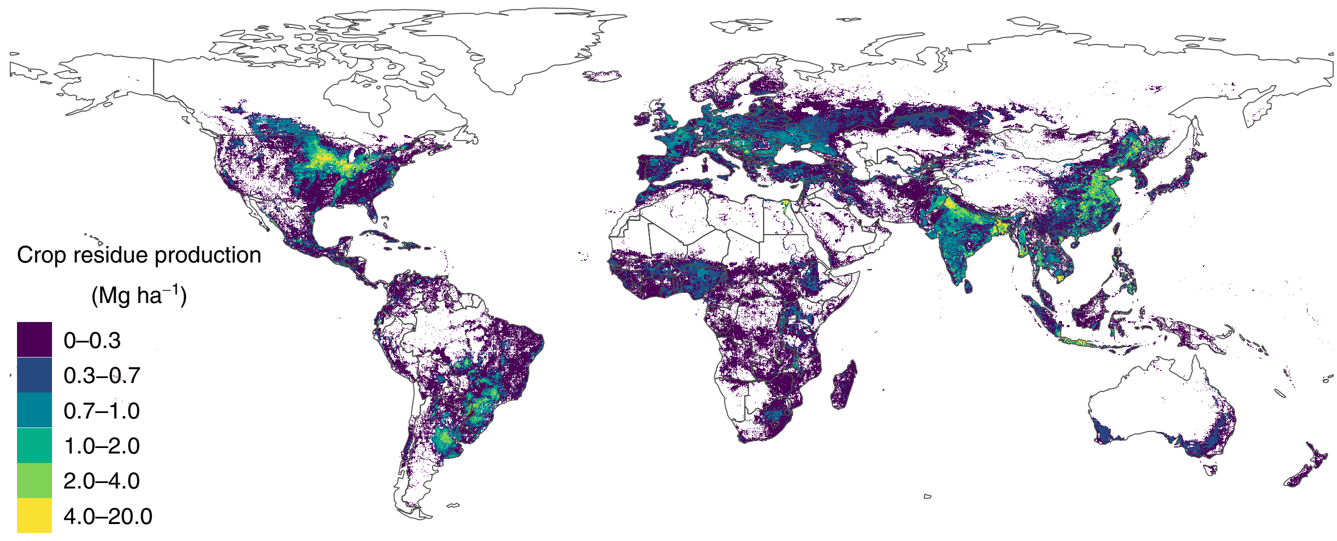
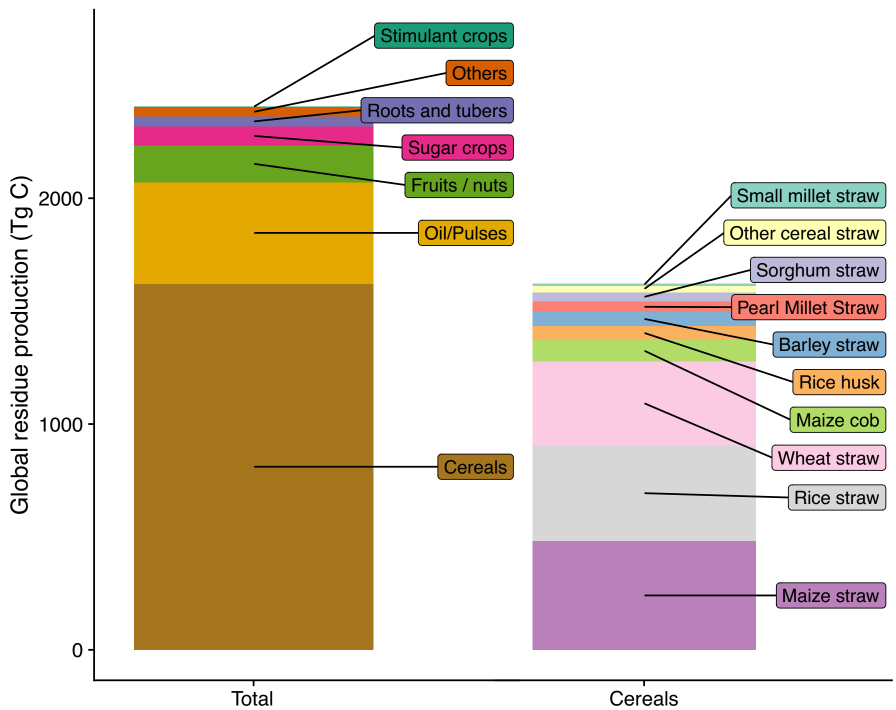


FIGURE 1 Spatial distribution of annual crop residue production per unit area of total land in a grid cell (Mg C ha^{-1}). Note that high-resolution (5×5 min of arc) spatial rasters of these data (both totals and also disaggregated by crop) are available for download (see Data Availability Statement).

FIGURE 2 Breakdown of global residue production by crop. The left hand bar shows the contribution of different classes of crop to the total. The individual crops that comprise these classes are shown in Table S12. The right hand bar shows the contribution of various cereal crops to the overall residue potential.



that are used in livestock production, the global potential for biochar production falls to 510 Tg C year^{-1}, of which 360 Tg C year^{-1} would remain sequestered after 100 years (Figure 4).

Not surprisingly, the countries with the largest sequestration potential broadly correspond to the countries with the largest productive land areas. In terms of the potential importance of biochar to each country's own climate change mitigation targets, more meaningful metrics are the sequestration density (i.e., sequestered carbon per unit land area of the country), and sequestered capacity relative to a country's current emissions (Figure 5). The countries with the highest technical potential sequestration density are Bangladesh (79 Mg C km^{-2} year^{-1}), Hungary (34 Mg C km^{-2} year^{-1}), Taiwan (32 Mg C km^{-2} year^{-1}), Denmark (32 Mg C km^{-2} year^{-1}), Serbia (30 Mg C km^{-2} year^{-1}), Vietnam (28 Mg C km^{-2} year^{-1}), and India (27 Mg C km^{-2} year^{-1}). These high sequestration densities are due to a combination of high fractions of land area

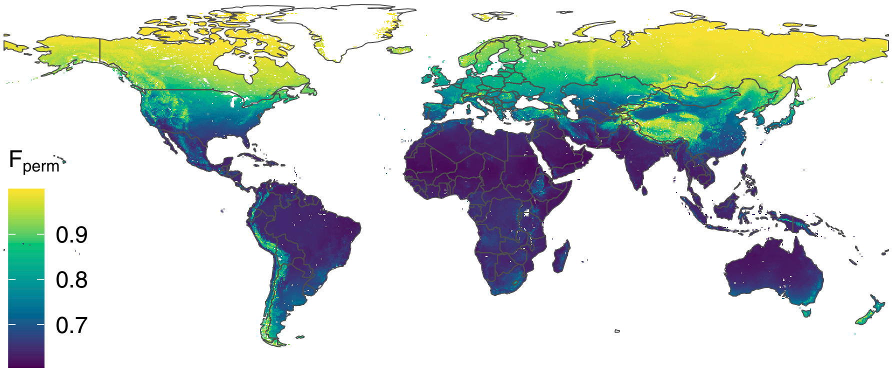


FIGURE 3 Fraction of biochar carbon (F_{perm}) remaining un-mineralized 100 years after addition to soil. F_{perm} is calculated as a function of pyrolysis conditions (assuming medium pyrolysis temperatures) and soil temperature, according to Woolf et al. (2021). Note that F_{perm} is not adjusted for soil moisture, therefore values are representative of agricultural lands that have moisture regulated by irrigation or drainage. Therefore, F_{perm} in unmanaged waterlogged or dryland soils may be higher than these values.

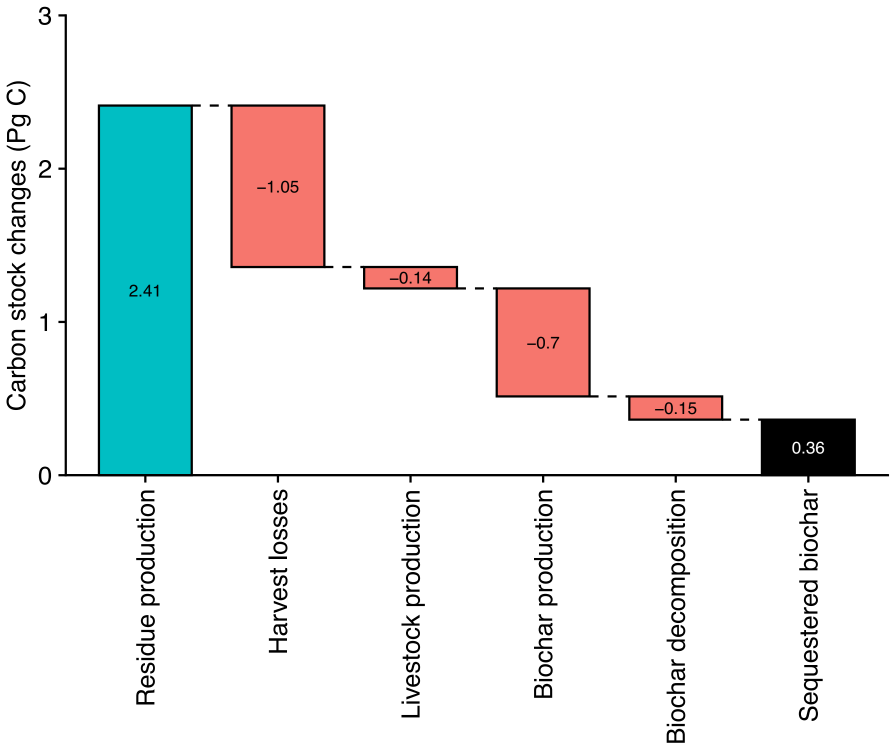


FIGURE 4 Waterfall plot showing how much of the initial global residue production (in Pg C year^{-1}) could be sequestered as biochar carbon, after accounting for constraints and losses. "Harvest losses" refer to the quantity of residues that would remain unharvested when accounting for maximum sustainable removal rates. "Livestock production" refers to residues that are currently used as fodder in livestock systems, and which could therefore not easily be diverted into biochar production without possible adverse consequences for food security. "Biochar production" refers to carbon that is lost as CO_2 during pyrolysis, assuming that organic volatiles are combusted for energy rather than also sequestered. Biochar decomposition refers to carbon losses due to mineralization of biochar during 100 years following its addition to soil.

under cropland (Bangladesh, Denmark, India, and Hungary are among the top 10 countries for cropland density); high residue crops dominating; and high intensity agriculture with a combination of high yields and (in the case of Taiwan and Vietnam) widespread multicropping. The countries with the highest technical potential sequestration as a proportion of current GHG emissions are Bhutan (68%), India (53%), Ghana (44%), Bulgaria (39%), Rwanda (35%), and Malawi (29%). In total, 12 countries have the technical potential to sequester over one fifth of their current emissions as biochar from CRs. The global average is a technical potential of 7%, and a constrained potential of 3% of current emissions.

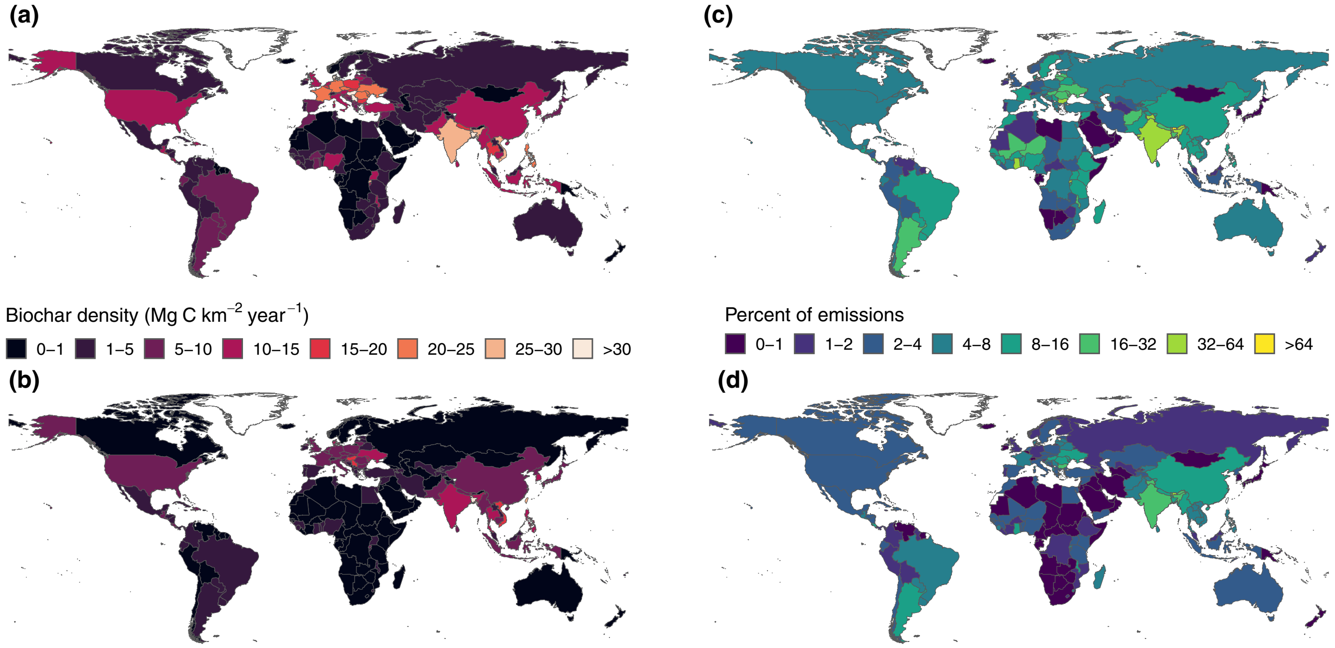


FIGURE 5 Carbon sequestered in biochar from crop residues, expressed as a fraction of country land area (a, b), and as a fraction of 2019 country-level GHG emissions (c, d). The top row (a, c) indicates the technical potential, utilizing all residues. The bottom row (b, d) indicates the constrained potential, accounting for the sustainably harvestable fraction of residues and residues used in livestock production.

4 | DISCUSSION

4.1 | Crop residue production

To contextualize these results, it is useful to compare our estimates of CR production to previous studies that use less granular data and smaller subsets of CR types. Overall, the energy content (LHV) from the CRs (straw from barley, maize, rice, soybean, sugarcane, and wheat) in this study is only 0.15% higher than previously reported by Bentsen et al. (2014; Table 1). However, large differences (up to 133%) are observed when comparing residues for specific crops (Table S13a–f). A similar trend (similar total estimates and larger differences between crops) is observed when we compare our residue production estimates with earlier estimates for other major agricultural regions of the world (Table 1). In particular, for India, our estimates are 2% higher than the values reported by Anand et al. (2022). For China, the difference is 3% when comparing the results of this study with the values reported by Fang et al. (2019). For EU27 + UK, we find the CR potential to be 20% lower than reported by García-Condado et al. (2019), and 10% higher than Scarlat et al. (2019). For the United States, our estimates are 17% higher than reported by Chatterjee (2013). However, it should be noted that the estimates from this study are not directly comparable to those in previous publications, due to differences in time scale.

4.2 | Biochar carbon sequestration potential

It is important to recognize that our estimates of biomass resource availability (and thus of constrained biochar potential) utilize a conservative estimate of the harvestable fraction, since this fraction is based on earlier studies that calculate how much residue must be retained to prevent soil degradation, but which do not account for the effects of returning biochar to the soil. It is expected that biochar addition to soils should allow for greater residue removal rates, while still maintaining healthy soil functions, for several reasons. First, biochar can substitute some of the functional attributes of non-pyrogenic SOC, such as cation exchange capacity (Domingues et al., 2020; Ghorbani et al., 2023) and water holding capacity (Omondi et al., 2016; Razzaghi et al., 2020). Second, negative priming by biochar can build stocks of non-pyrogenic SOC (Wang et al., 2016). Third, when biochar leads to increased crop growth, the amount of organic matter from residues and root biomass returned to soil can increase (Woolf et al., 2010). Further research will be required to determine how biochar affects the sustainable rate of residue removals.

The potential for biochar CDR estimated in this study falls within the range (0.3–1.3 Pg C year^{-1}) of previously published studies (Minx et al., 2018; Roe et al., 2021; Woolf et al., 2010). It should be noted that the overall climate change mitigation potential would also include

TABLE 1 Comparison of the estimated crop residue potential with previously published studies.

Reference	Crops	Coverage	Potential in our study	Potential estimated in the reference study
Bentsen et al. (2014)	Harvest residues: Barley, maize, rice, soybean, sugarcane, wheat	Global	65.99 EJ	65.89 EJ
Anand et al. (2022)	Harvest residues: Rice, wheat, sugarcane, sugarcane Process residues: Sugarcane bagasse	India	407.03 Mt	398.3 Mt
Fang et al. (2019)	Harvest residues: Rice, wheat, maize, cotton, peanut, sesame, sugarcane, sugarbeet, tobacco Process residues: Sugarcane bagasse, rice husk, peanut husk, corn cob	China	318 Mt C	308 Mt C
García-Condado et al. (2019)	Harvest residues: Cereals (wheat, rye, barley, oats, maize, triticale, sorghum, rice), oilseeds (rapeseed, sunflower, soybean), and sugar and starch crops (sugarbeet, potato)	EU27 + UK	348 Mt dry	418 Mt dry
Scarlat et al. (2019)	Harvest residues: Wheat, barley, rye, oat, maize, rice, rapeseed, sunflower	EU27 + UK	322 Mt dry	291 Mt dry
Chatterjee (2013)	Harvest residues: Corn, sorghum, barley, wheat, rice, sunflower, peanut, soybean, cotton, sugarbeet, sugarcane, potato, bean	USA	620 Tg	514 Tg

the emissions and avoided emissions in the full life cycle of the biochar, including the biomass supply chain (primarily harvesting and, transport, since we only include existing residues), conversion to biochar, emissions or emission reductions from use of biochar, and any avoided emissions from the decomposition of untreated biomass (e.g., methane emissions from rice residues). It would also need to consider the potential substitution of energy with pyrolysis energy and materials replaced by biochar.

4.3 | Sources of modeling uncertainty

One important source of uncertainty is the durability or permanence of biochar carbon sequestration. Multiple strands of evidence from laboratory incubations, field experiments, chronosequences, assessment of aged biochars, and global or regional budgets (Lehmann et al., 2015) combine to indicate that biochar decomposes at least one to two orders of magnitude more slowly in soil than the biomass from which it was made (Wang et al., 2016; Woolf et al., 2021). Nonetheless, accurately quantifying its decomposition rate and residence time, which vary with both biochar properties and environmental conditions, remains methodologically challenging. Uncertainty in the fraction of biochar expected to be mineralized over a specific time period grows larger the longer the time period. Over years to a few decades, mineralization is dominated by the more readily decomposed fraction of the material, which is easier to quantify in laboratory incubations. Longer term extrapolations using two- or three-pool exponential decay models derived from laboratory incubations conducted over a few years or less is inherently conservative, since decay rates are expected to fall over time as the most readily decomposed fractions are depleted (Lehmann et al., 2015). Woolf et al. (2021) estimated via bootstrapping that the 95% confidence interval on the mean for F_{perm} over 100 years is ± 0.08, for all biochars and at a soil temperature of 14.9°C. F_{perm} was weakly correlated with pyrolysis temperature ($R^2 = 0.13$) and more closely with the elemental hydrogen to organic carbon ratio ($R^2 = 0.33$). The F_{perm} values shown in Figure 3 and used in our calculations additionally include a correction factor for the soil temperature where the biochar is applied. This soil temperature correction was derived from the empirical relation between Q_{10} and soil temperature (Lehmann et al., 2015). This Q_{10} regression model was reported by Lehmann et al. (2015) to have a R^2 of 0.73, but since the RMSE was not provided it is not possible to convert this into a quantitative uncertainty on the F_{perm} values derived from it. Overall, temperature sensitivity of decomposition of biochar and organic matter alike is an area of active research (Davidson & Janssens, 2006; Elsgaard & Eriksen, 2023). For more detailed discussions of biochar permanence and its uncertainty see, for example, Lehmann et al. (2015), Wang et al. (2016), and Woolf et al. (2021).

Spatially explicit crop yields, which are also crucial in our model, lack a well-quantified assessment of uncertainty. Consequently, we are unable to provide an overall estimate of uncertainty. Our crop yield values are primarily derived from MapSpam data, which are largely based on FAOStat data (Yu et al., 2020). These data are subjected to spatial downscaling using a statistical model and spatial covariates. It is important to note that FAOStat acknowledges the challenge in assessing the dataset's overall accuracy due to its collection by member countries (FAO, 2022). While we cannot, therefore, offer a comprehensive estimate of uncertainty on the overall results, we have qualitatively described and discussed the sources of uncertainty (see section 6 and Table S15).

5 | CONCLUSIONS

CRs are an important and spatially heterogeneous resource that offer a promising resource for bio-technologies, natural resource management, developing a circular economy, and for climate change mitigation. The spatially explicit dataset of residue production generated in this study can be used for a wide range of organic resource assessments to guide planning and decision-making from global to regional and landscape scales.

Total global CR production was estimated to be 2.4 Pg C year^{-1}. The technical potential for biochar production if all these residues were utilized is estimated to be around 1 Pg C year^{-1} (3.7 Pg CO_2e year^{-1}), while the potential constrained by existing uses and harvest losses is 0.51 Pg C year^{-1} (1.8 Pg CO_2e year^{-1}). This leads to substantial 100-year biochar carbon storage in the range of 0.36–0.72 Pg C year^{-1} (1.25–2.64 Pg CO_2e year^{-1}), equivalent to between 3% and 7% of current annual global anthropogenic CO_2 emissions.

Detailed planning of actual biochar projects would also require a full life-cycle assessment, which is dependent on the precise details of the technology and system designs to be implemented. Nonetheless, given that previous life-cycle assessments of biochar from CRs indicate that the CDR impact of sequestered carbon is typically the largest contributor to the overall GHG impact (Lehmann et al., 2021), the CDR potential calculated here provides a robust indication that biochar from CRs has the technical potential to provide an important contribution to climate change mitigation.

Finally, we would like to emphasize the large spatial heterogeneity in this potential, leading to some countries (e.g., China, the United States, India, Brazil, and Argentina) having very large overall potentials, while other countries (e.g., Bhutan, India, Ghana, Bulgaria, Rwanda, and Malawi) could feasibly meet a large share of their climate change mitigation goals using biochar from CRs.

AUTHOR CONTRIBUTIONS

Dominic Woolf and Stephen A. Wood conceptualized the project. Shivesh Kishore Karan led the crop residue resource assessment. Dominic Woolf led the biochar production and carbon sequestration modeling. Shivesh Kishore Karan and Dominic Woolf wrote the manuscript, with the first draft by Shivesh Kishore Karan. Dominic Woolf produced the graphics. All authors contributed to method development, and to commenting on and revising the manuscript.

ACKNOWLEDGMENTS

We thank Chandrakant Singh for assistance with python code for spatial analysis.

CONFLICT OF INTEREST STATEMENT

All authors except Elias S. Azzi declare that there is no conflict of interest regarding the publication of this article. Elias S. Azzi reports a relationship with Puro.Earth Oy that includes consulting or advisory.

DATA AVAILABILITY STATEMENT

Complete spatial datasets showing global distribution of crop residue production, and both technical and constrained biochar potentials for each of the 42 crops in this study available for download. Data for crop residue production can be accessed at https://doi.org/10.7910/DVN/TSU0IE (Karan et al., 2023). Data on Biomass feedstock availability, biochar production, and biochar carbon sequestration can be accessed at https://doi.org/10.7910/DVN/Y6NGFM (Woolf et al., 2023). These data were derived using the following resources available in the public domain:

1. Harvard Dataverse: Global Spatially-Disaggregated Crop Production Statistics Data for 2010 Version 2.0 https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/PRFF8V.
2. geoBoundaries: A global database of political administrative boundaries. https://www.geoboundaries.org/downloadCGAZ.html.
3. Phyllis2: Database for the physico-chemical composition of (treated) lignocellulosic biomass, micro- and macroalgae, various feedstocks for biogas production and biochar. https://phyllis.nl/.

4. Global Soil Bioclimatic variables at 30 arc second resolution. (Lembrechts et al., 2022) https://zenodo.org/record/7134169.

ORCID

Shivesh Kishore Karan https://orcid.org/0000-0002-0037-6759
Dominic Woolf https://orcid.org/0000-0001-9344-9496
Elias Sebastian Azzi https://orcid.org/0000-0002-4865-3401
Cecilia Sundberg https://orcid.org/0000-0001-5979-9521
Stephen A. Wood https://orcid.org/0000-0002-9551-8165

REFERENCES

Anand, A., Pathak, S., Kumar, V., & Kaushal, P. (2022). Biochar production from crop residues, its characterization and utilization for electricity generation in India. *Journal of Cleaner Production*, *368*, 133074. https://doi.org/10.1016/j.jclepro.2022.133074

Baruch-Mordo, S., Kiesecker, J. M., Kennedy, C. M., Oakleaf, J. R., & Opperman, J. J. (2019). From Paris to practice: Sustainable implementation of renewable energy goals. *Environmental Research Letters*, *14*(2), 024013. https://doi.org/10.1088/1748-9326/aaf6e0

Bentsen, N. S., Felby, C., & Thorsen, B. J. (2014). Agricultural residue production and potentials for energy and materials services. *Progress in Energy and Combustion Science*, *40*, 59–73. https://doi.org/10.1016/j.pecs.2013.09.003

Borchard, N., Schirrmann, M., Cayuela, M. L., Kammann, C., Wrage-Mönnig, N., Estavillo, J. M., Fuertes-Mendizábal, T., Sigua, G., Spokas, K., Ippolito, J. A., & Novak, J. (2019). Biochar, soil and land-use interactions that reduce nitrate leaching and N_2O emissions: A meta-analysis. *Science of the Total Environment*, *651*, 2354–2364. https://doi.org/10.1016/j.scitotenv.2018.10.060

Chatterjee, A. (2013). Annual crop residue production and nutrient replacement costs for bioenergy feedstock production in United States. *Agronomy Journal*, *105*(3), 685–692. https://doi.org/10.2134/agronj2012.0350

Cornelissen, G., Pandit, N. R., Taylor, P., Pandit, B. H., Sparrevik, M., & Schmidt, H. P. (2016). Emissions and char quality of flame-curtain "Kon tiki" kilns for farmer-scale charcoal/biochar production. *PLoS One*, *11*(5), e0154617.

Davidson, E. A., & Janssens, I. A. (2006). Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. *Nature*, *440*(7081), 165–173. https://doi.org/10.1038/nature04514

Domingues, R. R., Sánchez-Monedero, M. A., Spokas, K. A., Melo, L. C., Trugilho, P. F., Valenciano, M. N., & Silva, C. A. (2020). Enhancing cation exchange capacity of weathered soils using biochar: Feedstock, pyrolysis conditions and addition rate. *Agronomy*, *10*(6), 824.

Elsgaard, L., & Eriksen, R. L. (2023). Temperature control on biochar decomposition in soil—Implications for long-term carbon sequestration. In EGU General Assembly 2023, Vienna, Austria, 24–28 April 2023, EGU 23-9326. https://doi.org/10.5194/egusphere-egu23-9326

Eurostat. (2022). Quarterly greenhouse gas emissions in the EU. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Quarterly_greenhouse_gas_emissions_in_the_EU

Fang, Y. R., Wu, Y., & Xie, G. H. (2019). Crop residue utilizations and potential for bioethanol production in China. *Renewable and Sustainable Energy Reviews*, *113*, 109288. https://doi.org/10.1016/j.rser.2019.109288

FAO. (2022). Faostat. Crops and livestock products: Metadata. https://www.fao.org/faostat/en/#data/QCL/metadata

Friedlingstein, P., O'Sullivan, M., Jones, M. W., Andrew, R. M., Gregor, L., Hauck, J., … Zheng, B. (2022, November 11). Global carbon budget 2022. *Earth System Science Data*, *14*(11), 4811–4900. https://doi.org/10.5194/essd-14-4811-2022

García-Condado, S., López-Lozano, R., Panarello, L., Cerrani, I., Nisini, L., Zucchini, A., Van der Velde, M., & Baruth, B. (2019). Assessing lignocellulosic biomass production from crop residues in the European union: Modelling, analysis of the current scenario and drivers of interannual variability. *GCB Bioenergy*, *11*(6), 809–831. https://doi.org/10.1111/gcbb.12604

Ghorbani, M., Konvalina, P., Kopeck, M., & Kolar, L. (2023). A meta-analysis on the impacts of different oxidation methods on the surface area properties of biochar. *Land Degradation & Development*, *34*(2), 299–312.

Griscom, B. W., Adams, J., Ellis, P. W., Houghton, R. A., Lomax, G., Miteva, D. A., Schlesinger, W. H., Shoch, D., Siikamäki, J. V., Smith, P., Woodbury, P., Zganjar, C., Blackman, A., Campari, J., Conant, R. T., Delgado, C., Elias, P., Gopalakrishna, T., Hamsik, M. R., … Fargione, J. (2017). Natural climate solutions. *Proceedings of the National Academy of Sciences of the United States of America*, *114*(44), 11645–11650. https://doi.org/10.1073/pnas.1710465114

Herrero, M., Havlik, P., Valin, H., Notenbaert, A., Rufino, M. C., Thornton, P. K., Blümmel, M., Weiss, F., Grace, D., & Obersteiner, M. (2013). Biomass use, production, feed efficiencies, and greenhouse gas emissions from global livestock systems. *Proceedings of the National Academy of Sciences of the United States of America*, *110*(52), 20888–20893.

IPCC. (2022). Summary for policymakers. In H.-O. Pörtner, D. C. Roberts, E. S. Poloczanska, K. Mintenbeck, M. Tignor, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, & A. Okem (Eds.), *Climate change 2022: Impacts, adaptation and vulnerability* (pp. 3–33). Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. https://doi.org/10.1017/9781009325844.001

Jeffery, S., Verheijen, F. G. A., Kammann, C., & Abalos, D. (2016). Biochar effects on methane emissions from soils: A meta-analysis. *Soil Biology and Biochemistry*, *101*, 251–258.

Joseph, S., Cowie, A. L., Van Zwieten, L., Bolan, N., Budai, A., Buss, W., Cayuela, M. L., Graber, E. R., Ippolito, J. A., Kuzyakov, Y., Luo, Y., Ok, Y. S., Palansooriya, K. N., Shepherd, J., Stephens, S., Weng, Z., & Lehmann, J. (2021). How biochar works, and when it doesn't: A review of mechanisms controlling soil and plant responses to biochar. *GCB Bioenergy*, *13*(11), 1731–1764. https://doi.org/10.1111/gcbb.12885

Karan, S. K., & Hamelin, L. (2021). Crop residues may be a key feedstock to bioeconomy but how reliable are current estimation methods? *Resources, Conservation and Recycling*, *164*, 105211. https://doi.org/10.1016/j.resconrec.2020.105211

Karan, S. K., Woolf, D., Azzi, E. S., Sundberg, C., & Wood, S. A. (2023). Global crop residue production circa 2010 (No. V1). Harvard Dataverse https://doi.org/10.7910/DVN/TSU0IE

Lal, R. (2005). World crop residues production and implications of its use as a biofuel. *Environment International*, *31*(4), 575–584.

Lehmann, J., Abiven, S., Kleber, M., Pan, G., Singh, B. P., Sohi, S. P., & Zimmerman, A. R. (2015). Persistence of biochar in soil. In J. Lehmann & S. Joseph (Eds.), *Biochar for environmental management: Science, technology and implementation* (Chapter 2, Vol. *2*, pp. 233–280). Earthscan.

Lehmann, J., Cowie, A., Masiello, C. A., Kammann, C., Woolf, D., Amonette, J. E., Cayuela, M. L., Camps-Arbestain, M., & Whitman, T. (2021). Biochar in climate change mitigation. *Nature Geoscience*, *14*(12), 883–892. https://doi.org/10.1038/s41561-021-00852-8

Lembrechts, J. J., van den Hoogen, J., Aalto, J., Ashcroft, M. B., de Frenne, P., Kemppinen, J., Kopecký, M., Luoto, M., Maclean, I. M. D., Crowther, T. W., Bailey, J. J., Haesen, S., Klinges, D. H., Niittynen, P., Scheffers, B. R., van Meerbeek, K., Aartsma, P., Abdalaze, O., Abedi, M., … Lenoir, J. (2022). Global maps of soil temperature. *Global Change Biology*, *28*(9), 3110–3144.

Liu, P. R., & Raftery, A. E. (2021). Country-based rate of emissions reductions should increase by 80% beyond nationally determined contributions to meet the 2 c target. *Communications Earth & Environment*, *2*(1), 1–10. https://doi.org/10.1038/s43247-021-00097-8

Lu, M., Wu, W., You, L., See, L., Fritz, S., Yu, Q., Wei, Y., Chen, D., Yang, P., & Xue, B. (2020). A cultivated planet in 2010—Part 1: The global synergy cropland map. *Earth System Science Data*, *12*(3), 1913–1928. https://doi.org/10.5194/essd-12-1913-2020

Maestrini, B., Nannipieri, P., & Abiven, S. (2015). A meta-analysis on pyrogenic organic matter induced priming effect. *GCB Bioenergy*, *7*(4), 577–590.

Matustik, J., Hnatkova, T., & Koci, V. (2020). Life cycle assessment of biochar-to-soil systems: A review. *Journal of Cleaner Production*, *259*, 120998.

Minx, J. C., Lamb, W. F., Callaghan, M. W., Fuss, S., Hilaire, J., Creutzig, F., Amann, T., Beringer, T., de Oliveira Garcia, W., Hartmann, J., Khanna, T., Lenzi, D., Luderer, G., Nemet, G. F., Rogelj, J., Smith, P., Vicente, J. L. V., Wilcox, J., & Dominguez, M. D. M. Z. (2018). Negative emissions—Part 1: Research landscape and synthesis. *Environmental Research Letters*, *13*(6), 063001. https://doi.org/10.1088/1748-9326/aabf9b

Monforti, F., Bódis, K., Scarlat, N., & Dallemand, J. F. (2013). The possible contribution of agricultural crop residues to renewable energy targets in Europe: A spatially explicit study. *Renewable and Sustainable Energy Reviews*, *19*, 666–677. https://doi.org/10.1016/j.rser.2012.11.060

Monforti, F., Lugato, E., Motola, V., Bodis, K., Scarlat, N., & Dallemand, J.-F. (2015). Optimal energy use of agricultural crop residues preserving soil organic carbon stocks in Europe. *Renewable and Sustainable Energy Reviews*, *44*, 519–529.

Neves, D., Thunman, H., Matos, A., Tarelho, L., & Gómez-Barea, A. (2011). Characterization and prediction of biomass pyrolysis products. *Progress in Energy and Combustion Science*, *37*(5), 611–630.

Omondi, M. O., Xia, X., Nahayo, A., Liu, X., Korai, P. K., & Pan, G. (2016). Quantification of biochar effects on soil hydrological properties using meta-analysis of literature data. *Geoderma*, *274*, 28–34.

Proville, J., Parkhurst, R., Koller, S., Kroopf, S., Baker, J., & Salas, W. (2020). Agricultural offset potential in the United States: Economic and geospatial insights. Environmental Defense Fund Economics Discussion Paper Series, EDF EDP, 20-01.

Razzaghi, F., Obour, P. B., & Arthur, E. (2020). Does biochar improve soil water retention? A systematic review and meta-analysis. *Geoderma*, *361*, 114055.

Ritchie, H., Roser, M., & Rosado, P. (2020). Our world in data. https://ourworldindata.org/co2-and-greenhouse-gas-emissions

Roe, S., Streck, C., Beach, R., Busch, J., Chapman, M., Daioglou, V., Deppermann, A., Doelman, J., Emmet-Booth, J., Engelmann, J., Fricko, O., Frischmann, C., Funk, J., Grassi, G., Griscom, B., Havlik, P., Hanssen, S., Humpenöder, F., Landholm, D., … Lawrence, D. (2021). Land-based measures to mitigate climate change: Potential and feasibility by country. *Global Change Biology*, *27*(23), 6025–6058. https://doi.org/10.1111/gcb.15873

Ronzon, T., & Piotrowski, S. (2017). Are primary agricultural residues promising feedstock for the European bioeconomy? *Industrial Biotechnology*, *13*(3), 113–127. https://doi.org/10.1089/ind.2017.29078.tro

Scarlat, N., Fahl, F., Lugato, E., Monforti-Ferrario, F., & Dallemand, J. F. (2019). Integrated and spatially explicit assessment of sustainable crop residues potential in Europe. *Biomass and Bioenergy*, *122*, 257–269. https://doi.org/10.1016/j.biombioe.2019.01.021

Scarlat, N., Martinov, M., & Dallemand, J.-F. (2010). Assessment of the availability of agricultural crop residues in the European union: Potential and limitations for bioenergy use. *Waste Management*, *30*(10), 1889–1897.

Schmidt, H.-P., Kammann, C., Hagemann, N., Leifeld, J., Bucheli, T. D., Sánchez Monedero, M. A., & Cayuela, M. L. (2021). Biochar in agriculture—A systematic review of 26 global meta-analyses. *GCB Bioenergy*, *13*(11), 1708–1730. https://doi.org/10.1111/gcbb.12889

Smith, P. (2018). Managing the global land resource. *Proceedings of the Royal Society B: Biological Sciences*, *285*(1874), 20172798.

Tisserant, A., & Cherubini, F. (2019). Potentials, limitations, co-benefits, and trade-offs of biochar applications to soils for climate change mitigation. *Land*, *8*(12), 179.

Wang, J., Xiong, Z., & Kuzyakov, Y. (2016). Biochar stability in soil: Meta-analysis of decomposition and priming effects. *GCB Bioenergy*, *8*(3), 512–523. https://doi.org/10.1111/gcbb.12266

Woolf, D., Amonette, J. E., Street-Perrott, F. A., Lehmann, J., & Joseph, S. (2010). Sustainable biochar to mitigate global climate change. *Nature Communications*, *1*, 56. https://doi.org/10.1038/ncomms1053

Woolf, D., Karan, S. K., Azzi, E. S., Sundberg, C., & Wood, S. A. (2023). Biochar from crop residues (no. V1). Harvard Dataverse https://doi.org/10.7910/DVN/Y6NGFM

Woolf, D., Lehmann, J., Fisher, E. M., & Angenent, L. T. (2014). Biofuels from pyrolysis in perspective: Trade-offs between energy yields and soil-carbon additions. *Environmental Science & Technology*, *48*(11), 6492–6499.

Woolf, D., Lehmann, J., & Lee, D. R. (2016). Optimal bioenergy power generation for climate change mitigation with or without carbon sequestration. *Nature Communications*, *7*(1), 13160.

Woolf, D., Lehmann, J., Ogle, S., Kishimoto-Mo, A. W., McConkey, B., & Baldock, J. (2021). Greenhouse gas inventory model for biochar additions to soil. *Environmental Science & Technology*, *55*(21), 14795–14805. https://doi.org/10.1021/acs.est.1c02425

Yu, Q., You, L., Wood-Sichra, U., Ru, Y., Joglekar, A. K. B., Fritz, S., Xiong, W., Lu, M., Wu, W., & Yang, P. (2020). A cultivated planet in 2010—Part 2: The global gridded agricultural-production maps. *Earth System Science Data*, *12*(4), 3545–3572. https://doi.org/10.5194/essd-12-3545-2020

SUPPORTING INFORMATION

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

How to cite this article: Karan, S. K., Woolf, D., Azzi, E. S., Sundberg, C., & Wood, S. A. (2023). Potential for biochar carbon sequestration from crop residues: A global spatially explicit assessment. *GCB Bioenergy*, *15*, 1424–1436. https://doi.org/10.1111/gcbb.13102