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LETTER

Biochar as a carbon dioxide removal strategy in integrated long-run mitigation scenarios

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Keywords: biochar, carbon dioxide removal (CDR), pyrogenic carbon capture and storage (PyCCS), bioenergy with carbon capture and storage (BECCS), co-benefits, GCAM

Supplementary material for this article is available online

Abstract

Limiting global warming to under 2 °C would require stringent mitigation and likely additional carbon dioxide removal (CDR) to compensate for otherwise unabated emissions. Because of its technology readiness, relatively low cost, and potential co-benefits, the application of biochar to soils could be an effective CDR strategy. We use the Global Change Analysis Model, a global multisector model, to analyze biochar deployment in the context of energy system uses of biomass with CDR under different carbon price trajectories. We find that biochar can create an annual sink of up to 2.8 $GtCO_2$ per year, reducing global mean temperature increases by an additional 0.5%–1.8% across scenarios by 2100 for a given carbon price path. In our scenarios, biochar's deployment is dependent on potential crop yield gains and application rates, and the competition for resources with other CDR measures. We find that biochar can serve as a competitive CDR strategy, especially at lower carbon prices when bioenergy with carbon capture and storage is not yet economical.

1. Introduction

Limiting global mean temperature change to less than 2 °C by 2100 will likely require the deployment of carbon dioxide removal (CDR) strategies to compensate for otherwise unabated emissions [1–3]. The latest report by the Intergovernmental Panel on Climate Change (IPCC) estimated a cumulative amount of CDR of 609 $GtCO_2$ between 2020 and 2100 (median value; full range 188–1520 $GtCO_2$) [4]. Commonly discussed CDR strategies include natural sink enhancements like afforestation and reforestation, soil carbon sequestration (SCS) and accelerated weathering, and engineering solutions like direct air capture and storage and bioenergy carbon capture and storage (BECCS). Biochar, the solid product of pyrogenic carbon capture and storage (PyCCS) [5], has been proposed as a CDR strategy [6–9] with relatively low cost [10, 11], high-technology readiness [12], and potential co-benefits in agricultural systems which could result in higher crop yields [13–15], a key benefit in a land-constrained world with a growing population [16, 17].

Biochar is a carbon-rich product created by the thermal decomposition of organic material under a limited supply of oxygen and at relatively low temperatures (<700 °C). Biochar can be used for soil improvement, animal and crop waste management, energy production, and climate change mitigation [18]. Biochar's CDR potential comes from the CO_2 converted by photosynthesis during feedstock production with the biogenic CO_2 transformed into a stable carbon form via pyrolysis [19, 20], a thermal process in the absence of oxygen that deconstructs bio-polymers into biochar, combustible syngas, and bio-oil [21]. The pyrolysis conditions (temperature level and retention time) and the feedstock quality (lignin content) define the biochar characteristics and ultimately its recalcitrant organic carbon content [22]. Today, biochar is used mainly for co-composting and applied to soils in small quantities, given that the main economic incentive relates to plant productivity improvements [12]. Because of faster growth performance in animals, biochar has also been used as a feed supplement [23]. The global biochar market is expected to grow at a compound annual growth rate of around 11% in terms of volume between 2022 and 2030 [24], and this growth rate could be much higher if biochar was valued for its carbon sequestration potential.

Biochar's carbon recalcitrance is an advantage over CDR strategies with uncertainties regarding their permanence, such as afforestation or SCS [25, 26]. Biochar offers benefits to agriculture, including increased crop yields [15], decreased use of nitrogen fertilizers [27], and increased water retention in soils [28, 29]. Biochar production also generates a valuable biogenic combustible syngas that can be used as carbon neutral energy and help mitigate climate change [9, 30]. Importantly, biochar competes for feedstocks with BECCS, i.e. bioliquid or biopower production with CCS. Biochar supply and demand have multiple interacting effects on cropland expansion and influence the availability of land for biomass for energy production and other land-based CDR options. These complex dynamics within the climate-energy-land-water system call for a comprehensive multi-sector framework on a global basis to capture interactions between systems.

Prior studies have concluded that biochar's mitigation potential is highest as a soil amendment versus a direct form of energy use [9, 19, 31]. Global biochar CDR potential is estimated in the literature to range from about 1 gigaton of CO_2 per year ($GtCO_2\ yr^{-1}$) [7, 20] to almost 5 $GtCO_2\ yr^{-1}$ [8], based on different sustainability criteria that would limit feedstock availability. This number could be as high as 6.3 $GtCO_2$ equivalent ($GtCO_2e$) if non-CO_2 impacts were included [32], as biochar application could also reduce methane and nitrous oxide emissions from soils [27, 33]. A recent study focusing on 155 countries found that as much as 3.5 $GtCO_2e\ yr^{-1}$ could be sequestered from biomass residue alone, with China (468 $MtCO_2e\ yr^{-1}$), the United States (398 $MtCO_2e\ yr^{-1}$), Brazil (303 $MtCO_2e\ yr^{-1}$), and India (225 $MtCO_2e\ yr^{-1}$) playing a key role [34]. Importantly, biochar could sequester carbon in an economical way while having a low impact on land, water, nutrients, and albedo [8, 19]. Crop yield improvements are a key economic driver for biochar deployment [35], although this could change in a world where sequestering carbon is also valued. Because of biochar's effects on different systems, several studies have called for the integrated assessment of biochar's carbon sequestration under climate change mitigation scenarios [19, 31, 32].

The goal of this study is to model biochar in an integrated assessment model (IAM), namely the Global Change Analysis Model (GCAM), and quantify biochar's carbon sequestration potential under integrated climate-energy-land-water systems. A recent study by Werner *et al* [35] analyzed the impact of higher yields from biochar application on cropland reduction and corresponding terrestrial carbon increase under different assumptions of amounts of land with biochar application. Our study differs in that we model the dynamic interactions that drive the scale and impact of biochar production and use under varying scenario assumptions. We address questions and challenges raised in the literature [1, 19, 30, 31] and explore the implications of various parameters in a comprehensive and integrated manner. We construct scenarios by varying carbon prices, which affect the economics of biochar supply and demand; biochar application rates, which affect the demand for biochar and its total global carbon sequestration potential; biochar yield improvements, which have been found in the literature to improve biochar's economics; and BECCS availability, which directly competes with biochar for feedstocks. We design 36 GCAM scenarios varying different biochar parameters and quantify its global carbon sequestration potential while analyzing tradeoffs in the energy, land, water, and climate systems.

2. Methods

2.1. Overview

Our study applies GCAM, a model used by the IPCC, to analyze the potential scale and impact of biochar as a CDR strategy. We develop 36 scenarios with varying assumptions regarding carbon prices, biochar application rates, crop yield improvements, and BECCS availability in GCAM v.5.3 (SM1 and SM2). The version of GCAM 5.3 used for this project is publicly available at: https://github.com/CandeBergero/GCAM_V5.3_biochar.

2.2. GCAM

GCAM is an integrated, global, multi-sector model that links the economy, land, energy, water, and climate systems. The model has been developed for the past 30 years, and it has been used in numerous studies, including the development of scenarios for national and international assessments for the IPCC and the Shared Socioeconomic Pathways (SSP2) [36]. GCAM is open-source with documentation available online (see: http://jgcri.github.io/gcam-doc/index.html), with additional explanations relevant to this study in SM3.

The model represents 32 geopolitical regions and 384 land regions. GCAM runs from 1975 until 2100 in 5 year time steps, with 2015 as the last historical calibrated period. Model input assumptions include population, labor productivity, technology characteristics and different policies. The outputs of model scenarios include emissions, prices, water and energy supply and demand, agricultural production, land use, and atmospheric concentrations and temperature.

2.3. Modeling biochar and PyCCS in GCAM

We model the pathways for both biochar supply and demand fully integrated with the energy, water, climate, and agricultural systems.

2.3.1. Biochar supply

When biomass is pyrolyzed, the organic carbon is converted to solid, liquid, and gaseous carbonaceous products [5]. The solid product of this process is biochar. In this study, we represent the production of biochar in GCAM as the result of PyCCS, through the process of slow pyrolysis, as it yields a higher proportion of carbon-rich char for CDR as opposed to fast pyrolysis methods which focus on producing liquid fuel and less char [5, 9, 22, 37]. There is a broad range for biochar yields in the literature based on the feedstocks used, the kiln temperature and the residence time, among many other factors. For example, Schmidt *et al* [5] describe a slow pyrolysis process at temperatures between 450 °C and 700 °C. For the purposes of our long-term, global analysis, we have assumed a biochar pathway that is representative of production to maximize biochar and CDR at large scales.

We model lignocellulosic feedstocks for biochar in GCAM as coming from bioenergy crops, and crop and forestry residues at potentially large scales. We have found the study by Roberts *et al* [9] to be the most relevant and comprehensive source for our techno-economic parameters for modeling a slow pyrolysis process for using lignocellulosic feedstocks to produce biochar for CDR at large scales. From Roberts *et al* [9], we have assumed the cost of the slow pyrolysis facility is 67.50 USD per ton of feedstock (which is equivalent to 246.44 USD per ton of biochar). More recent studies have similar biochar production costs that range from 184 to 254 USD per ton of biochar [38, 39]. See SM4 for additional sensitivities regarding biochar's cost of production. The production of 1 ton of biochar takes in 3.65 tons of biomass feedstock (switchgrass in that study, from which we generalize for all lignocellulosic feedstock in GCAM). The process yields 20.1 GJ of syngas and a small portion of bio-oil as co-products. We have assumed that the bio-oil co-product from slow pyrolysis is too low in energy content to have value in the energy system, following the assumptions of Brown *et al* [21]. We do model the syngas co-product, which is valuable in the energy system in scenarios where carbon emissions are constrained, and fossil natural gas must be phased out. Table 1 lists our slow pyrolysis assumptions.

Table 1. Representative slow pyrolysis assumptions*.

Metric	Value	Units
Non-energy cost	67.50	2023 USD per ton of feedstock
Biomass input	3.65	Tons of lignocellulosic feedstock per ton of biochar
Gas input[a]	0.2	GJ per dry ton of biochar
Syngas co-product[b]	20.1	GJ per dry ton of biochar
Net syngas co-product	19.9	GJ per dry ton of biochar

[a] GCAM modeling parameters based on original technical data in Roberts *et al* [9].

[b] We assume that the gas or thermal input to the pyrolysis facility is met by a fraction of the syngas co-product, which means there is no modeled energy input for biochar production.

2.3.2. Biochar demand

Several studies conclude that biochar could benefit crop production [12, 16, 19, 30]. In this study, we model the demand for biochar as coming from its use on agriculture. We have created additional crop pathways that explicitly demand biochar based on the economics of yield improvement, cost, and value of CDR. The crop production pathways with biochar application compete with conventional pathways based on relative profitability.

The biochar application rate is a key driver of its demand. Potential application rates vary from less than 10 to as high as 100 tons per hectare (t ha^{-1}) [12, 14, 40]. The long-term application rates in the literature remain uncertain, as few studies have analyzed biochar impacts for longer than a decade [41]. While it is known that some soils contain several meters of biochar [42], the timeframe for this accumulation, and the frequency of biochar application, remains uncertain. For our analysis, we assume one-time application rates of 10 and 20 t ha^{-1}, for each unit of cropland in each region, when chosen as economic, over our study horizon to year 2100. Note that although these application rates appear high compared to some current biochar practices, our focus is on biochar for CDR. Therefore, the economics of higher application rates, and corresponding higher carbon storage, can be favorable in future scenarios where CDR is highly valued. We conservatively assume that biochar is applied once in the time-period studied. Additionally, we run a sensitivity case with an upper limit of 100 t ha^{-1} between 2020 and 2100 (see SM5 for more details).

We performed a Scopus search for crop yield improvements from biochar application and found 145 publications relevant for analysis. Based on this search, we have assumed average yield improvements that vary based on the climate zone of each of the 32 GCAM regions (temperate or tropical) and based on the watering practice per land type (irrigated or rainfed). The average yield improvements of applying biochar that we are using for our study are 12% and

Table 2. Biochar demand and PyCCS assumptions.

Metric	Value	Source
Application rate	10 t ha^{-1} 20 t ha^{-1}	[14, 40]
Yield improvements	12% (tropical irrigated) 19% (tropical rainfed) 10% (temperate irrigated) 15% (temperate rainfed)	Refer to SM19
Net carbon sequestered (not including syngas)	56% of the carbon in the lignocellulosic feedstock	Refer to SM6

19% increase for tropical irrigated and rainfed land, respectively; and 10% and 15% increase for temperate irrigated and rainfed land, respectively. This range is consistent with the literature [14, 43].

The use of biochar for CDR is often referred to in the literature as PyCCS. For biochar's value for CDR, or PyCCS, the important factor is the net amount of carbon in the input biochar feedstock that is sequestered from the atmosphere over the long-term. The net amount of carbon sequestered depends on the carbon in the resulting biochar, its recalcitrance, and the content of the carbon in the syngas and the bio-oil [5, 31]. Since we are explicitly modeling the disposition of the syngas co-product, we can calculate that about 20% of the original feedstock carbon is contained in the syngas (conversely, 80% of the carbon is not in the syngas), which is consistent with the literature [5]. This syngas carbon can either be emitted or captured if economic based on carbon prices, and it is modeled in GCAM. Because we are not explicitly modeling the fate of the bio-oil based on Brown *et al* [21], we make a simple assumption that 70% of the carbon that is not in the syngas is sequestered, resulting in a net of 56% of the original feedstock carbon (see SM6 for a more detailed explanation of our assumptions). This implies that some fraction of the bio-oil carbon is sequestered, though we are not explicitly modeling the bio-oil co-product. This net rate is within ranges in the literature [9, 31], and is conservatively lower than the 67%–74% range that Schmidt *et al* [5] state for the combined process of slow pyrolysis biochar with sequestration of the bio-oil. Table 2 lists the assumptions for biochar demand.

Other technologies that demand biomass and sequester carbon in GCAM v5.3 include converting biomass to liquids through Fischer–Tropsch with CCS, which captures between 82% and 90% of the carbon in the feedstock; converting biomass to liquids with cellulosic ethanol and CCS, with capture rates between 26% and 90%; conventional biomass electricity generation with CCS, with capture rates of 85%–95%; electricity generation with biomass integrated gasification combined cycle with CCS, with capture rates of 85%–95%; and biomass production of hydrogen with CCS, with capture rates of 91%–94%. These values are in line with the literature [44, 45]. The carbon sequestered by these technologies is then stored permanently in on-shore and off-shore geological reservoirs. GCAM models carbon storage following cost curves based on resource availability, with costs increasing as the resource availability decreases. Because biochar does not require storing the carbon captured, it does not include this carbon storage cost.

We do not model the potential biochar impacts on reducing other emissions, such as nitrous oxide and methane [27, 33, 46] as GCAM does not directly estimate non-CO_2 emissions in biomass feedstocks but instead uses marginal abatement curves based on EDGAR v4.2 [47]. Additionally, we are not directly modeling the nutrient inputs from biochar into the soil [5, 48, 49], although some are captured in the modeled increased yields.

2.3.3. Scenario design

We have designed 36 scenarios that combine four carbon price paths (Reference, Low, Medium, and High), two application rates (10 and 20 t ha^{-1}), the inclusion of yield improvements from biochar application, and the availability of BECCS. The carbon prices modeled here are intended as representative of a general economic incentive for carbon management and emissions abatement in the energy and land use systems, where carbon is priced in an economically efficient manner, rather than any specific policy implementation. Given the uncertainties for both biochar production and consumption, our goal is to identify ranges of possibilities, rather than diagnose future biochar deployment. Our analysis includes 4 scenarios without biochar, and 32 scenarios with biochar deployment varying the other parameters (4 carbon price trajectories, 2 application rates, 2 yield options, and 2 BECCS options). Table 3 lists the scenario components modeled in our study (SM2 introduces the scenario matrix).

3. Results

The results shown here focus on carbon sequestration and biochar demand, syngas , and the effects on cropland and water. These results are meant to provide insight into the potential scale and impact of biochar and how that is affected by different assumptions.

3.1. Biochar carbon sequestration

From the modeled results, global biochar carbon sequestration increases more rapidly with higher

Table 3. Scenario components.

	Variations	Abbreviation	Description
Carbon Price	No carbon price High Medium Low	REF High Med Low	Carbon prices trajectories. We are modeling four trajectories: a no carbon price ('REF'), and three carbon price pathways. The High case is consistent with a 2.6 available at: global warming potential by 2100 in GCAM v5.3. The Medium trajectory has prices that are half of the High case. The Low case has a carbon price trajectory that is half of the Medium trajectory. For more details refer to SM1 and SM2.
Application Rates	0 tons ha^{-1} 10 tons ha^{-1} 20 tons ha^{-1}	0 10 20	The application rates are assumed as either 10 ('10') or 20 ('20') tons per hectare, applied only once during the modeled years (2020–2100). There is an application rate of 0 tons per hectare for the 4 scenarios that do not have biochar.
Yield Impacts	Default GCAM increase Biochar application yield increase	DY IY	In GCAM historical yields depend on production and land allocation. Future agriculture productivity increases are assumed based on FAO's estimates ("DY"). We have increased those estimates following the explanation on section 2.3 to reflect the benefits of the biochar applied to the soil ("IY").
BECCS	BECCS Available BECCS Unavailable	BECCS noBECCS	GCAM uses BECCS in three energy transformation sectors: electricity generation, refining, and hydrogen production. We have decided to either allow BECCS ('BECCS') or not ('noBECCS') for these transformation pathways.

carbon prices (figure 1(a)). Despite the large differences in carbon prices, biochar carbon sequestration never surpasses 2.8 $GtCO_2$ yr^{-1}. In the long-term biochar sequestration is affected by GCAM's assumption of limiting the amount of funds that can be applied to net negative emissions, which represents 1% of the region's GDP as a simplified proxy for the uncertain limit on the ability of economies to pay for subsidizing carbon when total emissions are net negative (see explanation in SM7). When BECCS is available there is a higher competition for the biomass feedstock, and thus global biochar carbon sequestration peaks earlier before declining. The peak-year is reached by 2095, 2080 and 2065 in the Low, Medium, and High carbon price trajectories, respectively. Before the peak-year, biochar carbon sequestration is the largest in scenarios with an application rate of 20 t ha^{-1} and increased yields, peaking at 2.1 $GtCO_2$ yr^{-1} in the High carbon price trajectory. With BECCS unavailable there is less competition for biomass and biochar carbon sequestration continues to grow throughout the century, reaching 2.8 $GtCO_2$ yr^{-1} in the High carbon price trajectory.

Modeling yield improvements provides additional sequestration potential since increased yield is an economic incentive for biochar deployment even without a carbon price. Doubling application rates generally more than doubles sequestration when there is a carbon price due to the economic value placed on CDR in these cases.

In scenarios without BECCS, there is less competition for biomass resources and higher carbon sequestration from biochar. However, overall carbon emissions in scenarios without BECCS are higher than scenarios with BECCS, leading to higher temperature increases by 2100 (refer to SM8). When BECCS is unavailable, the increase in biochar deployment is not enough to compensate for the lack of BECCS technology.

Although biochar carbon sequestration is substantial in these scenarios, its share of total carbon sequestration is smaller than most of the other sectors. Biochar carbon sequestration never exceeds 24% of total carbon sequestration in the second half of the century, with higher carbon sequestration from biochar in scenarios where BECCS is unavailable, as opposed to those where BECCS is allowed to deploy (Figure 1(b) and SM9 for details). Global biochar demand varies by region and is higher in tropical areas where the crop yield impacts are the highest (figure 2 and SM10). The impact of scenario assumptions on global biochar demand are the same as they are for biochar carbon sequestration (see SM10 for details). In a Reference scenario with no carbon price, modeling yield improvements alone increases biochar demand by 133%–147% compared to not including these improvements. Even with these increases in biochar deployment and its impact on CO_2 emissions and climate related variables (SM8), biochar demand for biomass never surpasses 15% of the total biomass demand from year 2060 when BECCS is available (SM11).

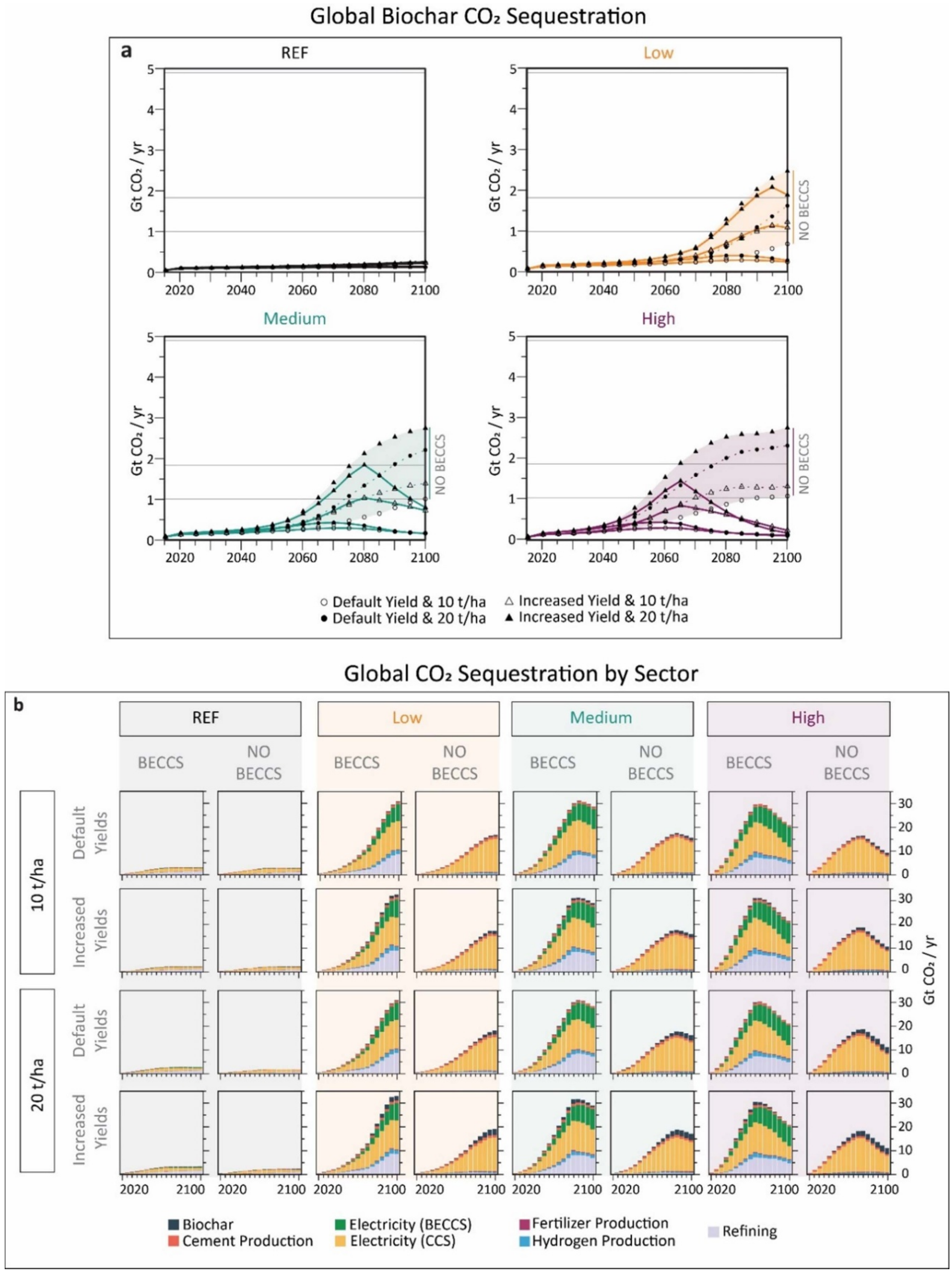

Figure 1. Global carbon sequestration from (a) biochar alone, and (b) from different sectors. The figure shows the 32 scenarios with biochar deployment, with the columns labeled REF, Low, Med, and High for carbon price paths. In (a) each facet and color represent a carbon price trajectory. Solid lines represent scenarios where BECCS is available, whereas dotted and shaded lines represent scenarios where BECCS is unavailable. Circle shapes represent scenarios with default yields and application rates of either 10 t ha^{-1} (white circle) or 20 t ha^{-1} (black circle). Increased yields are represented by triangle shapes, with 10 t ha^{-1} (white triangle) and 20 t ha^{-1} (black triangle). The grey horizontal lines on panel (a) represent the biochar carbon sequestration potentials found in the literature: Griscom *et al* [7] estimated over 1 $GtCO_2$ yr^{-1}, Woolf *et al* [20] estimated a sustainable potential of 1.8 $GtCO_2$ yr^{-1}, and Roe *et al* [8] estimated a maximum technical potential of 4.91 $GtCO_2$ yr^{-1}. In (b) each facet represents one scenario, each column represents a combination of carbon price and BECCS availability (e.g. 'REF & BECCS'), and each row represents a combination of the application rate and yield improvements (e.g. '10 t ha^{-1} & default yield'). Note that there are 32 scenarios out of 36, since the remaining 4 scenarios do not have biochar deployment.

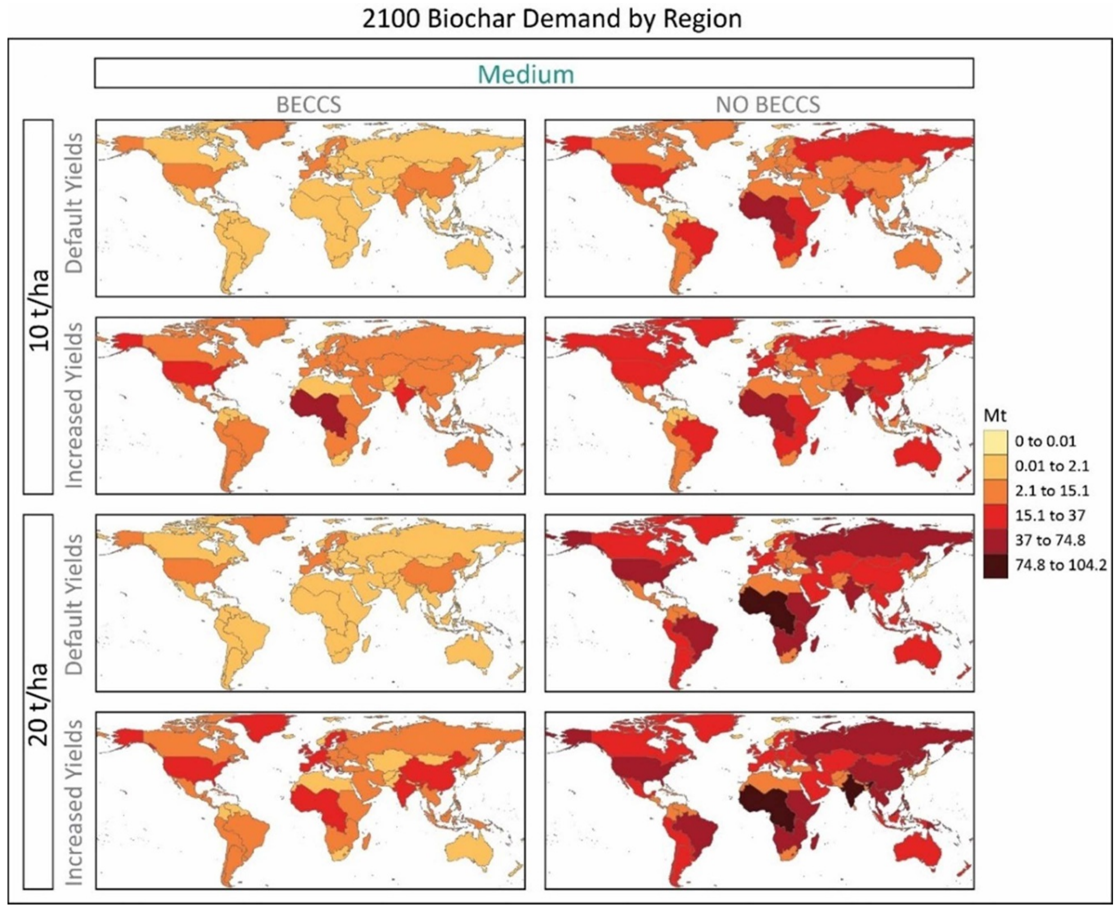

Figure 2. Regional demand for biochar by GCAM region in medium carbon price scenarios. Each map represents one scenario in 2100, with the rest of the carbon price scenarios in SM12, as well as 2050 results.

3.2. Syngas

The production of biochar yields syngas and bio-oil as co-products, though we have considered the bio-oil energy content is negligible in slow pyrolysis [9, 30]. The syngas has a low energy density, but it is biogenic and is economic as carbon-neutral energy in High carbon price scenarios where fossil natural gas is penalized. We assume that the syngas is upgraded and fed into the gas market along with other sources of gas, at which point it is a carbonaceous fuel. We model the option of using the gas with CCS in the energy system, increasing the net carbon sequestration impact of biochar when used. Globally, the syngas co-product is a small but important fraction of global natural gas production in the carbon price scenarios, reaching up to 14% of the total when BECCS are not allowed to deploy (figure 3).

3.3. Cropland in biochar application

From the GCAM results, cropland with biochar application grows in all scenarios, though scenarios with BECCS see less growth after mid-century (figure 4(a)). In the Reference scenario, biochar cropland allocation never exceeds 18%. In the High carbon price scenarios, cropland with biochar increases to almost 60% by 2100. In the scenarios without BECCS, cropland with biochar increases significantly when the carbon price is high.

Historically, most of the global cropland allocation is rainfed, and a small portion of it is irrigated. In scenarios without biochar, carbon prices give an incentive to intensify production with advanced technology. When biochar is introduced, the biochar-rainfed technology takes a larger share compared to the biochar-irrigated technology (figure 4(b)). This is a result of the assumption of relative greater yield improvements from biochar use on rainfed land than on irrigated land, which incentivizes a greater relative increase in rainfed plots than irrigated, though the absolute yields from irrigation remain higher (SM13 for cropland details, SM14 for other land impacts).

3.4. Water withdrawal reductions

Global water withdrawals grow with GDP and population in a Reference case without biochar from 3613 km^3 in 2015–4539 km^3 in 2100. All carbon price scenarios see higher global water withdrawals compared to the Reference case. Scenarios with yield improvements from biochar application have a small reduction of global water withdrawals compared to scenarios without. BECCS availability plays a different role depending on the carbon price: in

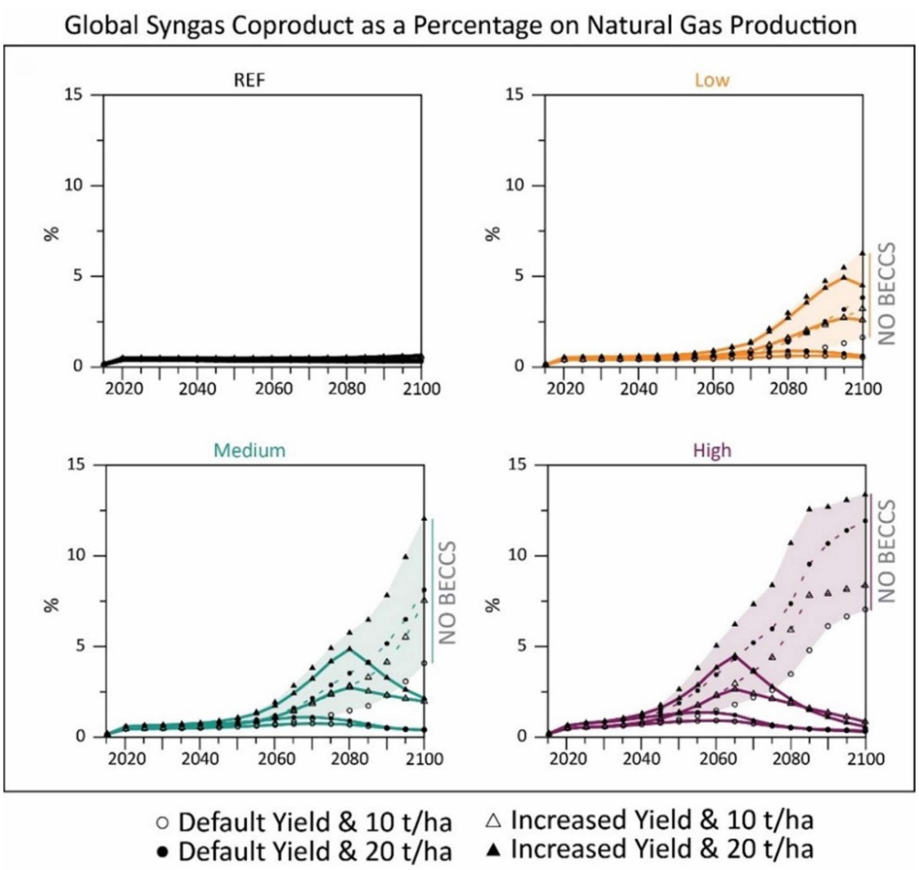

Figure 3. The percentage of syngas co-product on total natural gas production, under different carbon price paths. The figure shows the 32 scenarios with biochar deployment. Each facet and color represent a carbon price trajectory. Solid lines represent scenarios where BECCS is available, whereas dotted and shaded lines and shaded area represent scenarios where BECCS is unavailable. Circle shapes represent scenarios with default yields and application rates of either 10 t ha^{-1} (white circle) or 20 t ha^{-1} (black circle). Increased yields are represented by triangle shapes, with 10 t ha^{-1} (white triangle) and 20 t ha^{-1} (black triangle).

High and Medium carbon price trajectories, eliminating BECCS leads to lower water consumption in the medium-term, followed by an increase to 2100 compared to scenarios with BECCS. In the medium-term the elimination of BECCS reduces electricity generation demands for water; however, after the peak-year there is a higher demand for water for crops (SM16). In the Low carbon price trajectory, the water demand for crops between scenarios with and without BECCS is not as different, so the lower total water consumption is explained by the reductions in electricity water demand (figure 5(a), SM16).

Yield effects reduce water consumption for crops between 0.1% and 3% in 2100 (figure 5(b)). Although the percentage is small, global water withdrawals for crops represent almost 60% of the total in the base year (2015), so the absolute quantities are large. This is caused by two factors. First, modeling higher yields means less land allocated to cropland for the same crop production (detailed in the methods), which results in lower water consumption. Second, based on our assumptions, yield increases are relatively higher for rainfed plots than irrigated plots, though both see an absolute increase. Since there is an economic incentive to deploy biochar, and biochar brings greater yields to rainfed plots, there is a shift to rainfed.

4. Discussion and conclusion

Our results suggest that biochar can play a significant role for CDR in long-term climate change mitigation. The total global carbon sequestration from biochar reaches up to 2.8 $GtCO_2$ yr^{-1}, which is within literature estimates of feasible amounts of sequestration [7, 8, 20, 32]. While we did not explicitly consider specific sustainability limitations in our modeling, our results are based on an integrated analysis of climate, energy, land, and water.

Biochar does stand in direct competition for resources with BECCS but is more competitive at lower carbon prices, which is similar to Woolf *et al* [29] findings. Across our scenarios, we find that biochar and BECCS are complementary technologies. Capping BECCS in favor of a higher biochar deployment results in a higher global warming potential and temperature increases by 2100.

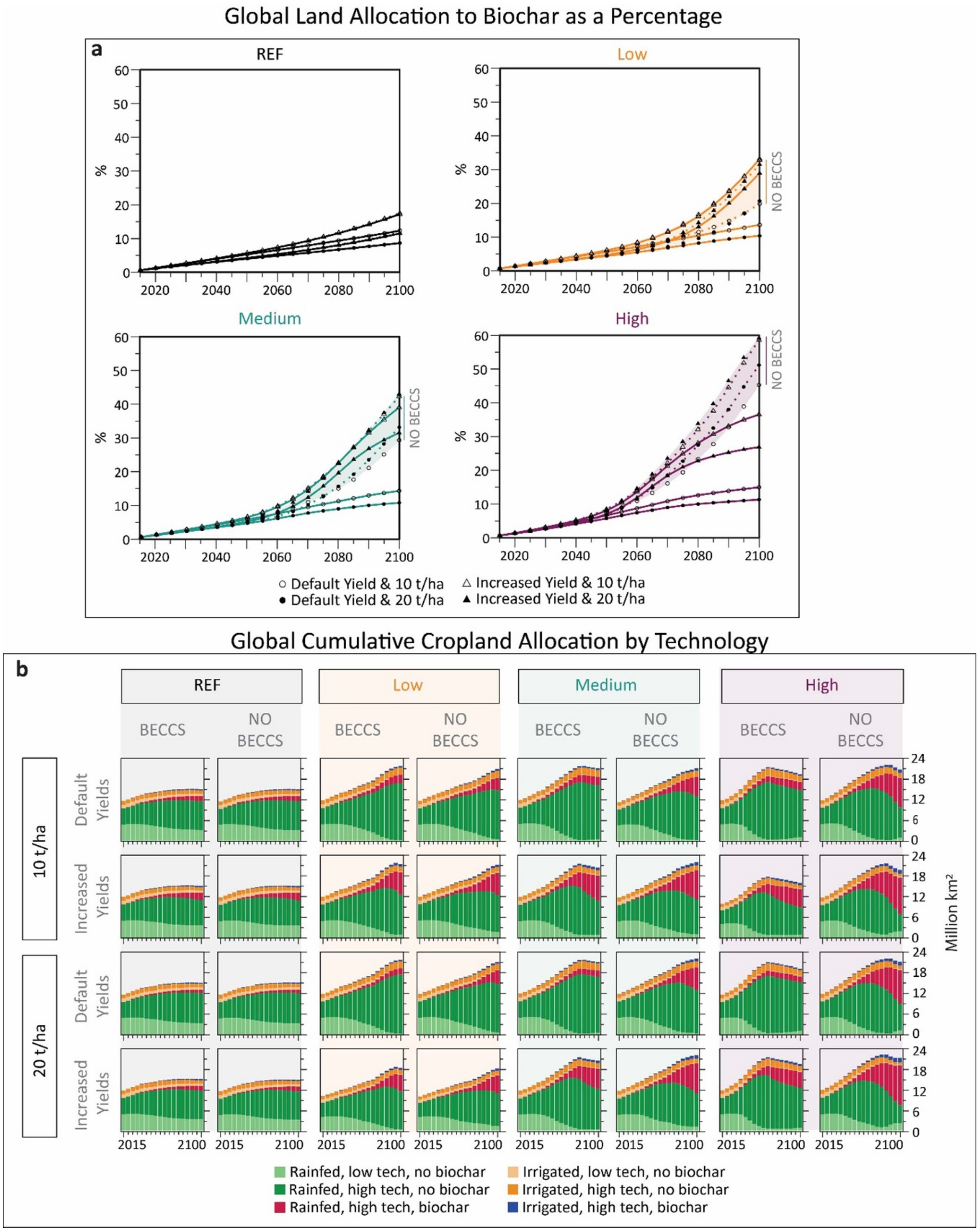

Figure 4. (a) Percentage of cumulative cropland allocation with biochar by carbon price trajectory, and (b) Global cumulative cropland allocation by irrigation method (rainfed and irrigated) and technology (Low and High) for land with and without biochar. In (a) solid lines represent scenarios where BECCS is available, whereas dotted and shaded lines and shaded area represent scenarios where BECCS is unavailable. Circle shapes represent scenarios with default yields and application rates of either 10 t ha^{-1} (white circle) or 20 t ha^{-1} (black circle). Increased yields are represented by triangle shapes, with 10 t ha^{-1} (white triangle) and 20 t ha^{-1} (black triangle). In (b) each facet represents one scenario, each column represents a combination of carbon price and BECCS availability (e.g. 'REF & BECCS'), and each row represents a combination of the application rate and yield improvements (e.g. '10 t ha^{-1} & default yield'). Note that we are modeling cumulative cropland allocation with and without biochar (SM13). The carbon sequestration of the biochar that has been applied to a plot of land is only captured in the model period when it is applied, and not carried over future model periods. Cropland allocation with biochar and carbon sequestration from biochar application are related, but different concepts.

BECCS technologies in GCAM capture over 90% of the carbon embodied in the feedstock, compared to the 56% net capture rate of biochar. Yet, BECCS requires higher carbon prices to be economically viable, and is deployed later in the century, while biochar sequesters carbon in earlier periods due to its relative lower cost and crop yield improvements. Thus, from a global climate change

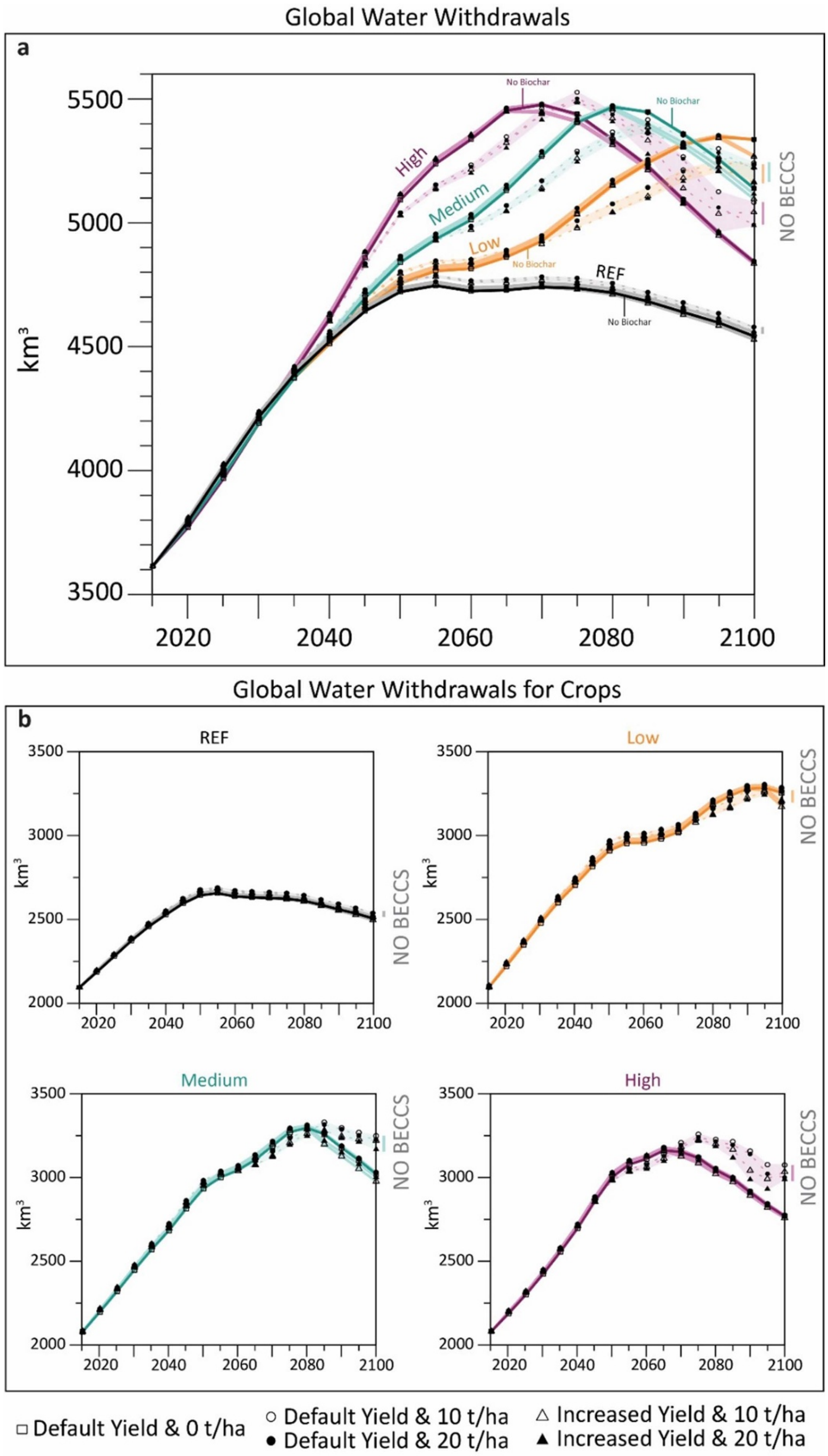

Figure 5. Total global water withdrawals (a) and global water withdrawals for crops (b). Each line represents one scenario, and each color represents one carbon price trajectory. A darker color represents a no-biochar case, and a lighter shade of the color represents scenarios with biochar. Solid lines represent scenarios where BECCS are available and dotted and shaded lines those where BECCS is unavailable. A square shape represents default yields and 0 application rates, a circle represents default yields, and a triangle represents increased yields. The white circular and triangular shapes represent application rates of 10 t ha^{-1}, whereas a black shape represents application rates of 20 t ha^{-1}. Note that scale on y-axes does not start at 0. Regional water withdrawals for crops available in SM17.

mitigation perspective, mechanisms for regional biochar deployment should be incentivized rapidly. Apart from mitigating climate change, biochar can also support food security and enhance a circular economy [50].

The assumed application rate, a parameter that varies widely in the literature is a critical component [12]. Without a payment for carbon sequestration, biochar's profitability is determined solely by crop yield improvements or reduction in inputs (i.e. water, fertilizer) [14, 32]. This is consistent with today's lower application rates seen in practice, where biochar is mixed with fertilizers and compost [48]. We find that higher application rates mean more biochar would have to be purchased per unit of land, decreasing the land profit rate, and resulting in less land using biochar than when a lower application rate is assumed. The opposite occurs when carbon drawdown is valued. Then, a higher application rate implies a higher profit rate per unit of land and the share of land in biochar is higher than with a lower carbon value. This suggests that a carbon pricing regime drives biochar deployment and facilitates the activation of co-benefits attributed to biochar in cropland systems [51]. Accounting for other ecosystem services that are provided by biochar, such as the reduction of soil contaminants and the increase of biogenic soil organic carbon, could make biochar even more valuable [41, 52, 53].

Finally, our results showed an indirect co-benefit related to water demands in crop production, which is consistent with other studies [54]. Because the biochar application was shown in the literature to have higher relative improvement on yields from rainfed crops than from irrigated, biochar had a greater relative impact on the profitability of rainfed crops. In turn, this differential impact on profitability resulted in higher future shares for rainfed crops and lower shares for irrigated crops in the biochar scenarios. Less demand for irrigation meant less demand for water, lowering its cost in places where water is constrained.

There are some limitations to our findings since there are uncertainties about the long-term global physical impacts of biochar as well as its potential demand. The application rates vary widely in the literature [12] and few studies consider recurrent applications of biochar. The long-term analyses of biochar focus on its effects within a decade [55], and our analysis goes to the end of the century. While it is known that biochar increases soil organic carbon, even after 100 years of being applied, and that it sequesters carbon in a recalcitrant form [42], there are uncertainties regarding how much biochar to apply and how often it should be re-applied. These are important assumptions that drive biochar demand and therefore its carbon sequestration. These questions could be addressed in empirical field trials, and their results could be used to recalibrate our model when data become available. Also, our study did not account for the logistical and infrastructural challenges related to a global production and application of biochar.

Despite these limitations, our study showed the relevance of biochar as a CDR strategy, particularly when carbon prices are low, and the importance of modeling biochar in an integrated framework that considers energy, land, water, and climate. Future studies should consider the trade-offs among multiple pathways of biochar production and use, considering the degree of recalcitrance or lability of the biochar produced, and the alternatives for application to soils, industrial uses, or burial for carbon sequestration. The disposition of the slow pyrolysis bio-oil and its potential for additional CDR at large scales also needs to be explored in more detail. Finally, future work should focus on adding more land-based CDR pathways into GCAM, and potentially other IAMs, to analyze climate mitigation in the full breath of CDR, particularly important given the different tradeoffs of the technologies [56]. If CDR technologies become a facilitator for a well below 2 °C target, then having a more complete understanding of their potential and linked tradeoffs becomes essential.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://github.com/CandeBergero/GCAM_V5.3_biochar.

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Author contributions statement

C B, M Wi, and M We performed the experiments. C B, M Wi, and P L designed the study.

Y W researched and compiled data. C B, M Wi, M We, and P L wrote the paper.

Conflict of interest

The authors declare no competing interests.

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