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Biochar in climate change mitigation

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Climate change mitigation not only requires reductions of greenhouse gas emissions, but also withdrawal of carbon dioxide (CO_2) from the atmosphere. Here we review the relationship between emissions reductions and CO_2 removal by biochar systems, which are based on pyrolysing biomass to produce biochar, used for soil application, and renewable bioenergy. Half of the emission reductions and the majority of CO_2 removal result from the one to two orders of magnitude longer persistence of biochar than the biomass it is made from. Globally, biochar systems could deliver emission reductions of 3.4–6.3 $PgCO_2e$, half of which constitutes CO_2 removal. Relevant trade-offs exist between making and sequestering biochar in soil or producing more energy. Importantly, these trade-offs depend on what type of energy is replaced: relative to producing bioenergy, emissions of biochar systems increase by 3% when biochar replaces coal, whereas emissions decrease by 95% when biochar replaces renewable energy. The lack of a clear relationship between crop yield increases in response to fertilizer and to biochar additions suggests opportunities for biochar to increase crop yields where fertilizer alone is not effective, but also questions blanket recommendations based on known fertilizer responses. Locally specific decision support must recognize these relationships and trade-offs to establish carbon-trading mechanisms that facilitate a judicious implementation commensurate with climate change mitigation needs.

Effective climate change mitigation requires both reductions of greenhouse gas (GHG) emissions and withdrawal of atmospheric carbon dioxide (CO_2) to achieve the net zero emissions required to meet the Paris Agreement goal[1]. Use of biochar as a soil amendment to both reduce GHG emissions and deliver CO_2 removal (CDR) was first proposed as a global strategy for climate change mitigation only 15 years ago and has been intensively studied over the past decade[2]. Biochar is produced by the anoxic thermochemical conversion of biomass through pyrolysis processes that generate recoverable heat and fuels, such as gases and condensable volatiles, besides the solid biochar, an environmentally persistent material characterized by high carbon and low oxygen and hydrogen contents[3]. This Review provides an in-depth overview of the scientific progress in understanding the biogeochemical mechanisms of biochar persistence, its effects on CO_2, nitrous oxide (N_2O) and methane (CH_4) emissions from soil, and on plant growth and concomitant CO_2 uptake, and explores the trade-offs between energy generation and carbon sequestration. Of particular importance is the ensuing balance between GHG emission reductions and CDR, which mainly depends on prioritizing either energy generation to offset fossil fuel use or sequestering biochar, through choices of feedstock type and production conditions, which lead to different systems-level climate mitigation outcomes. Optimization of emissions reduction, CDR and non-climate effects, such as crop yield enhancement, is needed, for which we lay out research priorities and policy mechanisms.

Climate-relevant biochar effects

The climate change mitigation effects of biochar hinge not only on its material properties, but also on the effects of its production and deployment on GHG emissions across its entire life cycle. An important distinction exists between the reductions of CO_2, N_2O, CH_4 and soot emissions, and the withdrawal of CO_2 from the atmosphere (CDR) (Fig. 1). Biochar systems can affect both GHG emissions and CDR through: (1) reduced carbon mineralization and non-CO_2 emissions from biochar itself in comparison with those from unpyrolysed biomass; (2) emissions associated with the thermochemical conversion of biomass as well as avoided fossil fuel emissions if energy is produced (potentially with carbon capture and storage, CCS); and (3) changes in GHG emissions after the biochar additions to soil, which include increased plant growth (and so stores additional carbon in vegetation), lower non-CO_2 GHG emissions from soil and reduced mineralization of soil organic matter. Full life-cycle impacts also include emissions associated with the transport, storage and incorporation of biochar—current assessments conclude that these make only minor contributions to the overall GHG inventory[4–7]. Indirect climate change effects can also be caused by land use changes to grow feedstocks or land sparing, changes in biomass management (transportation, storage and landfilling)[8], reduced requirements for irrigation[9] and changes in fertilizer needs[10] or albedo[11]. These indirect effects vary greatly between biochar systems, yet emergent patterns show that, with the use of sustainably sourced feedstock (either regrown or true wastes), the emission reductions of GHGs (expressed in equivalents of CO_2, CO_2e), which include those of CH_4 and N_2O, vary from 0 to 1.6 tCO_2e per ton of biomass to produce the biochar[5–7,12], whereas the addition of biochar instead of unpyrolysed residues to flooded rice can reduce emission by up to 3.9 $tCO_2e\,t^{-1}$ biomass due to the large warming potential of CH_4 emissions[6].

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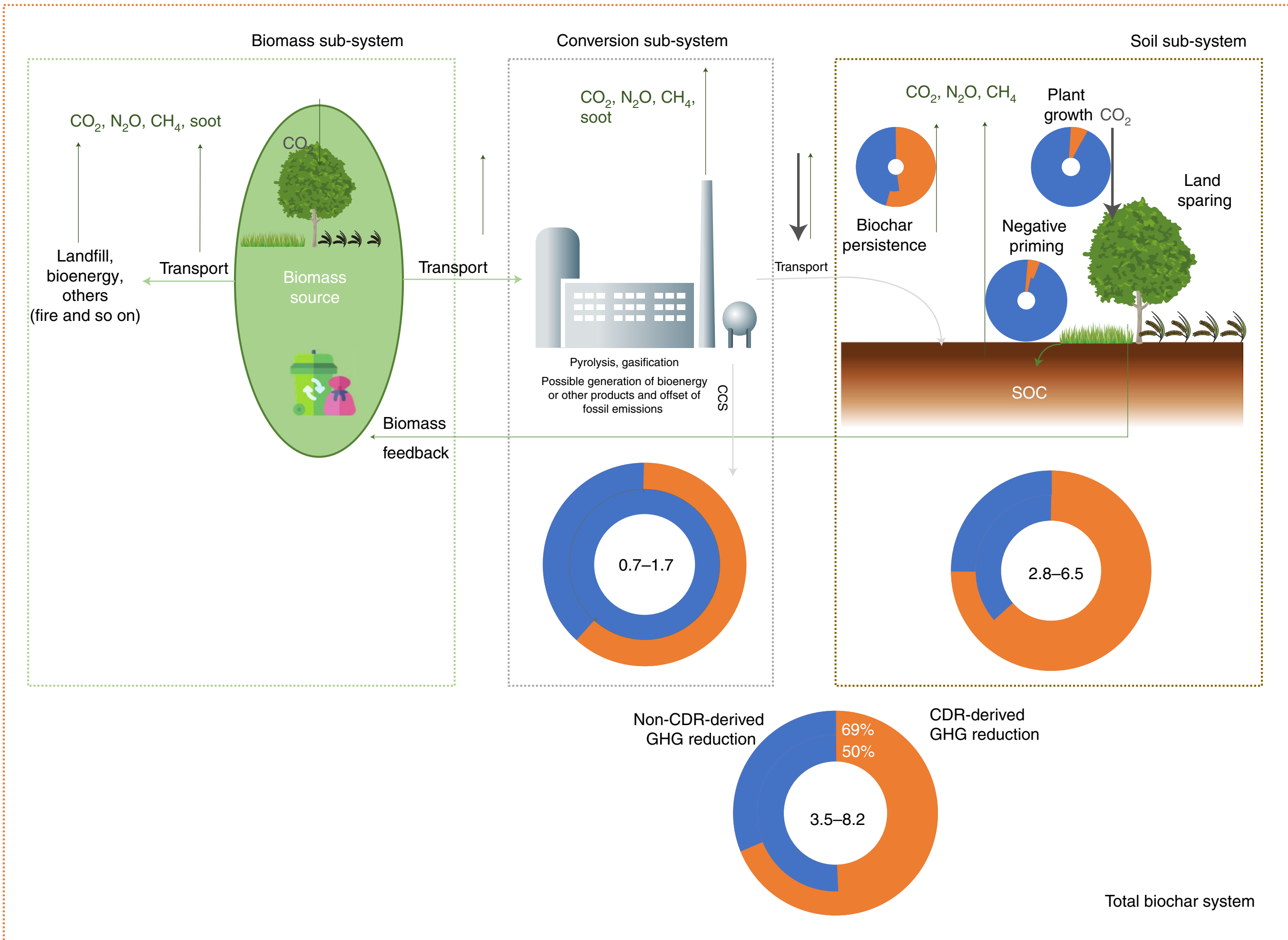

Fig. 1 | Climate mitigation effects of biochar systems within the total biochar system. Emission reduction through avoided biomass disposal dominates in the biomass sub-system (here we assume that biomass is sustainably produced, with no change in land carbon stock in the biomass system, and exclude land sparing due to the lack of data at a global scale). In the conversion system, CDR can be achieved through CCS. In the soil system, CDR is mostly delivered through a lower mineralization of the biochar than that of the unpyrolysed residue, and to a lesser extent by increased plant growth[16], negative priming[89] and by an unknown contribution of land sparing. Doughnuts show the numerical ranges of global annual GHG emission reductions ($PgCO_2e\,yr^{-1}$), with the minimum (orange inner ring) and maximum (orange outer ring) CDR as a proportion of the net GHG emission reduction by adopting biochar systems (blue comprises emission reductions that do not lead to CDR, for example, avoided fossil fuel emissions and N_2O reductions)[16,89]. Credit: tree, crop, grass and bin icons reproduced from Flaticon.com

GHG emissions are altered by all of these effects, but the net removal of atmospheric CO_2 is only delivered in four direct ways: (1) the higher persistence of pyrolysed compared with unpyrolysed biomass (48–54% of the net GHG emission reductions (all the data from Fig. 1)); (2) increased growth of plants in soils to which biochar was added (8%), if this increased biomass is itself converted into biochar or other long-lived carbon products (Fig. 1); (3) reduced mineralization of the existing soil organic carbon (SOC) together with an increased retention of new plant residue inputs (often called negative priming (4–6%; Fig. 1); and (4) CCS of pyrolysis gases and liquids.

Biomass sources and biochar production

The largest differences between biochar systems in their climate change mitigation potential per unit of biochar produced stem from the choice of biomass source. At one extreme, the use of forests that store carbon in their living biomass could create a large release of CO_2, assuming that the forest used to make biochar is not regrown after harvest (Fig. 2). Use of the forest biomass for biochar and other pyrolysis products should therefore be restricted to sustainably managed forests, which ensures that both the spatial extent and productive potential of existing forests do not decrease or, better, increase, and to postharvest residues (mill waste and so on). When the purpose-grown biomass crops are harvested for biochar production and then regrown, subsequent cycles of regrowth, biochar production and application can build increasing carbon stores over time (Fig. 2). When using biomass feedstocks that would decompose if unpyrolysed, such as plant litter or prunings, decomposition would release CO_2 more slowly than thermochemical conversion[13]. Yet most agricultural residues decompose on annual timescales and therefore constitute a low carbon debt compared with the large increase in carbon persistence through pyrolysis (Fig. 2)[14]. The largest emission reductions are achieved if the biomass would otherwise generate not only CO_2 but also N_2O, CH_4 or soot in the near term, such as in landfills, manure storage or residue burning. Recycling nutrient-rich wastes, such as excreta, therefore constitutes untapped opportunities for emission reductions through their use as biochar feedstock, even with a lower return of plant-available nitrogen, which facilitates the return of other nutrients to farmland

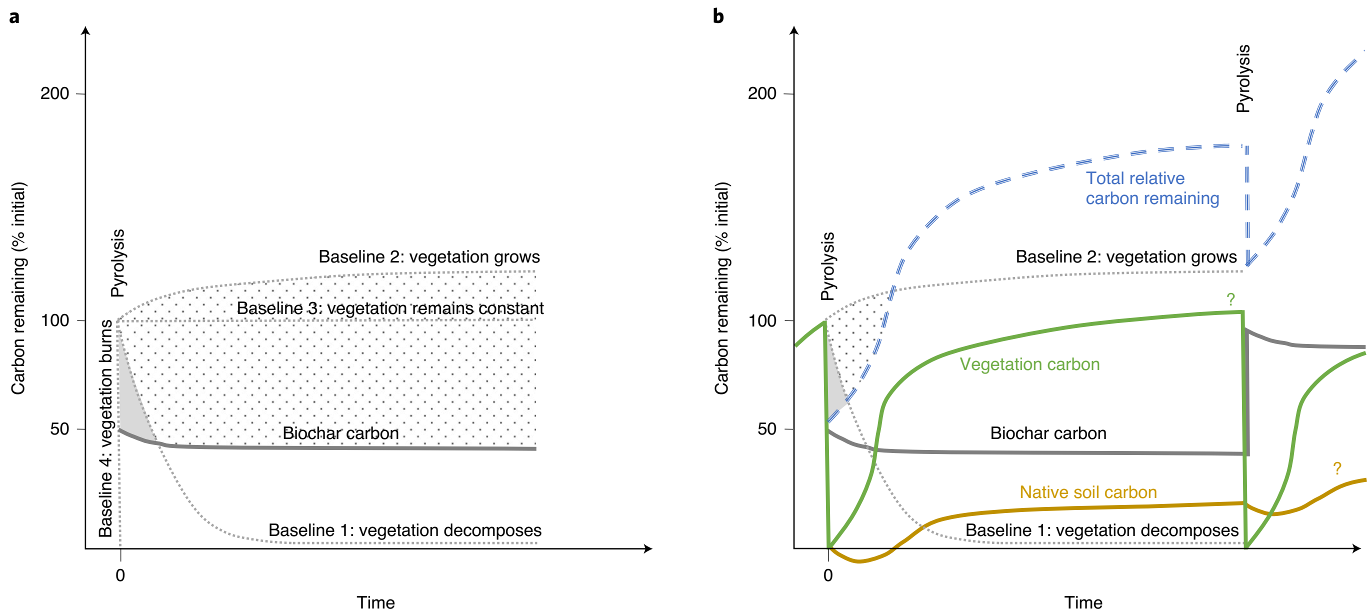

Fig. 2 | Relative carbon remaining with biochar systems compared with those of alternative baselines. a, Pyrolysis conversion volatilizes 50% of biomass carbon and retains most (>90% over decadal timescales) of the remaining carbon as persistent biochar compared with that of decomposing vegetation if litter or crop residues are used as the pyrolysis feedstock (baseline 1), which creates a small carbon debt (grey shade). Compared with growing or constant vegetation (baselines 2 and 3), a large carbon debt (dotted shade) would be generated. **b**, This debt will only be compensated if regrowing vegetation generates larger carbon stores than the baselines (question marks indicate additional research needed). Biomass harvested for wood products, bioenergy or CCS are not shown.

and also the management of water quality, pathogens and organic contaminants[15].

At the global or regional scale, the widest differences in total climate change mitigation potential of biochar stem from different assumptions about how much biomass and land are allocated to biochar production. With only organic residues and wastes allocated to biochar (that is, excluding biomass crops), the technical potential[16] of emission reductions is estimated at 2.4–3.9 $PgCO_2e\,yr^{-1}$, 44–49% being CDR (Methods). If annual and perennial biomass crops are grown on 100% of the abandoned cropland that has not subsequently become urban, forest or pasture and 6% of pasture is converted into multipurpose agroforestry without loss of fodder[16], the potential of emission reductions increases by 40–64% to 3.4–6.3 $PgCO_2e\,yr^{-1}$, 49–59% being CDR. Land sparing by increased crop growth might allow a large but still poorly explored increase in CDR: under the assumption of a 25% crop yield increase in the (sub)tropics, dedicated biomass crops for biochar production on that land alone may sequester 2.3 $PgCO_2e\,yr^{-1}$ in biochar, and an additional 1.7 $PgCO_2e\,yr^{-1}$ with CCS (average 2020–2100)[17], which increases the global mitigation potential to 7.4–10.3 $PgCO_2e\,yr^{-1}$, with 5.7–7.7 $PgCO_2e\,yr^{-1}$ or 75–77% of the net emission reductions being CDR.

Persistence of biochar

Net CDR by implementing biochar systems commonly rests on the persistence of biochar (Fig. 1). Not only is the microbial carbon mineralization of biochar reduced by one to two orders of magnitude compared with that of unpyrolysed residues[18], but also concomitant N_2O and CH_4 emissions from organic matter added to the soil under reducing conditions is largely avoided when pyrolysed above 450 °C (ref. [19]).

The increased carbon persistence in biochar can be explained by a fundamental change in molecular composition and, specifically, the increased proportion of fused aromatic structures[3,20–22] that increase with longer pyrolysis times and lower ash content of the feedstocks[23]. The proportion of fused aromatic structures can be estimated by the relative amounts of carbon to hydrogen or oxygen atoms (Fig. 3a), because both hydrogen and oxygen are displaced by carbon during fusion of the aromatic rings[24].

Thus, the atomic ratios of hydrogen to organic carbon (H/C_{org}) or oxygen to organic carbon (O/C_{org}) can be used to predict the extent of biochar mineralization[25,26] (Fig. 3b): 95% of the tested biochars with $H/C_{org} < 0.5$ showed a carbon persistence of over 50%, which averaged at 82%, after 100 years (Fig. 3a). The resistance to various oxidizing agents can be used to predict mineralization over periods of weeks to months[27], as it reflects the proportion of the easily mineralizable fraction. To predict the persistence over centennial timescales, the vastly different fast- and slow-mineralizing fractions of biochars require separate quantification using repeated measurements of either the mineralized or the remaining biochar over at least annual timescales using isotopic tracing[26].

Over centennial timescales, the observed differences in persistence between different biochars (Fig. 3) are of lower importance than the differences in persistence between biochar and unpyrolysed biomass. The difference in life-cycle emission reductions was found to be less than 10%, irrespective of whether 80 or 90% of the biochar carbon remains after 100 years[4,7,28,29]. If used in long-lived products, such as building materials, the biochar carbon sink is secure as long as the product is not burned. Redistribution and subsoil burial of biochar through erosion and leaching can decrease its mineralization, the extent of which depends on the conditions at the sites of erosion and deposition[30,31].

CH_4 and N_2O emissions from soil

Emissions of CH_4 and N_2O from soil that do not originate from the carbon or nitrogen in biochar may also change after biochar additions. Under saturated conditions, in which peat soils release CH_4 and where rapid electron transport occurs, net decreases in CH_4 emissions of up to 50% have been observed after biochar addition[32] due to the increased activities of methanotrophs in the oxic rhizosphere[33]. However, the average response has not shown a clear trend

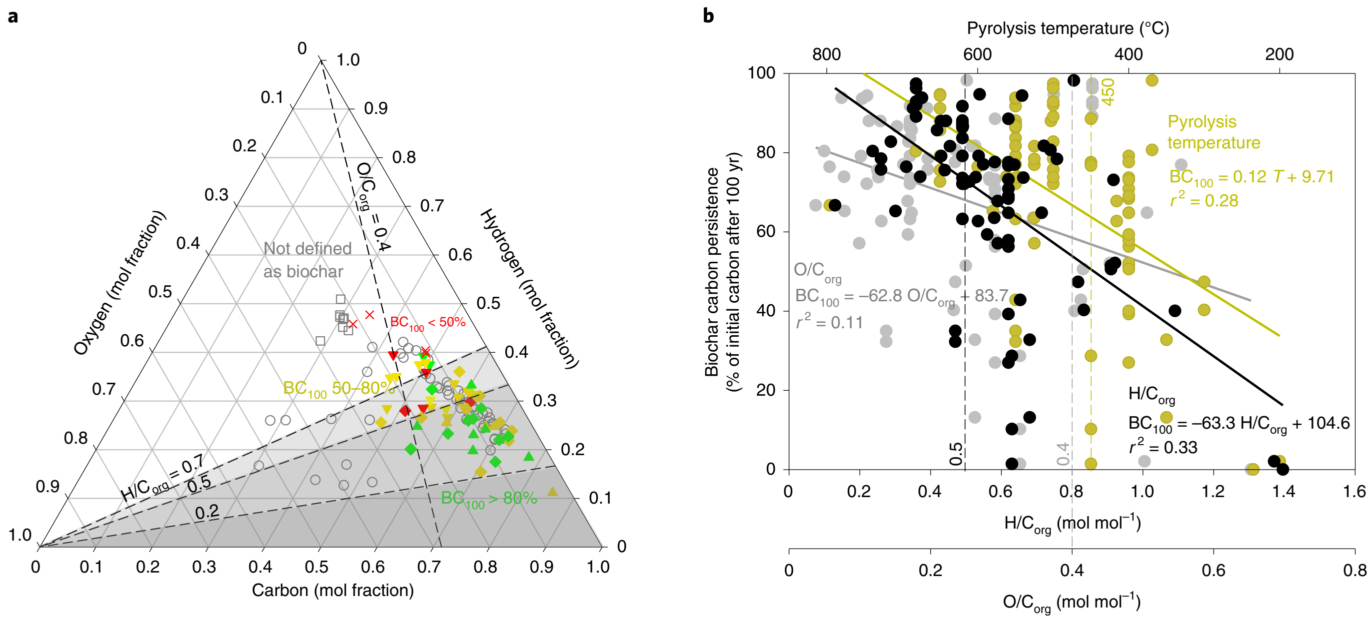

Fig. 3 | Persistence of biochar as a function of its carbon, oxygen and hydrogen content or its pyrolysis temperature. a, Thresholds of H/C_{org} of 0.7 and O/C_{org} of 0.4 capture most of the biochars (Methods). Colours indicate categories of how much biochar carbon remains after 100 yr (BC_{100}), symbols indicate pyrolysis temperatures (×, <350 °C; upside-down triangle, 350–450 °C; diamond, 450–600 °C; triangle, >600 °C), open circles show properties for a wider range of biochars[90] with open squares being the original feedstock. **b**, Relationship of molar H/C_{org}, O/C_{org} ratios and pyrolysis temperature (*T*) to biochar carbon remaining after 100 yr is strongest for H/C_{org} ($n=85$).

in paddy soils[34–36]. Under well-drained conditions, ash-rich biochars decreased CH_4 consumption, probably due to hindrance of the methanotroph activity by an increased electrical conductivity in the soil solution from associated ash[37]. In comparison, a higher net soil CH_4 consumption after the additions of high-temperature woody biochars has been attributed to better gas diffusion[38], potentially augmented by electron transport through biochar's fused aromatic ring structure, as shown for anaerobic conditions[32].

N_2O emissions are reduced by 38%, on average, in the first year of application, with net emission reductions of >10% documented for several years[39]. Lower N_2O emissions are a result of several mechanisms, which include transient microbial nitrogen immobilization or abiotic retention mechanisms, to some extent, but microbial reduction of N_2O to N_2 is the most likely multi-annual effect. This microbial reduction can result from a greater expression of N_2O reductase genes[39], pH increase and increased electron-transfer ability by functional groups on biochar surfaces[40], facilitated by electron transfer through biochar's fused aromatic ring structure, which is promoted by a higher pyrolysis temperature[41]. Transformation of N_2O to N_2, which thus avoids N_2O emission, is a permanent mitigation benefit, as the nitrogen has left the soil system so the effect cannot be reversed. The persistence of high-temperature biochars also means that this net decrease in N_2O emissions may continue over the lifetime of the biochar, even though the oxidation of biochars over time may reduce their electron-transfer capabilities through the biochar[41] and current meta-analyses have not unambiguously confirmed ongoing N_2O emission reduction[39]. Concomitant reduction of indirect N_2O emissions through decreases in nitrogen leaching[39] or reductions in the release of ammonia[42] and NO by biochar[43], however, are poorly quantified.

Mineralization of native SOC

Mineralization of native soil organic matter has often been found to increase (positive priming) within the first few weeks after biochar additions, but predominantly to decrease (negative priming) over the long term (more than two years) by 4% on average[18,44]. Negative priming effects have been found 6–10 years after biochar additions[45,46], averaging 0.5–1.2 tC ha^{-1} yr^{-1} (1.7–4.4 tCO_2e ha^{-1} yr^{-1}), and in soils that were enriched in biochar-type materials hundreds to thousands of years earlier[47–50]. Negative priming as a result of biochar additions may therefore by itself be an important CDR contribution that can be larger than that of many other soil management techniques, which often result in sequestration rates of <0.2 tC ha^{-1} yr^{-1} (<1 tCO_2e ha^{-1} yr^{-1}) (ref. [51]).

The main cause of the lower mineralization of native soil organic matter is the stabilization of organic compounds due to their adsorption to biochar, which is promoted by the high surface area and carbon contents of biochars produced at temperatures above 450 °C (ref. [44]). Biochar thus acts as a new reactive surface, consistent with the accepted mechanisms of soil organic matter stabilization[52,53].

Comparisons with the priming effects of equivalent amounts of unpyrolysed organic matter must be included in contexts in which this organic matter would be applied in the field. Isotope studies are indispensable and may even need to include methods to distinguish three carbon sources[45,54,55], namely biochar, native soil organic matter and plant or other organic inputs. Long-term studies, including studies that involve repeated applications, are needed to ascertain the ceiling that this additional carbon accrual may reach[52], and should consider interactions with inorganic carbon[56].

Plant growth for CDR

The effects of biochar on plant growth are important for three reasons: increased photosynthesis would remove additional CO_2 from the atmosphere (if retained in the soil, plants, biochar or other products); greater crop yields may provide an incentive for adoption of the technology; and increased productivity can enable land sparing[57] and thereby increase the overall potential for land-based climate-change-mitigation strategies on Earth's finite terrestrial surface[58]. Global crop response data indicate average yield increases of 9–16% when both both field and greenhouse experiments are

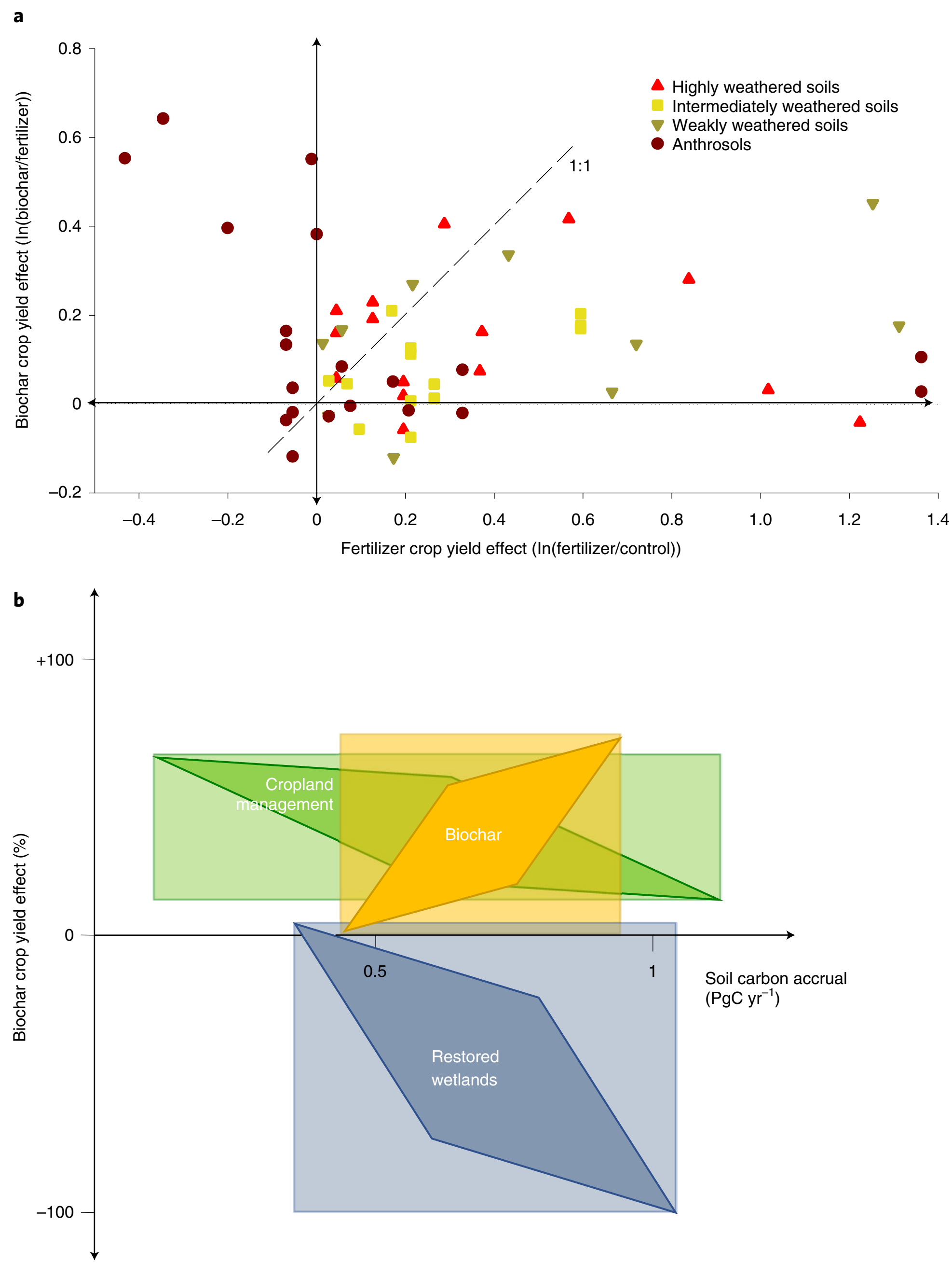

Fig. 4 | Global plant growth responses and CDR with biochar. a, Crop responses to inorganic fertilizers are not correlated with crop responses to biochar (r^2 = 0.006, P = 0.56, n = 58; data from ref. [61]), which indicates opportunities to increase crop yield and biomass accrual across many different soil conditions, complementary to inorganic fertilizers. **b**, Crop yields are typically higher with greater SOC contents, yet with often uncertain and nonlinear relationships between organic C contents and yield (indicated by the large diamonds within the boxes); crop yields, by definition, decrease when land use is converted from crop production to wetlands and may decrease when aboveground biomass is prioritized for soil carbon sequestration in lieu of crop harvest (boxes show the range of global aggregate data for SOC accrual and crop yield) (Methods). Indirect land use change is not considered.

included[59,60] or 15% for fertilized field experiments, the magnitude of which is comparable to fertilizer responses at the same sites[61]. However, crop yield responses to biochar additions do not neatly separate by soil type, or correlate with responses to inorganic fertilizers (Fig. 4a), which suggests that responses to biochar cannot be predicted from responses to fertilizers, but that biochar can be a valuable complementary approach. Some expected soil–crop–biochar interactions emerge, such as the positive response when high-pH biochar is added to acidic soils or no response when neutral or alkaline soils are amended[61]. However, crops grown in alkaline soils showed the same yield increase as those in acid soils to the amendment of biochar with a pH of <9 (ref. [61]), which indicates opportunities for biochar use beyond acid soils. Instances in which biochar-based fertilizers with biochar application rates of <2 t ha^{-1} (ref. [62]) have increased crop yields in soils non-responsive to conventional fertilizers suggest opportunities for biochar to complement traditional fertilizers.

Filling crop yield gaps or reclaiming mine land and degraded landscapes may provide some of the most promising avenues to incentivize CDR using SOC accrual including biochar, yet rely on

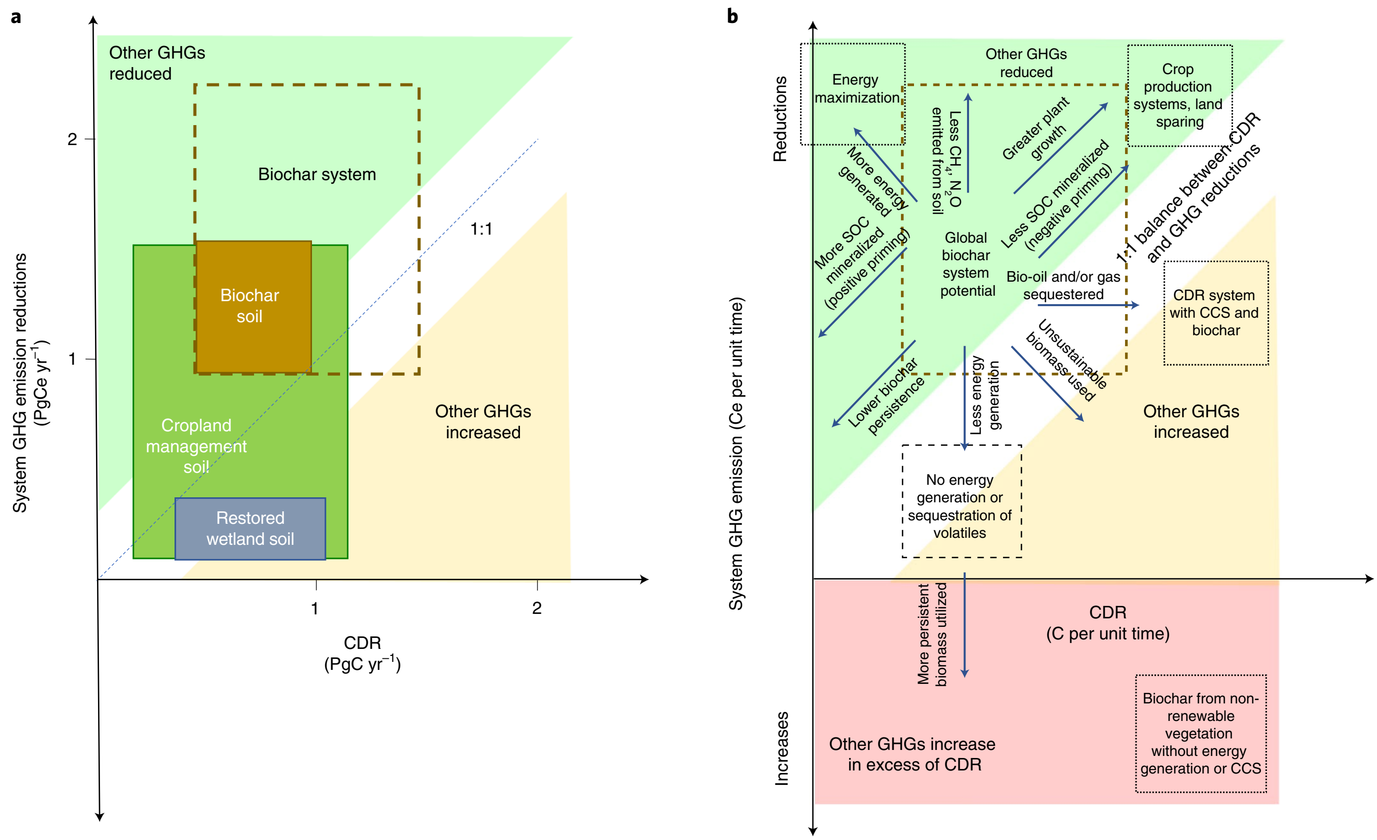

Fig. 5 | Relationship of GHG emission reductions and CDR. a, Global data of biochar soil CDR and GHG emission reductions in comparison with those of cropland management and wetland restoration (solid boxes; only for the soil system in Fig. 1) and those of the total biochar system CDR and GHG emission reductions (dashed box; all the systems in Fig. 1) (Methods). **b**, Different biochar system types and effects of system changes. Boxes indicate system types and arrows indicate different soil responses after biochar additions or energy use. Without the soil effects (plant growth and emissions of non-biochar C and N from soil), CDR (mostly by soil carbon accrual in biochar) relates 1:1 with GHG emission reductions. Ce, carbon equivalents.

collective action of farmers, industry and consumers[63]. An additional incentive for farmers to use biochar in soil management may be provided by improved product quality[64], which has received little attention.

CDR and GHG emission reductions

The relationship between CDR and emission reductions differs between alternative climate change mitigation strategies that enhance SOC (Fig. 5a). With a global adoption of biochar, the ratio of net emission reductions to CDR by SOC accrual tends to be greater than unity, which indicates a positive feedback from secondary GHG impacts (assuming no CCS and a low use of plantations). In comparison, global adoption of improved cropland management has a lower ratio of net emissions reduction to soil CDR (Fig. 5a). At the other extreme, wetland restoration shows lower emission reductions than those of CDR on a carbon-equivalent basis, because as SOC increases in saturated environments, CH_4 and N_2O emissions typically also increase, with the possible exception of adding biochar[65]. These relationships illustrate potential trade-offs and synergies between soil CDR and emission reductions that require recognition of nonlinearities and the effects on plant growth, soil GHG emissions or indirect land use change. Therefore, modelling should be employed that captures such interactions between biochar and other land-based approaches, including but not limited to integrated assessment models to generate defensible comparisons[66].

We distinguish between five general biochar system types: those that maximize energy generation, maximize crop production, include CCS, have no or low energy generation, or use non-renewable biomass (dotted boxes in Fig. 5b). The three main differences between these biochar systems relate to: (1) the fate of the biomass and its associated emissions if it were not converted into biochar (biomass sub-system in Fig. 1); (2) the efficiency of conversion (that is, how much biochar is produced per unit feedstock) and what material or energy products are generated and used in carbon storage (for example, biochar versus capture of CO_2 as part of a CCS approach (conversion sub-system in Fig. 1)); and (3) the deployment of biochar and its resultant effects on plant growth and emissions from soil (soil sub-system in Fig. 1).

The slightly greater emission reductions of biochar systems than those of soil CDR (biochar lies above the 1:1 line in Fig. 5) mean that emission reductions are generated in excess of the sequestered biochar; these largely stem from avoided emissions in the biomass sector (avoided landfill and avoided CH_4 in rice) and reduced emissions from soil (N_2O and CO_2)[12,16]. Higher emission reductions at the same CDR (upward arrow in Fig. 5b) may be delivered by reducing non-CO_2 emissions (CH_4 and N_2O) from soil[34–36,39] or replacing the more emission-intensive energy sources (for example, coal instead of natural gas)[12,16,67]. Increasing both CDR and emission reductions at the same time (arrows to the upper right in Fig. 5b) requires greater crop yields to enable land sparing[17] or negative priming[44–47].

Increasing the energy output to displace fossil fuel emissions at the expense of biochar production will decrease the CDR (unless the emissions are sequestered using CCS)[17], because of the inverse relationship between biochar and energy production[68]. As less energy generation in favour of biochar production reduces the GHG emis-

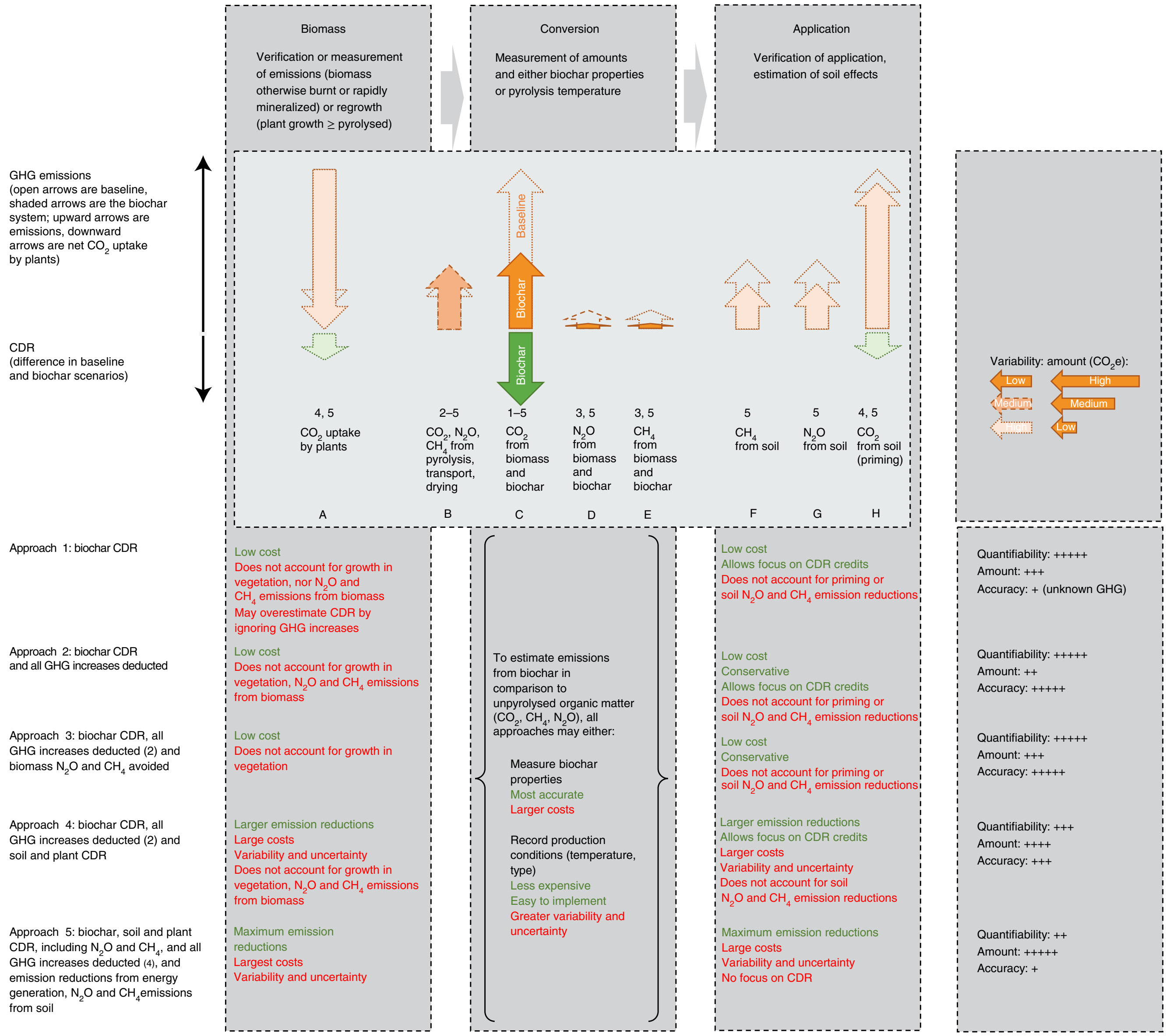

Fig. 6 | Framework for carbon accounting approaches that focus on GHG emissions, CDR and their combination. Eight fluxes (A–H) deliver changes in GHG and CDR between biochar systems (filled arrows) and baseline (open arrows). Five approaches, 1–5, show increased amounts of GHG emission reductions balanced by decreased quantifiability and increased accuracy. Accuracy, amounts and quantifiability are shown in relative terms using categories. Any CO_2 emission reduction between baseline and biochar systems (orange arrows) is shown as a CDR (green arrows). Green text, advantages; red text, disadvantages.

sions from soil, the potential global emission reductions of biochar systems are 22–27% greater than those of bioenergy displacing fossil fuels, with a larger effect where soil fertility is low or non-CO_2 emissions are high[16].

Reductions in emissions and CDR are smaller with a lower biochar persistence and greater positive priming (arrows to the lower left in Fig. 5b). Lower emission reductions at similar CDR (downward arrow in Fig. 5b) are the result of biochar systems that have no opportunity to generate or utilize energy, which may be the case with highly distributed and small in-field conversion systems or at remote locations where biomass is harvested for fire prevention or the management of invasive species[69]. The use of biomass that is not rapidly renewed, or pyrolysis without energy capture, must be considered within a full life cycle[69] and ecological perspective[70] to determine whether it is a viable climate change mitigation approach.

Carbon accounting and trading

Verification of the various GHG emission reductions and CDR as well as their possible monetization requires a carbon accounting system that compares the implementation of biochar systems with business as usual[71], and includes soil amendment or disposal of unpyrolysed organic residues (Fig. 6). The abatement value (CDR and/or emission reductions) of biochar systems can, to some extent, be monitored at the point of conversion. The amount converted and the properties of the resultant biochar material can be reported more easily (cheaper and less variable) than measuring or modelling soil carbon accrual or GHG emissions at the site of application. For broader-scale national or global accounting, biochar persistence may be estimated from the pyrolysis temperature[72]. In project-scale or monetized trading systems, indicators of persistence (such as the H/C_{org} ratio) may be measured directly[26]. The conversion of a comparatively rapidly mineralizing biomass to a slowly mineralizing biochar is irreversible for biochar placed in soil, fed to animals or used for applications such as building materials or road bases, and can be considered a permanent carbon removal over centennial timescales, but the actual application to soils or materials must be verified. All GHG emissions (which include N_2O and CH_4) and carbon stock changes have to be estimated (Fig. 6). For soil emissions (D–H in Fig. 6) these can, in most cases, be conservatively ignored, whereas biomass use and biochar production use (A–C in Fig. 6) must be monitored[72].

A focus on CDR rather than merely GHG emission reductions of biochar systems for carbon trading leverages the verifiable conversion of easily decomposable biomass into persistent biochar (C in Fig. 6). A market focus on CDR alone may command higher prices than GHG emission reductions of biochar systems[73]. In addition, the 30% increase of carbon prices associated with so-called nature-based solutions from 2019 to 2020 in comparison with the 16% decreases associated with renewable energy[74] during the same period suggest that rewarding environmental co-benefits, which include, but are not limited to, water quality or biodiversity, is currently favoured by the market.

Life-cycle changes in GHG emissions must be verified, and any net emissions at the system level must be deducted from the amount of carbon sequestered. Further development is required to examine whether life-cycle emission reductions can be reliably and cost-effectively included to compensate for emissions during conversion (B in Fig. 6). Differences in CH_4 emissions between decomposing biomass or biochar itself (E in Fig. 6) are easily verifiable but are only relevant in some cropping systems (for example, flooded rice). At the other extreme, negative priming of native SOC may be a large additional CDR (H in Fig. 6) but expensive to verify, and it may rely on modelling that is yet to be developed.

The biomass used for biochar could in many situations (albeit not all) be used solely or partly to generate energy products[28], either by converting the biomass feedstock directly (for example, by combustion for bioelectricity or heat) or by using the biochar as fuel (as done with traditional charcoal). Depending on the type of fuel that is replaced, emission reductions by generating energy vary widely: emissions could be 3% higher for producing biochar than energy if coal is displaced, but 21–29% lower if oil or natural gas are displaced and 95% lower if solar, wind or nuclear energy is displaced (Methods). Whether energy generation rather than carbon sequestration leads to greater GHG emission reductions therefore depends on local situations[28,29,75,76]. As the energy system is increasingly decarbonized, producing biochar will become increasingly favourable compared with using biomass to generate energy[4].

Biochar applications that sequester carbon must also compete with the market value of any energy product[77]. Condensation and catalytic or biological conversion of gases can generate liquid transportation fuels that may generate greater income than crop yield increases[78]. Carbon markets that only value emission reductions together with the higher commercial value of liquid transportation fuels compared with that of biochar in soil will, in most cases, provide an incentive to generate energy products over CDR[76,77,79,80]. Such a market incentive may only tilt towards biochar and CDR once the transportation sector is decarbonized, CDR is valued by the carbon market at higher prices than reduced emissions[81], or where energy products cannot be produced or utilized (for example, remote areas)[77].

Outlook

Quantifying the long-term persistence and potential concomitant effects of biochar on soil and vegetation requires decadal-scale research on plant growth responses, biomass use, biochar persistence, priming, CH_4 and N_2O emissions from soil, and identification of drivers for adoption of CDR versus emission reductions (Extended Data Table 1). High priority areas for optimization in the implementation of biochar systems include sustainable biomass sourcing and plant growth to maximize CDR, whereas adoption requires government and market incentives, education, reliable crop yield increases to enhance farm income, and shovel-ready waste management systems. Decision-support tools are needed to guide selection of suitable biochar systems to achieve local objectives at the scale at which farm or land use decisions are made.

New directions to enhance climate change mitigation benefits of biochar systems are encouraged, such as combinations with other conversion technologies before pyrolysis (for example, anaerobic digestion), with sequestration of the CO_2 evolved during conversion (CCS), or with inorganic carbon capture in soil. Biochar from woody materials together with high-nutrient containing-wastes[82] or silicate rock powder[83] can be combined with conventional mineral or organic fertilizers into commercial granular fertilizers, so that existing global fertilizer supply networks can be employed to deliver CDR with each fertilization[84]. Economic hurdles to implementation may be lowered by non-soil uses of biochar (animal feed[4,85], construction material[86], energy storage[87], catalysts[88] and so on) and by non-energy uses of condensable and non-condensable gases (including bioplastic, microbial food and so on), which require further research and development to ascertain their climate change mitigation and economic value.

As urgency increases to not only reduce GHG emissions, but also to reduce CO_2 in the atmosphere, biochar or other CDR approaches have to be critically evaluated for their broader impacts on the environment and society in addition to climate change mitigation. Prioritizing approaches will require a global societal discussion about—for example—whether we value persistent organic carbon in soils more than carbon injected into geological formations, CDR more than GHG emission reductions, and how incentives and effective governance structures may be set up by governments, markets and consumers.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, statements of data availability and associated accession codes are available at https://doi.org/10.1038/s41561-021-00852-8.

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Methods

Global emissions and CO_2 reduction. The global GHG emissions and emission reductions through implementation of biochar systems were calculated using the BGRAM algorithm[16] with two biomass availability scenarios identified as the 'alpha' and the 'maximum sustainable technical potential' (MSTP) scenarios. The alpha scenario, values for which provide the lower bound to ranges given in Fig. 1 and the text, assumes the conversion of biomass residues and wastes available using current technology and practices. The MSTP scenario assumes conversion of the maximum fraction of the global biomass resource that can be harvested without endangering food security, habitat or soil conservation and thus is used to generate the upper bound of the ranges reported.

Calculations for each biomass scenario[16] yielded annual and cumulative estimates of increases and decreases in emissions over the course of 100 years; the maximum annual difference in these emissions is reported here. Emission increases include the net losses in SOC due to biomass removal, biomass and biochar transport emissions, emissions for the incorporation of biochar by tillage, CO_2 emissions during biomass conversion (pyrolysis or bioenergy) and CO_2 emissions from the decomposition of biochar stored in soil. Emission decreases include CO_2, CH_4 and N_2O from biomass avoided by its conversion into biochar, displacement of fossil CO_2e emissions by bioenergy generated during the biomass conversion (using fossil CO_2e intensities adjusted to the 2018 global averages[91]), soil CH_4 and N_2O emissions following biochar application to soils and increases in net primary productivity in soils to which biochar is applied.

Estimates of CDR were calculated by subtracting emissions of CH_4 and N_2O (biomass and soil) and displaced fossil-CO_2e emissions from the total net GHG emissions after adjusting net primary productivity for the fraction of non-CDR emissions reductions. For net GHG emission and CDR estimates that include negative priming we assumed a 7–10% range for a 100 yr increase in SOC per unit of biochar carbon added (that is, an average annual increase of 0.07–0.10% in SOC per unit of biochar carbon added). This assumption is conservative compared with both the short-term (<10 yr) and tightly constrained field data with known biochar amendment rates[45,46,92] that show annual increases of 10% or more, and a long-term (100 yr) model of biochar amendments to three contrasting soils[89] with mean annual increases close to 1%. A meta-analysis of short-term (mostly less than 3 yr) laboratory priming studies[18] shows a mean 3.8% total increase across all studies.

The data given here are applicable to a globally relevant mixture of biochar persistence, biochar production, energy production, crop productivity responses and so on. The values exclude CCS, SOC priming and land sparing, except where explicitly mentioned. Where included, CCS of the pyrolysis CO_2 emissions assume a 91% capture efficiency (MSTP scenario only). Land sparing refers to the effect by which crop production is increased per unit area and thereby either allows other areas to be taken out of agricultural production (and, for example, reforested or afforested) or allows farmers to forgo further expansion into natural areas (and, for example, reduce deforestation), which reduces emissions and increases CDR[17,57].

Biochar persistence. The proportion of biochar carbon that remains after 100 yr was calculated with a double-exponential model from experiments with at least 1 yr of replicated mineralization data using isotope tracing ($n=86$; expanded from ref. [72] with additional data from refs. [93–96]). Mineralization rates were adjusted to the average global temperature of 14.9 °C using a nonlinear relationship between temperature and Q_{10} temperature coefficient[26]. The carbon, hydrogen and oxygen values in Fig. 3a were calculated as molar fractions of their sum.

Global crop yield and SOC accrual. The range of global aggregate data (1) for SOC accrual was taken from ref. [97] (2) for GHG balances with biochar from ref. [16] and (3) for GHG balances with land use change or improved cropland management from ref. [51].

Crop yield changes with biochar additions to soil in comparison to fertilizer responses (Fig. 4) were obtained from ref. [79]. Crop yield with cropland management was assumed to increase by 33% with an increase of SOC to 1% organic carbon[98]. This was calculated using the midpoint of the following relationships of SOC and crop yield: crop yields can be increased by 20–70 kg ha^{-1} for wheat, 10–50 kg ha^{-1} for rice and 30–300 kg ha^{-1} for maize with every 1 Mg ha^{-1} increase in the SOC pool in the root zone[98]. Crop yield in soils with organic carbon contents greater than 1% were assumed not to increase with further increases in SOC. The relationship between crop yield and SOC is still poorly quantified at a global scale, and these values are to be taken with caution.

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Author contributions

All the authors contributed to the discussions that formed the basis for this Review, and to the writing and editing of the manuscript. M.C.-A. analysed the crop yield data, J.L. and D.W. quantified the biochar persistence, and D.W. and J.E.A. re-analysed global GHG emission data. M.L.C. took the lead on the section on non-CO_2 emissions, T.W. on priming, D.W., A.C. and C.K. on biomass use, and C.A.M. on erosion. J.L. drew the figures and Extended Data Table 1.

Competing interests

The authors declare no competing interests.

Additional information

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Extended Data Table 1 | Recommendations for environmental and socio-economic optimization and research on the climate change mitigation effects of biochar systems

		Recommendation for optimization during implementation	Recommendation for research and development		Priority for optimization during implementation	Priority for research
CO_2 removal	Biomass sources	Sustainable production, residues, waste utilization	Spatial assessment, optimization, life-cycle assessments, IAM[b] development		High	High
	Plant growth	Decision support, demonstration, extension	Decadal, field, repeat biochar application, biochar-based fertilizers, demonstration, root C input, indicators[a]		High	High
	Movement (erosion, leaching)	Incorporation	Decadal, landscape, demonstration, fluvial monitoring		High	Medium
	Priming	Pyrolysis temperature >450°C, low-ash feedstock, application to mineral soil	Decadal, field, repeat biochar application, organic soils, demonstration, equivalent soil mass, indicators[a]		Medium	High
	Persistence of biochar	Pyrolysis temperature >450°C, soil incorporation	Decadal, field, demonstration, reference materials, equivalent soil mass, indicators[a]		Medium	Medium
GHG reductions and other climate forcing	Nitrous oxide from soil	Pyrolysis temperature >550°C	Decadal, field, repeat biochar application, demonstration, yield scaling, indicators[a]		High	High
	Methane from soil	Pyrolysis temperature >550°C	Basic mechanism of reduction, indicators[a]		Medium	High
	Albedo	Incorporation, maximize plant cover	Plant and soil albedo		Low	Medium
	Nitrous oxide from biochar	Pyrolysis temperature >450°C, low-N feedstock	Indicators[a]		Low	Low
	Methane from biochar	Pyrolysis temperature >450°C	Indicators[a]		Low	Low
Adoption	Market incentive	Carbon trading, reference materials, safeguards	Large-scale monitoring of incentives, indicators[a]		High	High
	Crop yield	Decision support, demonstration,	Decadal, field, repeat biochar application,		High	High

Recommendations are grouped by priority for optimization during implementation and for research. Priority indicates a relative priority at the present time that will shift as knowledge is generated (high priority given where knowledge is low, explainable variation or sensitivity to differences are high). [a]Includes metrics for modelling and monitoring in the context of predictions and industry or public regulation. [b]Integrated Assessment Models. [c]Diversity, equity and inclusion.