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Estimates vary but credible evidence points to gigaton-scale climate change mitigation potential of biochar

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Biochar is a carbon dioxide (CO_2) removal strategy that supports food security, sustainable land management and the circular economy. Nineteen published studies estimate global climate change mitigation potential of biochar at 0.03 to 11 Pg CO_2 equivalent yr^{-1}. Reconciling this range requires consideration of biochar science. Biochar systems durably sequester carbon, can reduce soil greenhouse gas (GHG) emissions, displace fossil fuel emissions through use of syngas, and avoid GHG emissions from residues. We reviewed the contributions to CO_2 removal and GHG emissions reduction. Divergence between studies arises from differences in scope, definition of potential, and assumptions about biomass availability, biochar technologies and reference systems. Seven of the 19 studies reviewed relied one original study. Recent independent assessments estimate sustainable mitigation potential of biochar systems at 2.6-10.3 Pg CO2 equivalent yr^{-1}. New assessments are needed, utilising integrated assessment models that incorporate latest understanding of biochar processes and feedstock availability.

Strategies to reduce greenhouse gas (GHG) emissions are critically important but will not be sufficient to achieve the temperature goal of the Paris Agreement. The IPCC[1,2] has shown that it will also be necessary to remove carbon dioxide (CO_2) from the atmosphere. Biochar is one of the few technologically mature strategies available to deliver CO_2 removal (CDR). Biochar systems, that involve production of biochar for use as a soil amendment, combine a biological removal process with a durable storage mechanism[3]. Biochar systems can provide benefits for climate change adaptation, land degradation management, food security[4] and human health (e.g. Mohammadi et al.[5]).

Biochars are charcoal-like heterogeneous porous materials produced by heating organic matter such as forestry residues or straw in an oxygen-limited environment, generally used as soil amendments[6]. Biochars vary widely in their properties, dependent on feedstock and production conditions. The production process is exothermic: a small amount of external heat is required to initiate pyrolysis, whereafter combustible gas is released, which is commonly used to fuel the process. Excess pyrolysis gas (also known as syngas) can be used as a renewable energy source for heat or electricity generation, replacing fossil fuels. Thus, renewable energy is a co-product of biochar production. Biochar production systems are sometimes also termed pyrogenic carbon capture and storage (PyCCS). In this review, biochar is assumed to be produced with other co-products of biomass pyrolysis, that is, bio-oil and syngas.

The primary contribution of biochar systems to climate change mitigation is CDR achieved through the persistence of biochar: biochar carbon persists in soil over centuries[7–9] which greatly delays the oxidation of biochar compared with its biomass feedstock. Biochar can contribute additionally to climate change mitigation by building soil C through reduced mineralisation of soil organic matter[10], reducing nitrous oxide (N_2O) and methane (CH_4) emissions from soil[11], and through fossil fuel displacement[12]. Besides mitigation contributions, biochar could play an integral role in system-level strategies for sustainable development and the circular bioeconomy[13–15].

While there has been intense activity to elucidate the mechanisms of biochar impacts on soil properties and plant response[16], there are relatively few studies on the climate change mitigation value of biochar systems. Life cycle assessments (LCA) of biochar systems show wide variation between feedstocks, pyrolysis conditions, and biochar applications, though most biochar systems show substantial net climate benefits. In their Special report on Climate Change and the Land[17], the IPCC reported mitigation potential for biochar in the range 0.4–1.2 t CO_2 equivalent t^{-1} dry feedstock.

There are few studies on global mitigation potential of biochar. One of the most comprehensive studies of biochar mitigation potential, by Woolf et al.[12], estimated global sustainable mitigation potential to be ~3.7–6.6 Pg CO_2 equivalent yr^{-1}. Synthesising available literature, the IPCC Sixth Assessment Report[18] estimated theoretical potential of 0.2–6.6 Pg CO_2

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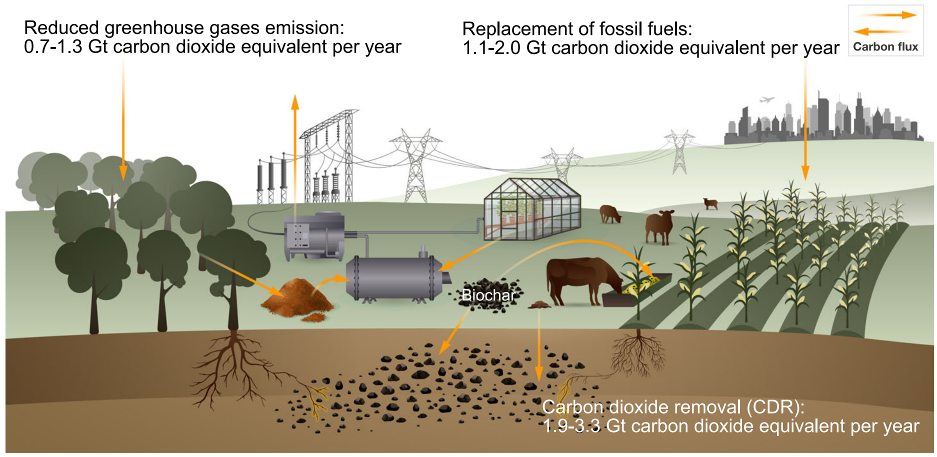
Fig. 1 | Schematic diagram of key factors that contribute to climate change mitigation in biochar systems. Numbers refer to mitigation potential fluxes derived from Woolf et al. [12] expressed in Gt CO_2 equivalent yr^{-1}. Adapted from Joseph et al. [16].



equivalent yr^{-1}. There have been no critical reviews focussed solely on mitigation potential of biochar systems.

This paper reviews the literature on potential mitigation through biochar, examining the scope and assumptions applied, to pinpoint the basis for the wide variation between studies. We start by reviewing the various processes that provide GHG mitigation in biochar systems. We distinguish the contributions of different GHG mitigation processes to the net mitigation potential, separating CDR and GHG emissions reductions (Fig. 1 and Supplementary Table 1). We examine the relationship between studies of mitigation potential and distinguish novel analyses from those based on earlier studies. Here we show that most studies since 2010 are not new analyses, but instead many are based on the study by Woolf et al.[12], sometimes misquoted or selectively extracted. Differences between studies sometimes arise from confusion between CO_2 vs. C due to the unusual choice of units in the study by Woolf et al.[12], but, more importantly, are largely due to differences in scope of the study (CDR and emissions reduction processes included) and assumed biomass availability.

Climate change mitigation contributions of biochar systems

Persistent biochar carbon

The conversion of biomass to biochar, via pyrolysis, greatly delays the oxidation of biomass. Biochar has a mean residence time (MRT) in soil of hundreds to thousands of years[9,19]. The key factors controlling the persistence of biochar-C are feedstock type, the highest pyrolysis temperature, and duration of pyrolysis, which determine the degree of aromatisation. Long-term persistence of biochar is predicted from multi-year incubation studies using isotopic difference to quantify loss of biochar carbon. Biochar carbon is commonly assumed to comprise two pools: (1) the labile pool, the small fraction of biochar C that is susceptible to rapid mineralisation, comprising aliphatic-C, phenolic-C, and carbohydrate C, and (2) the persistent pool, the aromatised C that mineralises very slowly[20,21]. Estimating MRT commonly involves applying a double first-order exponential decay model. Azzi et al. [19] demonstrated the sensitivity of BC100 (fraction of biochar carbon remaining after 100 years) to the curve-fitting approach. The H/C ratio is an effective predictor of biochar persistence[19]; for biochars with $H/C < 0.7$ (considered a threshold for classification as biochar) the BC100 is 60–90%. Sanei et al.[22] identified that biochars produced at temperatures > 550 °C are dominated by inertinite, with estimated half-life of 100 million years, and that random reflectance (Ro) is an effective method to characterise biochar carbon pools of differing stability. The CDR due to biomass conversion to biochar is determined by the biochar yield per unit of feedstock and the relative mineralisation rate of the biochar carbon in comparison with the unpyrolysed feedstock. Conversion rates from biomass-C to biochar-C are generally 20–50%, with lower recoveries, but greater persistence, at higher pyrolysis temperatures[23,24].

Impact on soil carbon dynamics

Biochar amendment can decrease mineralisation of native soil organic matter (SOM)[9] and newly added organic matter[10,25,26], increasing soil organic carbon (SOC) stocks. The capacity of biochar to increase total soil organic C beyond the addition of persistent biochar-C is both a function of the properties of the biochar and those of the soil.

Change in the mineralisation rate of SOM induced by organic amendments is known as priming[27]. Meta-analyses of biochar-induced priming based on incubation studies in the absence of plants indicate an initial phase of positive priming (20 days[28]; 2 years[29]) followed by negative priming, with an average decrease in the mineralisation rate of SOM of 3.8% (−8.1 to 0.8% for different soils and biochars) compared with the unamended control[9]. Studies of soil-plant-biochar interactions have similarly reported increased mineralisation of native SOM over 66 days[30] but reduction in mineralisation of 19–29% over longer periods[31,32]. A decadal study in an acidic Ferralsol showed that wood biochar can increase soil C through soil aggregation processes that slow the mineralisation of new C (e.g. root exudates, root detritus, microbial necromass) resulting in ongoing soil C accumulation over 10 years after one biochar application[10,26]. Long-term negative priming has also been recorded from wood biochar applied to a neutral pH Mollisol[33]. Essentially, application of biochar protects SOM from microbial breakdown. This phenomenon is likely applicable to soils with high clay content. However, in sandy soils, biochar is found to enhance priming, and aggregate formation is limited by absence of clays.

Besides its direct effect on SOC stocks, biochar-induced increase in SOM can enhance plant growth through its effect on soil water holding capacity and aggregation, and soil fertility and cycling of nutrients, further increasing SOC input to the soil.

Additional mitigation through enhanced plant growth

Biochar facilitates biotic and abiotic soil-plant-microbe reactions, particularly in the root zone, that can enhance nutrient and water supply to plants, thereby enhancing plant growth[16]. Meta-analyses have found that, on average, biochar increases crop yield by 10–42%[16]. The greatest responses are observed in acidic tropical soils and sandy soils in the drylands, while small or nil yield responses are often observed in temperate climates and high fertility soils[16,34,35]. Biochar-induced productivity enhancement stores additional C in vegetation, offering additional CDR, and extra biomass could be used to make more biochar.

Emissions reduction—non-CO_2 GHG from soil and composting

Meta-analyses have found that biochar application can effectively mitigate N_2O and CH_4 emissions from soil in the short to medium term, though the effects vary widely[36–43].

Meta-analyses of the impact of biochar on soil N_2O emissions showed an average reduction of 12% in the field compared with the unamended control[43] and reduction of 38% combining both field and laboratory conditions[36]. The interacting biotic and abiotic processes involved in decreasing N_2O emissions include direct sorption and reaction of greenhouse gases on biochar surfaces, and changes in soil properties such as porosity, pH, availability of substrates, and microbial community composition and activity[11,16]. Separate meta-analyses of C sequestration[44] and N_2O emissions[36,42] suggest a strong synergy between CDR and emissions reduction in biochar systems, in contrast with alternative organic amendments that tend to increase soil N_2O emissions[45]. With respect to CH_4, application of biochar can reduce emissions from waterlogged soils (especially acid soils), but biochar commonly decreases the CH_4 sink of upland soils[40,46].

Studies of soil emissions typically do not compare emissions after addition of biochar with the emissions that would arise from application of the equivalent amount of unpyrolysed biomass (commonly about three times more material). This comparison, which is applicable when considering alternative uses of a finite biomass source, would likely reveal a greater mitigation impact of biochar systems on soil emissions in many circumstances.

Recent syntheses have improved understanding of processes underlying biochar-induced decrease in GHG emissions from soil, and enhanced the capability to predict the potential impact based on biochar properties, soil types and environmental factors[11,16]. However, there are still uncertainties regarding the longevity of influence on soil emissions and indirect effects through impacts on leaching and volatilisation of nitrogen (N)[47].

Addition of biochar to composting organic matter can reduce the emissions of N_2O and CH_4[48,49], through sorption of N on biochar surfaces, increasing N retention, and oxidation of CH_4 by methanotrophs. Biochar can also indirectly lower N_2O emissions through lower N leaching and volatilisation.

Emissions avoided

Avoided emissions are emissions that occur outside the biochar supply chain, that are indirectly reduced or prevented through the adoption of biochar systems, including through the use of pyrolysis gases as renewable energy, modified management of organic residues and wastes, and reduced fertiliser manufacture.

Pyrolysis gases released during the production of biochar are combusted to produce heat to drive the pyrolytic process, and excess gas can be used as a renewable energy source to displace fossil fuels used for electricity and/or heat. The amount of excess syngas produced is greater for feedstock materials with lower moisture content, which therefore require less energy to reach pyrolysis temperatures, and greater at higher pyrolysis temperatures, which produce a higher yield of gas relative to biochar. In a life cycle assessment of climate change mitigation potential of biochar production in China, the fossil fuel displacement through bio-electricity production was calculated at 0.2–6.7 t CO_2-equivalent t^{-1} biochar applied for biochar produced from crop residues, 0.2–8.2 t CO_2 equivalent t^{-1} for forest residues, 0.3–2.1 t CO_2-equivalent t^{-1} for livestock manure, 0.1–1.7 t CO_2 equivalent t^{-1} for sewage sludge, and 0.4–2.8 t CO_2 equivalent t^{-1} for food waste[50], where the lower and higher values relate to pyrolysis temperatures of <300 °C and >500 °C, respectively. Although additional fuel is required for biomass transportation, feedstock processing, and biochar production, the associated GHG emissions (0.1–1.5 t CO_2 equivalent t^{-1}) are small compared with the fossil fuel displacement[50]. The mitigation value of bioenergy co-produced with biochar depends on the GHG intensity of displaced energy products, and the efficiency of gas capture and electricity generation[51]. Greatest mitigation is achieved where syngas is used for heat rather than electricity, and where GHG-intensive electricity sources such as brown coal are displaced. While it is acknowledged that economic cost from pyrolysis energy is higher than some other renewable energy sources such as solar, pyrolysis energy could play an important role as a dispatchable energy source, firming the grid as intermittent energy sources expand.

Pyrolysing organic wastes such as poultry litter avoids N_2O and CH_4 emissions that arise during handling, storage and land application of the unpyrolysed waste[11]. Biochar is an effective and efficient way to recycle nutrients in biosolids and other organic residues that are otherwise lost and cause pollution if landfilled, combusted or discharged to waterways. Biochar and biochar-fertilizer combinations can reduce leaching and volatilisation losses of soil N, thus increasing N use efficiency[52,53], reducing the amount of chemical fertiliser required, and therefore avoiding the manufacturing emissions of GHG-intensive N fertilisers.

Key Factors that affect estimates of mitigation potential

Definition of mitigation potential

Estimates of mitigation potential of a strategy can be categorised into four types: (1) technical potential, (2) economic potential, (3) sustainable potential, and (4) feasible potential[54]. *Technical potential* is the theoretical maximum mitigation that a strategy could deliver, determined by biogeophysical limits, with known technology. *Economic potential* is the technical potential that can be realised economically under assumed costs, benefits, and costs of alternative options. *Sustainable potential* is the portion of the technical potential that allows for other societal objectives such as biodiversity conservation, maintenance of the natural resource base, and food security. *Feasible potential* considers geophysical, ecological, technological, economic, social and institutional barriers to adoption, to determine the likely rate of implementation at a specified time. The magnitude of estimates of potential generally decreases, while uncertainty and subjectivity increase, moving from technical through economic and sustainable to feasible potential. Most assessments of mitigation potential of biochar have focussed on technical or sustainable potential, and several consider economic potential.

Scope of analysis regarding GHG fluxes

As discussed in 'Climate change mitigation contributions of biochar systems', factors that contribute to mitigation through biochar systems are: CDR, reduced non-CO_2 GHG emissions, and avoided emissions, particularly from fossil fuel displacement. CDR includes the carbon stabilised through pyrolysis, often expressed as carbon remaining after 100 years (BC100) (see 'Persistent biochar carbon') and can also include negative priming (see 'Impact on soil carbon dynamics') and enhanced plant growth (see 'Additional mitigation through enhanced plant growth'). All studies include carbon sequestered in biochar, but the latter two sources of CDR are omitted in most assessments of mitigation potential.

Adoption of biochar systems can reduce N_2O and CH_4 emitted from soil (see 'Emissions reduction—non-CO_2 GHG from soil and composting'), and avoid GHG emissions from feedstock handling (collection, transport and storage), landfill, and production of electricity and heat (see 'Emissions avoided'). Some studies of global mitigation potential include many of these components (e.g. Woolf et al.[12]), though none that we reviewed contains all. Other mitigation components that could be considered include reduced manufacturing emissions from fertiliser production due to lower fertiliser requirements, and reduced fuel use in cultivation (due to reduced soil strength) or irrigation pumping (due to enhanced water holding capacity). However, while these are included in some LCA studies of specific biochar systems, we are not aware of any global studies of mitigation potential that include them.

Assumptions for key variables

Assumptions for several key variables influence the potential derived in each assessment: (1) available biomass (2) products of pyrolysis; and (3) persistence of biochar carbon.

Availability of biomass. To estimate the global mitigation potential of biochar systems, one must quantify the available biomass. Biomass residues and wastes that are already aggregated at processing facilities e.g. poultry litter, feedlot manure, urban greenwaste, nut shells, cotton gin trash, sawmill and paper mill residues are desirable biochar feedstocks. The current fate of the residues must be considered, to determine the amount available for biochar, and the net effect on GHG emissions. Food residues, urban greenwaste and biosolids are often landfilled or incinerated, so diversion for biochar has no risk of 'leakage', that is, inducing increased emissions elsewhere as a result of adopting biochar systems. Conversely, although crop residues make highly-effective biochar[16], they are commonly retained on site to preserve soil moisture, control weeds and reduce erosion risk, and sometimes used for fuel, animal bedding or animal feed, so diversion for biochar could lead to leakage, through provision of alternative sources for these functions. Nevertheless, in high-yielding crops (e.g. irrigated cereals, sugarcane) residues are often burned to facilitate crop establishment or manage disease and pests. Pyrolysing these residues in place of in-field burning also offers benefits for the environment by avoiding GHG emissions especially CH_4[55], and for human health by avoiding particulate emissions[5]. Manure is often spread in fields as organic fertiliser, so diverting for biochar could increase demand for synthetic fertiliser, however, it would reduce emissions of N_2O from manure handling, and provide environmental and health benefits through reduced eutrophication and risk of transfer of pathogens.

Studies of technical potential consider the total quantities of biomass theoretically available for biochar production, while studies of economic or sustainable potential consider constraints such as competition from alternative uses, sustainability and food security implications and costs. Studies commonly use bottom-up assessments of feedstock available, for example, based on statistics for crop yields or area harvested, to estimate available crop and forest residues (e.g. Woolf et al.[12]; Roe et al.[56]). However, it should be noted that a number of uncertainties are associated with such global assessments, arising from the choice of crops, definitions of crop residues, assumptions for ratios of residues to crop yields (harvest index), consideration of technical, environmental and economic limitations, and annual variability in yields[57,58]. In a review of published global estimates for residue availability for bioenergy use, Hanssen et al.[59] found a range of 12–76 exajoule (EJ) yr^{-1} in 2050 for eight bottom-up studies and attributed this variation to different methodologies, definitions and criteria for assessing availability.

Besides biomass residues, another feedstock considered in many studies is purpose-grown biomass crops, so a key assumption is the quantity of land available for dedicated biomass production. Risks to biodiversity, food security and vulnerable communities need to be considered. The use of marginal land and abandoned land for purpose-grown biomass minimises these risks, and substantial potential has been identified (e.g. Field et al.[60]). Furthermore, production of biomass for biochar that is then applied to the same land could restore degraded land, enhancing productivity. However, the definition and extent of marginal land are debated, and depend on the intended land use[12,61], thus estimates of marginal land area are highly uncertain and purpose-specific[60,61]. Uncertainties regarding marginal land estimates arise from temporal and spatial variation in productivity and land use, related to seasonal conditions and transhumance patterns, for example. In a recent assessment of potential of land-based climate change mitigation strategies on abandoned cropland, Gvein et al.[62] estimated 67–115 Mha of abandoned cropland available for biomass crops, excluding priority biodiversity conservation areas, in 2050. The authors noted high uncertainty of projections with respect to location of abandoned cropland, associated with inter-model differences and different socio-economic pathways, but commented that results at global scale were largely consistent and insensitive to the individual scenario.

The biomass availability assumed by Woolf et al.[12] was based on the estimate derived by Field et al.[60] who combined remotely sensed land use change products to identify the abandoned crop and pasture land area, which they coupled with spatial estimates of net primary productivity (NPP) from Randerson et al.[63] From this, Woolf et al.[12] estimated that up to 1250 Mt dry matter of purpose-grown biomass could be produced sustainably by 2100, while safeguarding biodiversity and food security. Besides high uncertainty regarding the land area, using the potential NPP to estimate lignocellulosic energy crop productivity provides a crude approximation, as realised NPP is dependent on the plant species.

Smith[64] back-calculated from the CDR potential estimate of Woolf et al.[12], to estimate the land requirement for biomass crops of 40–260 Mha for 2050. In contrast, Werner et al.[65] used a process-based vegetation model to derive spatially explicit estimates of available biomass, and determined 'land- and calorie-neutral' production potential of purpose-grown biomass in 2100 for a scenario that constrained cropland to current area and maintained calorie production to ensure for food security through biochar-mediated yield increase. Assuming a yield increase of 15% from 2t biochar ha^{-1} biochar applied to tropical and subtropical croplands, they determined that 13.7 Mha of cropland was freed for biomass production.

Competition for biomass is likely to be a considerable constraint to biochar production. Competing uses of manures and food waste include compost, fertiliser and biogas, while bio-electricity, liquid biofuels and heat currently compete for crop and forestry residues and purpose-grown biomass. Competition for sustainable aviation fuel is likely to be strong in the future, as the growing airline industry has limited options to reduce emissions[66]. Several of the studies considered in this review explicitly addressed competition for residues by assuming that some fraction of the residues produced will continue to be used for feed, energy and/or soil protection (e.g. Woolf et al.[12]; Powell and Lenton[67]; Griscom et al.[68]). Integrated assessment models (IAMs) often assume that most available biomass is used for bioenergy: IAMs suggest strong demand for biomass for heat, bio-electricity and liquid biofuels for transport, and also for biochemicals, with proportions of each varying between socio-economic pathways, and large allocation to electricity with CCS under ambitious mitigation targets[69]. If the biomass assumed to be used for bioenergy in these models is instead used for biochar, energy will need to be produced from other sources, which should be factored into calculations of the net climate impact of alternative uses of biomass.

Biochar yield and persistence of biochar carbon. As discussed in 'Persistent biochar carbon', the carbon contained in biochar is highly persistent in soil, and persistence varies with feedstock and pyrolysis conditions. Pyrolysis conditions also determine the biochar yield, with lower yield—but higher persistence—at higher temperatures. Biochars comprise a mixture of organic compounds with different durabilities. Biochar carbon persistence is usually characterised in terms of MRT for the recalcitrant fraction, or BC100, the fraction remaining after 100 years[19]. Most studies apply the same assumptions for persistence across all feedstocks and include only the carbon assumed to be retained beyond 100 years. For example, Roe et al.[56] assumed 50% conversion of biomass carbon to biochar; 97% recalcitrant fraction with half-life of 556 years, with 80% retained beyond 100 years. Similarly, Werner et al.[70] assumed 55% conversion, and MRT of >750 years, with 90% of biochar carbon retained. In contrast, Woolf et al.[12] used a dynamic approach, modelling biochar carbon kinetics using a 2-stage exponential decay function assuming a half-life for the recalcitrant fraction of 300 years, and demonstrated the strong sensitivity to this assumption.

Overview of biochar mitigation potential studies, and relationships between studies

In this review, we considered 19 peer-reviewed articles on global biochar mitigation potential published between 2010 and 2022 (Supplementary Table 1). We illustrate the range of estimates for each of the major contributors to mitigation, i.e., CDR, emissions reduction, and emissions avoidance (Fig. 1). Some studies focus on a limited range of mitigation contributions, such as CDR only (e.g. Smith[64]). Some limit scope by focussing on one technology (e.g. Pratt and Moran[71]) or one feedstock (e.g. Roberts et al.[72]) or one farming system (e.g. Lenton[73]).

The highest estimate was 11 Pg CO_2 equivalent yr^{-1}, for technical potential including CDR, bioenergy and avoided N_2O[67], while the lowest estimate was 0.03 Pg CO_2 equivalent yr^{-1} for economic potential[74]. Estimates of biochar's global technical mitigation potential based only on CDR range from 0.3 Pg CO_2 equivalent yr^{-1} [68,75] to 4.9 Pg CO_2 equivalent

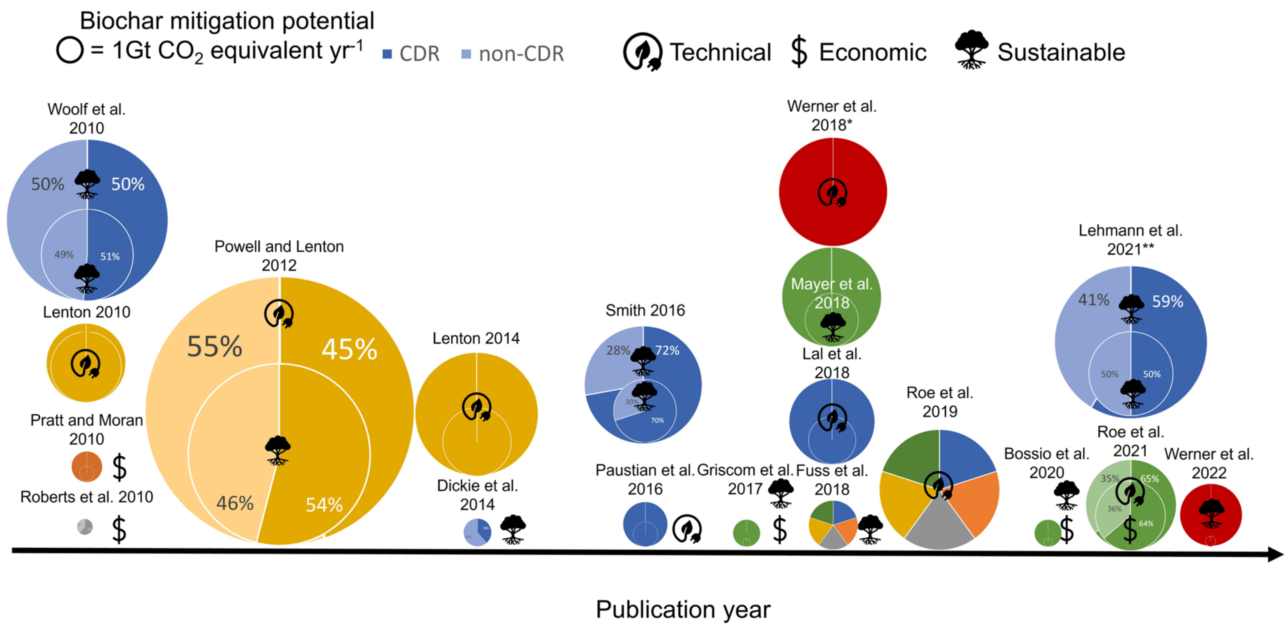


Fig. 2 | Magnitude of mitigation, and relationship between studies of biochar mitigation potential. Colour scheme indicates the relationships between studies: related studies share the same colour tone. The area of the circle shows the annual mitigation potential (see Key for interpretation) with the outer and inner circles showing maximum and minimum potentials, respectively. The proportions of carbon dioxide removal (CDR; darker shade) and non-CDR (lighter shade) are presented if quantified in the corresponding study. Symbols are used to show the type of assessment: technical, economic, or sustainable potential. *Shows the 'biochar basic' assessment, providing 100 Gt C removal over 2020–2100 (see Supplementary Table 1). ** Range for feedstock from organic residues, wastes, and biomass crops on abandoned cropland (see Supplementary Table 1).

yr^{-1} [67]. As shown in Fig. 2, 13 out of 15 papers published since 2011 are not new analyses and of these, seven papers are based on Woolf et al.[12] Since 2011, there are two essentially independent analyses of technical potential that have not relied on biomass data, biochar yields, or biochar persistence from Woolf et al.[68,70].

The most comprehensive and widely cited study of biochar mitigation potential was conducted by Woolf et al. [12], who estimated 'maximum sustainable technical potential' of biochar systems, allowing for competition for non-waste biomass and applying safeguards to protect biodiversity and ensure food security. According to the definition in 'Definition of mitigation potential', this aligns with sustainable potential (i.e., a sustainable subset of the technical maximum). Their estimate includes mitigation through carbon sequestered in biochar, avoided emissions of CH_4 and N_2O, and displaced fossil fuel emissions. Woolf et al.[12] estimated global mitigation potential at 3.7–6.6 Pg CO_2 equivalent yr^{-1} between 2010 and 2100, with peak rates reached after 60 to 100 years of adoption. Half of the mitigation is due to the carbon sequestered in biochar, 30 % to displacement of fossil-fuel energy and 20 % to avoided emissions of CH_4 and N_2O. Their higher estimate assumes biomass crops could be grown on 380 Mha of abandoned and degraded cropland and pasture that has not subsequently been converted to urban land or forest. The lower estimate includes biochar produced from available wastes and residues, together with 10% of the technical potential for agroforestry and 50% of the technical potential for biomass crops. Biochar-enhanced productivity on cropland was estimated to contribute 33–59 Pg CO_2 equivalent to the cumulative avoided emissions over 100 years, assuming these additional crop residues were converted to biochar. The findings of Woolf et al.[12] have been misquoted due to the confusing units used, *viz.* 'Pg CO_2 −C equivalent', which has been misinterpreted as Pg CO_2 equivalent, leading some papers to report Woolf's estimate of maximum mitigation potential as 1.8 Pg CO_2 equivalent (e.g., Paustian et al.[76]; Werner et al.[70]; Dumortier et al.[77]).

The study by Woolf et al.[12] has been widely recognised and utilised in subsequent studies. Reflecting its impact, seven of the 19 global studies we reviewed derived their estimates from Woolf et al.[12] Smith[64] selected components of the mitigation assessed by Woolf et al.[12]., excluding displaced fossil fuel emissions. The mitigation potentials estimated by Dickie et al.[78], through biochar application to croplands were based on assumptions and methods of Woolf et al.[12], but restricted feedstocks to residues only for 2030. Lehmann et al.[79] revised the estimate of Woolf et al.[12], using the same model over a timeframe of 100 years but with updated equations for biochar persistence, emissions reduction and negative priming. Other studies have modified the values of Woolf et al.[12] For instance, Lal et al.[80] stated that their estimate is based on the gross rate of C sequestration of 1.28 Pg C y^{-1} from Woolf et al.[12] with 'corrections for the energy used in pyrolysis … and in restoration of degraded lands', but the justification and derivation of these adjustments was not provided.

Other studies provide estimates of biochar mitigation potential derived from a synthesis of studies that include Woolf et al.[12] and its derivates. For instance, Fuss et al.[75] based their estimate on Woolf et al.[12], Paustian et al.[76], Lee and Day[81], Roberts et al.[72], Lomax et al.[82], Pratt and Moran[71], Griscom et al.[68], Powell and Lenton[67], and Smith[64], deriving an 'authors' assessment' of sustainable potential. Roe et al.[74] reviewed largely the same range of studies, adding Fuss et al.[75], and classified them as technical, sustainable or economic potentials (Fig. 2).

Besides Woolf et al.[12], we have identified five independent groups of analyses to date. Three were published in 2010 and reported economic potential[71,72] or technical potential[73]. The economic potential was derived either from bottom-up analysis of the costs and abatement potentials from large-scale and stove/kiln scale biochar projects for 2030 in developed and developing regions, respectively[71], or LCA of a biochar system using only corn stover as feedstock[72], producing estimates of 0.65 Pg CO_2 equivalent yr^{-1} [72] to 1.24 Pg CO_2 equivalent yr^{-1} [71]. For the technical potential, Lenton[73] estimated global CDR potential for 2050 through biochar produced from shifting cultivation biomass to be 0.9–1.3 Pg CO_2 equivalent yr^{-1}, based on shifting cultivation fires in 2010, that is, a narrow choice of feedstock and land use system. Lenton subsequently investigated the mitigation potential of biochar from biomass residues and included avoided N_2O emissions from soil and bioenergy alongside CDR[67], then collated values from several studies to estimate CDR through biochar systems at 2.75-4.95 Pg CO_2 equivalent yr^{-1} [83].

The fourth independent group is based on Griscom et al.[68] who included biochar in their seminal review of 'natural climate solutions'. They estimated the cost-effective (marginal abatement cost <100 USD tCO_2 equivalent) CDR potential of biochar systems to be 0.3 Pg CO_2 equivalent yr^{-1} and a 'maximum potential with [environmental and social] safeguards' (equivalent to sustainable potential in this review) of 1.1 Pg CO_2 equivalent yr^{-1} in 2030. The potential is calculated based on unused crop residue only, from assessments of sustainable supply of biomass for bioenergy in 2030, biochar C persisting in soil for >100 years and excluding reduced or avoided emissions. Subsequently, Bossio et al.[13] presented the estimate from Griscom et al.[68], unchanged, in their review of soil-based natural climate solutions, while Mayer et al.[84] averaged the values from Griscom et al.[68] and Woolf et al.[12], for CDR only for 2100. Roe et al.[56] expanded the analysis from Griscom et al.[68] using bottom-up estimates of available crop residues, based on FAOSTAT data, and including avoided fossil fuel and soil N_2O and CH_4 emissions in their estimate of global mitigation potential.

The fifth independent group is based on Werner et al.[70] who considered the total demand for CDR until 2100 and assessed how this could be provided by biochar, utilising purpose-grown feedstocks (woody and grass crops), modelled using the process-based dynamic global vegetation model (LPJmL). This demand-driven approach differs from most biochar potential studies that applied a supply-driven approach based on feedstock availability. The authors assessed a 'basic biochar' scenario (technical potential of biochar CDR) at the lower end of the negative emission demand up to year 2100, of 100 Pg C, which will deliver annual CDR of 4.58 Pg CO_2 equivalent yr^{-1}. However, this scenario would require land comparable to the area used for wheat production. The same authors[65] then took a supply-driven approach to estimate sustainable CDR through biochar, again using LPJmL to model biomass production of purpose-grown crops in the tropics and subtropics, but constraining biomass crops such that no additional cropland was required and calorie production was maintained. They estimated sustainable CDR potential through biochar of 0.44 to 2.62 Pg CO_2 equivalent yr^{-1}, depending on the assumed yield response to biochar.

Recommendations

Our review reveals a wide range of estimates of biochar potential, from 0.03 to 11 Pg CO_2 equivalent yr^{-1}, with divergence largely due to differences in scope and assumed feedstock availability. Unsurprisingly, studies that limit feedstock to biomass residues and wastes, and consider CDR only, generally reach lower estimates than those that include purpose-grown biomass crops, and consider avoided or reduced GHG emissions in addition to CDR. Of the 19 studies reviewed, five are independent analyses, and while seven relied on the original study by Woolf et al.[12], sometimes misquoted, misinterpreted or selectively extracted. The three most recent independent assessments[56,65,79] estimate sustainable CDR potential at around 2.7 Pg CO_2 equivalent yr^{-1} and total mitigation, including reduced and avoided emissions of up to 10.3 Pg CO_2 equivalent yr^{-1}. Thus, it is clear that biochar systems have substantial potential to contribute to climate change mitigation, including the vital challenge of CDR. Policy-makers should assess the barriers to adoption and upscaling of biochar in their jurisdictions, and introduce measures to facilitate biochar expansion, as part of their portfolio of mitigation strategies.

Most assessments reviewed have included only a subset of the mitigation contributions that can be delivered through biochar systems, with major emphasis on CDR. There is a clear need for new comprehensive assessments of global mitigation potential of biochar systems, that quantify reduced and avoided emissions as well as the CDR contribution to mitigation, incorporating the latest understanding of biochar persistence and impacts on GHG fluxes.

The potential for synergies rather than trade-offs between C sequestration and mitigation of non-CO_2 GHG emissions make biochar preferable to other soil amendments and soil C sequestration as a climate change mitigation strategy[45]. Future studies should simultaneously quantify the soil CH_4 and N_2O emissions and changes in soil organic C stocks due to priming, to represent the full impact of biochar systems on net GHG balance, and compare biochar with alternative organic amendments. However, there are challenges and obstacles for including these factors in global-scale assessments. As discussed in 'Emissions reduction—non-CO_2 GHG from soil and composting', soil GHG emissions and priming are strongly influenced by soil types and environmental parameters, that widely differ around the globe. The value of applying mean values from meta-analyses is questionable. A granular approach to estimation of soil GHG emissions would require data on soil types and environmental factors to be collected or simulated in a consistent way at a global scale. Furthermore, long-term studies that simultaneously monitor changes in soil organic C stocks and effects on N_2O emissions are needed, to inform estimates of mitigation potential.

To enable comprehensive holistic assessment, biochar should be included in the process-based IAMs[85] that are used in scenario analyses to investigate global mitigation pathways, to inform climate policy development. Most pathways that limit global warming to less than 2 °C include large areas of biomass crops for bioenergy, and bioenergy with carbon capture and storage (BECCS)[2], because most IAM studies currently rely on CDR through BECCS and afforestation/reforestation to meet temperature targets[86]. The land allocated to bioenergy crops could potentially be used instead to grow biomass for biochar. To date, very few IAM studies have included biochar, but one recent study using the Global Change Analysis Model (GCAM) found that global CO_2 removals from biochar reach 0.2–0.3 Pg CO_2 yr^{-1} in scenarios that limit warming to below 1.5 °C in 2100[87]. Inclusion of biochar in IAMs will enable estimates of global mitigation potential that take into consideration competing land uses, impacts on food production and energy systems from the production of biomass for pyrolysis and utilisation of biochar as a soil amendment, and influences of carbon markets. Inclusion in IAMs will also facilitate comparison between alternative mitigation strategies, particularly between the use of biomass for biochar and for bioenergy and BECCS, as demonstrated by Fuhrman et al.[87] The competition for biomass, land and financial resources between alternative mitigation strategies is likely to have a large impact on mitigation realised through biochar systems.

Data availability

No datasets were generated during the current study. Data analysed are provided in Supplementary Table 1 available in Figshare via University of Adelaide at https://figshare.com/s/e519743bcd405d0ab4ff?file=52983086.

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Author contributions
AC and HW conceived and planned the study. HW reviewed and assessed the literature with support of AC. HW and AC planned and drafted the manuscript. HW prepared the figure summarising results.

Competing interests
The authors declare no competing interests.

Additional information

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