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Biochar

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Carbon dioxide removal potential of biochar with biomass supply from bioenergy crops in China

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Abstract

Biochar and bioenergy crop cultivation with carbon capture and storage (BECCS) are two major negative emission technologies for carbon dioxide removal (CDR). However, biochar production is limited by biomass supply, while BECCS depends on costly CCS infrastructure and faces storage constraints. Here, a novel combination of biochar with biomass supply from dedicated bioenergy crops (BCBE) is proposed to overcome their respective limitations. Through retrofitting current biomass power plants in China with pyrolysis systems or CCS, biomass power plants are assumed to use either residues from agriculture and forestry or from dedicated bioenergy crops on abandoned croplands to meet their capacity for biochar production. Based on these plants, the CDR potential and the economic cost of BCBE are first investigated by considering different components in the life cycle of biochar, and are compared with an alternative scenario using bioenergy crops supply for BECCS. Locations for building new pyrolysis plants are then identified and the achievable CDR under biomass utilization scenarios is estimated. With 73% agricultural and half forestry residues or 84% bioenergy crops supplied to plants, the CDR potential of BCBE is 25.8 Tg CO_2 $year^{-1}$ (95% CI: 23.6–32.4 Tg CO_2 $year^{-1}$), comparable to that of biochar derived from agricultural and forestry residues (29.8 Tg CO_2 $year^{-1}$, 95% CI: 28.2–36.8 Tg CO_2 $year^{-1}$). Despite the lower CDR potential of BCBE compared with BECCS, the cost of BCBE (\$9.6 t^{-1} CO_2) is much lower than that of BECCS (\$90.9 t^{-1} CO_2). With newly built pyrolysis plants supplied with bioenergy crops and agricultural and forestry residues, the maximum CDR of all biochar sources can reach 1880.4 Tg CO_2 $year^{-1}$. Thus, deploying biochar on a large scale with additional biomass supply from bioenergy crops is expected to contribute substantially to achieving China's carbon neutrality goal. However, critical uncertainties remain regarding plant retrofit feasibility, technology integration, and the biomass supply chain.

Highlights

- Biochar from energy crops has a similar CDR potential to agricultural and forestry residue-derived biochar.
- Biochar is a more cost-effective CDR option than BECCS, making it more viable in practice.
- Large-scale biochar deployment could play a key role in China's path to carbon neutrality.

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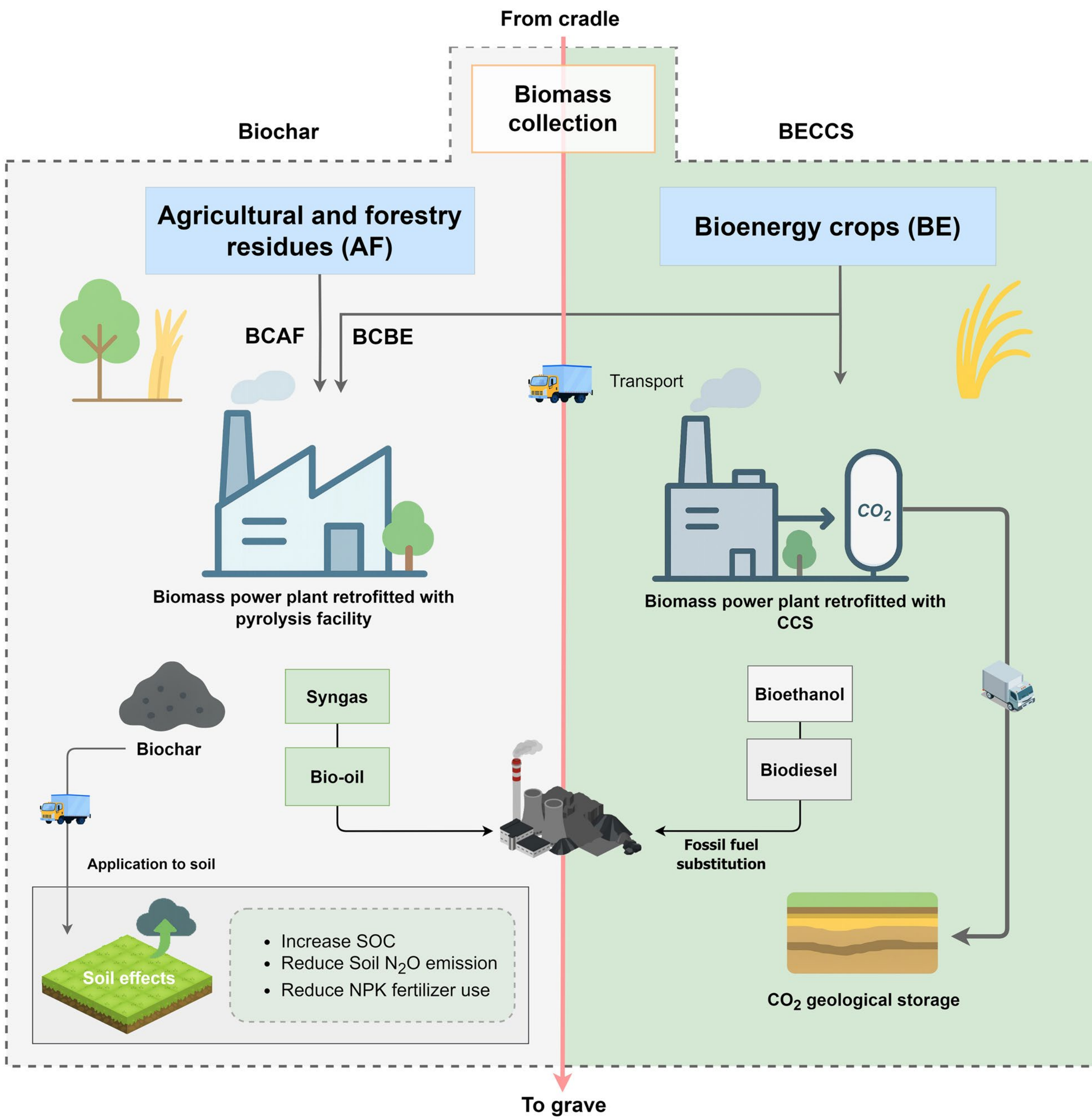
Keywords Biochar, Bioenergy crop, BECCS, Carbon dioxide removal, Life cycle analysis

Graphical Abstract



1 Introduction

Global scenarios for limiting global temperature rise to below 1.5 or 2 °C rely heavily on carbon dioxide removal (CDR) technologies (Rogelj et al. 2018). One promising CDR technology is biochar, a carbon-rich product of biomass pyrolysis under oxygen-limited conditions (Lehmann 2007), which has been widely used as a soil amendment to improve soil quality and crop yields (Wu et al. 2019). Its strong resistance to decomposition allows for long-term carbon sequestration, lasting decades to centuries depending on pyrolysis temperature and soil properties (Fang et al. 2014; Wang et al. 2016). The pyrolysis process also produces bio-oil and syngas, which can replace fossil fuels in power generation, thereby avoiding CO_2 emissions (Yang et al. 2021). Biochar is primarily sourced from agricultural and forestry residues (Karan et al. 2023; Li et al. 2024), and feedstock availability may constrain its CDR potential. In China, the CDR potential of biochar has generally been estimated from scenarios which make various assumptions about the amount of biomass available for biochar production (Deng et al. 2024; Lu et al. 2022; Yang et al. 2021; Zheng et al. 2023), but which neglect the spatial distribution of pyrolysis plants and the actual biomass supply chain for biochar production and application at the plant level. The CDR potential of biochar in China has been estimated to range from 518.2 Tg CO_2 year^{-1} (assuming 73% of agricultural residues are transformed to biochar, Zheng et al. 2023) to 990 Tg CO_2 year^{-1} (100%, Deng et al. 2024). Most biomass residues in China are already used—as fertilizer (43.2%), animal feed (18.8%), fuel (11.4%), base material (4.0%), and raw material (2.7%) (Huo et al. 2019)—leaving only a limited biomass supply for biochar production. The fraction of agricultural and forestry residues actually available for biochar production may be less than 1% (Lu et al. 2022; Xia et al. 2023), suggesting that large-scale biochar deployment could increase competition for biomass residues and land.

Dedicated bioenergy crops such as miscanthus, switchgrass, poplar and eucalypt can be cultivated on land unsuited for food production including abandoned croplands (Robertson et al. 2017). They demand less intensive management and often require lower fertilizer inputs than food crops (Cadoux et al. 2012; Miguez et al. 2008; Yang et al. 2018). As a result, bioenergy crop cultivation on abandoned croplands is a viable option for reducing the competition for agricultural or forestry land. Bioenergy crop cultivation with carbon capture and storage (BECCS) is another major CDR technology which has been widely adopted in various climate mitigation scenarios (Fuss et al. 2018; Rogelj et al. 2018). BECCS achieves negative CO_2 emissions by converting bioenergy crops into energy, with the emitted CO_2 captured and stored underground permanently (Rosen 2018). However, BECCS has not yet been fully developed and still faces significant challenges, including high CCS costs, the risk of CO_2 leakage and other environmental concerns (Fajardy and Mac Dowell 2017). These factors may hinder its large-scale deployment in the near future. To overcome the limitations of both technologies—namely, the limited biomass supply for biochar and the high costs and leakage risks associated with BECCS—this study proposes the novel and promising alternative approach: using bioenergy crops as feedstock for biochar and energy (i.e., bio-oil and syngas) production.

The CDR potential and economic viability of biochar deployment have been widely estimated from regional to global scales (Deng et al. 2024; Han et al. 2022; Wang et al. 2024). Agricultural and forestry residues are currently the most common feedstock for biochar production. For example, a global life cycle analysis of biochar from available agricultural residues was conducted based on the locations of 144 commercial biochar companies, resulting in a carbon removal potential of 6.6 Tg CO_2 year^{-1} with a revenue of \$177 million at a carbon price of \$50 t^{-1} CO_2 (Han et al. 2022). Bioenergy crops cultivated on marginal lands offer an additional biomass source that can enhance the climate mitigation potential of biochar. A recent study assessed the spatial CDR potential of biochar in China by focusing on the comprehensive biomass supply from agricultural, forestry, grass residues, and bioenergy crops, ranging from 0.92 to 1.29 $GtCO_2$ year^{-1}, with bioenergy crops contributing 35.4–38.2% (Deng et al. 2024). At the global scale, 2.0–13.8 M ha of land has been identified as suitable for dedicated bioenergy crops, and the resulting life cycle CDR potential has been estimated at 11–257 Tg CO_2 year^{-1} based on a grid-level analysis (Løvenskiold et al. 2022). Comparisons of different CDR technologies have further examined trade-offs in CDR potential, economic viability and environmental effects to guide co-deploying strategies across regions, including biochar and BECCS (Løvenskiold et al. 2022; Deng et al. 2025; Yang et al. 2021). However, most existing studies overlooked the biomass supply–demand chain at the plant level, particularly the role of explicit road networks, leading to biases in mitigation potential and cost estimation. For example, a plant is usually assumed to be located at the center of a grid cell with a fixed biomass collection radius in many large-scale spatial analyses (Deng et al. 2024; Løvenskiold et al. 2022; Gautam et al. 2023). This simplification partly reflects the current lack of pyrolysis plants, which are constrained by limited feedstock availability, insufficient policy incentives for costly plant construction, low public acceptance, and uncertainties regarding integration with the existing agricultural system, energy infrastructure, environment safety, and policy. Therefore, it is urgent to incorporate potential pyrolysis plant locations, actual biomass supply routes, and the use of bioenergy crops as additional feedstocks into the life cycle analysis of biochar. This approach, combined with explicit evaluation of trade-offs among biomass sources and technological pathways, will enable more realistic estimates of the CDR potential and cost-effectiveness for future deployment of biochar.

This study first quantifies the CDR potential of biochar with biomass supply from dedicated bioenergy crops (termed BCBE) based on the existing 426 biomass power plants in China. Biomass supply routes for each plant are determined by explicitly considering road networks and plant capacity (Methods). The cost and benefit of BCBE are then estimated using life cycle analysis to calculate a critical carbon price threshold beyond which the plants become profitable (Methods). By assuming different levels of biomass availability to supply biomass power plants (Table S1), the CDR potential and cost of BCBE are evaluated and compared with those of biochar derived from agricultural and forestry residues (BCAF), biochar from both bioenergy crops and agricultural-forestry residues (BCBEAF), and BECCS (Fig. S1). Finally, this study identifies the optimal locations for building new pyrolysis plants and explores the potential for biochar CDR of newly built plants in China.

2 Materials and methods

2.1 Biomass feedstock

High-resolution (1 km × 1 km) biomass maps for agricultural and forestry residues (AF), and bioenergy crops cultivated on abandoned cropland (BE) in China were used (Wang et al. 2023). In this dataset, agricultural and forestry residues were derived from provincial statistics and allocated to cropland and forest grid cells based on the land use map and net primary productivity (NPP) (Wang et al. 2023). The agricultural residues included those from rice, maize, wheat, other grains, cotton, canola, peanuts, soybeans, and potatoes. The forestry residues include wastes from wood exploitation and processing, leaves and branches from bamboo harvesting, and residues from forest logging. These forestry residues are currently used in raw materials, papermaking, agricultural use, and energy production (Xia et al. 2023). Bioenergy crop yields used in this study were obtained from Li et al. (2020), who consider five types: miscanthus, switchgrass, willow, poplar, and eucalyptus. The yield map of bioenergy crops was based on a global yield dataset of 3963 field observations combined with climatic and soil variables, and was upscaled using a random forest algorithm (Li et al. 2020). This map reflects the potential yield distribution of bioenergy crops under varying climatic and edaphic conditions. The bioenergy yields were then overlapped on abandoned cropland to avoid competition with cropland (Wang et al. 2023). For each grid cell, the bioenergy crop with the highest yield among the five types was selected to be analyzed in this study (Fig. 1a). The biomass maps were validated against existing studies at both provincial and national levels. A detailed description of the biomass data production process and source is provided by Wang et al. (2023).

2.2 Biomass power plants

Using data from the Global Energy Monitor, 426 biomass power plants currently operating in China were identified (https://globalenergymonitor.org/) (about 23.7% are waste incineration power plants). The dataset provides information on each plant's location, installed capacity, and operating status. These plants have installed capacities ranging from 15 to 165 MW, with an average capacity

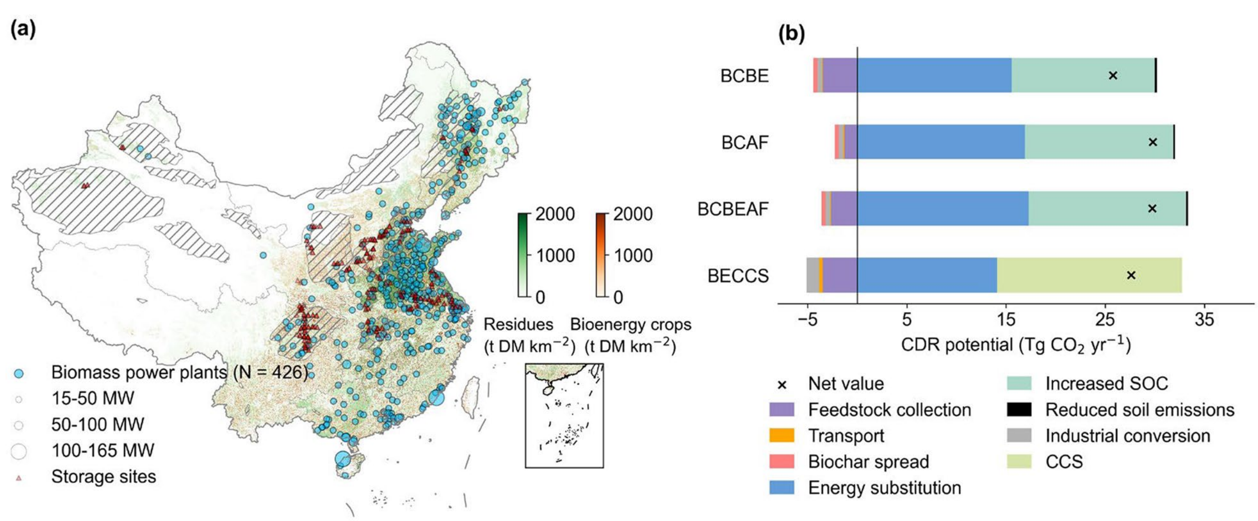


Fig. 1 Spatial distribution of biomass yields, biomass power plants and storage sites, and CDR potential of biochar in China. In **a** the size of the blue circles represents the installed capacity of existing biomass power plants, red triangles are CO_2 storage sites (Fan et al. 2023), and the shaded areas denote onshore sedimentary basins that can be used for carbon storage. **b** CDR potentials of biochar produced from bioenergy crops (BCBE), agricultural and forestry residues (BCAF), a combination of both these two biomass types (BCBEAF), and bioenergy crop cultivation with carbon capture and storage (BECCS) in China

of 35.36 MW. Most biomass power plants are concentrated in eastern China, while relatively few in central and western regions (Fig. 1a). This distribution reflects the strategy of siting plants close to biomass resources to minimize transport costs. Eastern regions such as Henan, Shandong, and Heilongjiang province have abundant agricultural residues (Fig. S2) (Guo et al. 2022; Liu et al. 2014), and also benefit from well-developed transportation networks, whereas central and western regions are less accessible.

The number of pyrolysis plants in China is currently limited. Biomass power plants have comparable capacities to pyrolysis plants for biomass preprocessing and are typically located in areas rich in biomass resources. Their existing supply chains can support the operation of pyrolysis facilities, reducing redundant investments in biomass pretreatment infrastructure and facilitating energy substitution in power plants. Therefore, it is assumed that the biomass power plants can be retrofitted with pyrolysis facilities for biochar production. In practice, such retrofits face challenges due to technology differences, the high cost of pyrolysis equipment, and insufficient policy support for biochar production and its application in soil for carbon sequestration (Yang et al. 2021).

For BECCS, it is assumed that biomass power plants can be retrofitted with the CCS system. Retrofitting CCS technology may also face challenges, such as high construction and operational costs, technology limitations, and the need for robust policy support to enable the large-scale cultivation of bioenergy crops (Wang et al. 2022). However, the retrofitting with pyrolysis facilities or CCS systems does not alter the biomass processing capacity, consistent with the actual capacity of existing biomass power plants (Fig. 1a).

2.3 Supply of biomass feedstocks to biomass power plants

The installed capacity of each plant was converted into a feedstock processing capacity based on the assumptions on biomass calorific value and the plant's operating hours (Table S3). To ensure sufficient feedstock to meet plant capacity, 24% of agricultural residues were designated as poultry feed, and 3% for industrial raw materials following Yang et al. (2010). The remaining portion (73%) was allocated to biochar production, compared to the current small fraction of less than 1% (Lu et al. 2022). The assumption is reasonable because residues currently used in biomass power plants could be partially reallocated or shared through retrofitting for co-production of energy and biochar. In addition, residues presently returned directly to fields could be partially substituted with biochar application, thereby maintaining soil fertility and enhancing soil organic carbon (SOC) stability. It should be noted that pyrolysis leads to nitrogen (N) loss and may alter the soil C:N balance upon biochar addition (de Oliveira Paiva et al. 2024), which differs from the effects of returning raw residues. However, this study focuses on the technical potential of biochar under current plant capacities without explicitly considering the nutrient balance, which is consistent with assumptions widely adopted in previous studies (Deng et al. 2024; Yang et al. 2021). Thus, the 73% allocation represents a plausible reprioritization pathway under future industrial integration and policy incentives.

For forestry residues, half of the total biomass was allocated to biochar production; the rest was used to satisfy the amount of forestry residue retained in ecosystems, recommended to be 20 t ha^{-1} (about 25% of aboveground biomass residues) to sustain the soil nutrients cycle and maintain soil organic carbon (Gregg and Smith 2010). The whole area of each marginal land grid cell (1 km^2) was assumed to be available for bioenergy crop cultivation, and the bioenergy crop yield (t Dry matter (DM) km^{-2}) was assumed to be fully available for biochar production, with an estimated collection coefficient of 84% (Yang et al. 2010).

Biomass collection started from the nearest biomass grid cell (bioenergy crops or agricultural and forestry residues), expanding outwards until the plant's biomass processing capacity was met (i.e., collected total biomass $\leq$ plant capacity). If plants were close to one another and competed for biomass in the same locations, the biomass was directed to the nearest plant. The distance between plants and biomass sites was calculated using the road network (https://www.naturalearthdata.com/) and the locations of biomass supply sites and plants. The detailed transport calculations are described in Supplementary Text 1.

With the constraints of plant capacity and road accessibility, this study determines biomass supply routes and supply quantities for each plant from either dedicated bioenergy crops or agricultural and forestry residues. By incorporating road transportation accessibility at the biomass power plant level, the spatially explicit analysis offers a more realistic estimation of CDR potential and economic cost across the entire chain from biomass supply to biochar application.

2.4 Life cycle analysis

2.4.1 Goal and scope

Based on the assumed biomass availability for power plants in each grid cell (Table S1), life cycle analysis was used to estimate the net CDR and cost–benefit of biochar with biomass supply from bioenergy crops (BCBE), biochar from agricultural and forestry residues (BCAF), and bioenergy crop cultivation with carbon capture and storage (BECCS). The supplied biomass was collected and transported to the respective retrofitted plants for industrial conversion, followed by either biochar application in fields for BCBE, BCAF, and BCBEAF or carbon capture and storage for BECCS. The net values from the life cycles of BCBE, BCAF, BCBEAF, and BECCS (Fig. S1) were summed separately across all plants to evaluate the total CDR potential and economic costs in China.

The life cycle analysis was conducted in accordance with the methodological framework of ISO 14040 (ISO 2006). A cradle-to-grave approach was applied based on inventory data from the literature and a functional unit of 1 tonne of dry biomass. It primarily relied on available biomass maps and inventory data. The system boundary (Fig. S1), key assumptions, and data sources (Table S2-S3) are described in the following sections and in the supplementary information (Supplementary Text 2 and 3).

2.4.2 CDR potential

Briefly, the boundary for the life cycle of biochar included carbon removal from SOC increase following biochar addition, carbon emissions from feedstock collection and transport, pyrolysis processes, and biochar application, as well as carbon emissions avoided by replacing fossil fuels with syngas and bio-oil, and reducing soil greenhouse emissions with biochar addition (Fig. S1). Biochar application not only increases SOC through the input of stable carbon in biochar but also alters native SOC (Han et al. 2022; Zimmerman et al. 2011). The total SOC changes with biochar addition were predicted using a random-forest model trained with climate, soil, biotic, management, and biochar-related variables (Supplementary Text 4, Table S4). A biochar addition rate of 20 t ha^{-1} was used in the life cycle analysis, which is a typical rate reported in numerous field experiments and life cycle analyses (Deng et al. 2024; Roberts et al. 2010). In addition to SOC changes, the life cycle analysis also accounted for the inhibition of soil nitrous oxide (N_2O) emissions and the avoided emissions resulting from reduced chemical fertilizer use (Fig. S1). The transport distances included the distance from the biomass collection site to the biomass power plant and from the plant to the biochar application fields. This study assumed that biochar produced from bioenergy crops and agricultural residues was returned to the cropland where the feedstock originated, while biochar from forestry residues was transported and randomly applied to croplands near plants by diesel truck (Supplementary Text 2). The life cycle of BECCS differed from biochar in the biomass refining process and CCS (Supplementary Text 3). The key transport difference lay in the CO_2 transport distance from the plant to the storage site. The CO_2 storage sites were identified in saline aquifer basins and oilfields (Fig. 1a), and the CO_2 storage capacity was assumed sufficient to hold all CO_2 captured from existing biomass power plants in China (Fan et al. 2021). Transport of CO_2 to the storage sites was assumed via a road tanker. The related distance calculation can be found in Supplementary Text 1. The emission factors on detailed processes (i.e., feedstock collection, transportation) in the life cycle of biochar or BECCS are summarized in Table S3.

2.4.3 Cost–benefit analysis

The life cycle costs of biochar included feedstock collection costs, transportation costs for both feedstock and biochar, plant operating and capital costs, and biochar application costs. Benefits came from energy income, increased phosphorus (P) and potassium (K) nutrients, reduced fertilizer use costs due to improved fertilizer use efficiency with biochar addition, and carbon income from the carbon trading market at a given carbon price (Supplementary Text 2). For BECCS, the costs encompassed feedstock collection, transportation of feedstock and CO_2, plant operating and capital costs without CCS, and additional CCS costs including retrofitting. The benefits were primarily from energy income and carbon income (Supplementary Text 3). The carbon income from carbon market was derived from the life cycle net CDR potential combined with a carbon price. Due to limited data on plant lifetime and costs, a 20-year plant lifetime and a 5% discount rate were assumed. This is a relatively conservative estimate compared with most coal-fired or renewable energy power generation equipment (20–40 years, Yuan et al. 2021), and it is commonly adopted in previous life cycle analyses of biochar (Deng et al. 2024; Roberts et al. 2010). The current biomass power plants were assumed to be fully retrofitted with pyrolysis facilities or CCS systems. The retrofit cost for pyrolysis was included in the operating and capital cost of the assumed pyrolysis plants and depends on the amount of processed biomass (Roberts et al. 2010) (Supplementary Text 2). CCS costs, including retrofitting costs such as technology investment and equipment installation, were based on data from the Annual Report on Carbon Capture, Utilization, and Storage (CCUS) in China (Supplementary Text 3). Other life cycle components and relevant parameters are detailed in Table S2-S3.

The carbon income refers to the revenue from carbon trading in the carbon market at a given carbon price. This study first compared the costs and benefits of BCBE, BCAF, BCBEAF, and BECCS without accounting for the carbon income in their cost–benefit analyses. It then calculated the net benefit in the life cycle of BCBE, BCAF, BCBEAF, and BECCS while considering carbon income from the carbon trading market at varying carbon prices, and identifies the critical carbon price threshold beyond which the plant becomes profitable (i.e., net benefit > 0).

The carbon price threshold is the carbon value required to achieve breakeven, and thus a higher carbon price threshold represents a higher cost for carbon removal. Specially, the net benefits under the current carbon price of \$12.6 t^{-1} CO_2 in China (accessed on 20 December 2024, https://www.cneeex.com/) and \$76.5 t^{-1} CO_2 in European (https://finance.sina.com.cn/futures/quotes/EUA.shtml) were analyzed to provide a more realistic perspective on the potential role of carbon credit revenues in supporting biochar deployment. For the regional analysis of CDR potential and cost, China was divided into seven regions (Fig. S2).

2.4.4 Uncertainty analysis

Considering the complexity of biomass collection and transportation, diverse feedstock types, variable pyrolysis technologies, and soil responses to biochar addition, Monte Carlo simulations were used to estimate the uncertainty range of CDR potentials of BCBE, BCAF, and BCBEAF. Random values were generated from assumed normal distributions (Table S5), and after 1000 iterations, the 95% confidence intervals (95% CI) were calculated as the uncertainty range. In addition, sensitivity analysis was performed by perturbing one parameter (including the biomass availability, biochar/syngas yield, biochar addition rate, transport distance, soil N_2O inhibition rate, and emission factors of biomass collecting and transport) at a time while keeping all others constant. Four perturbation levels of − 50%, − 25%, 25%, and 50% were applied.

2.5 Building biomass pyrolysis plants

Constrained by the capacity and number of existing biomass power plants in China, a considerable amount of biomass from bioenergy crops cultivated on abandoned cropland and agricultural and forestry residues around plants remains unutilized, particularly in biomass-rich regions such as Henan and Shandong provinces (Fig. 4, Fig. S2). Previous studies show that the maximum feedstock transport distance for power plants is generally less than 100 km (Sammarchi et al. 2024; Zhang et al. 2023), with a few extending up to 200 km (Nivala et al. 2016). The 100 km is the maximum biomass collection distance for most co-firing power plants, as exceeding this distance could make the biomass supply cost higher than that of coal (Goerndt et al. 2013; Sammarchi et al. 2024; Zhang et al. 2023). Thus, in order to explore the potential maximum CDR of biochar implementation with current biomass power plants in China, it was assumed that plant capacity would be enlarged and the biomass collection radius would expand to 100 km for existing plants (Fig. S3).

After expanding the collection radius, substantial amounts of bioenergy crops cultivated on abandoned cropland (BE) and residues from agriculture and forestry (AF) remain uncollected in regions, such as the Southwest, that have few or no plants (Fig. 4a, Fig. S2). Therefore, building new pyrolysis plants in these regions needs to be prioritized. This study first mapped the net benefits for biochar by assuming one pyrolysis plant with a 100 km collection radius would be built in each grid cell (10 km × 10 km, Supplementary Text 1) of the remaining biomass, including BE and AF. The carbon income was included in the life cycle of biochar by assuming a realistic carbon price of \$20 t^{-1} CO_2. Locations profitable for building plants (i.e., with a positive net benefit) were then identified. New plants were assumed to be built sequentially from sites with the highest net benefit until a target of 50%, 80%, and 100% of the remaining biomass was used for biochar production. Two collection radii of 100 and 200 km for newly built plants were assumed, and the capacity of each newly built plant was defined as the total biomass collected within the specified radius. The cost of building new plants depended on their respective capacity (Supplementary Text 2). To ensure each plant was located in an area with uncollected biomass, previously collected biomass sites were excluded as potential plant locations. Finally, this study evaluated the CDR potential of biochar from the additional newly built plants in China.

3 Results

3.1 CDR potential of biochar

Assuming that existing biomass power plants could be retrofitted with pyrolysis facilities for biochar production (Methods), a total of 22.1 Tg DM $year^{-1}$ biomass was needed to meet the total capacity of the existing plants. If the capacity of these retrofitted plants was met with only agricultural and forestry residues, the biomass collection distance for these plants was $22.2^{+10.8}_{-5.6}$ km (median distance and interquartile range). If bioenergy crops were exclusively used as the biomass supply for biochar production, then 1.7 M ha of dedicated bioenergy crop cultivation was required, which corresponded to 3.1% of the current abandoned cropland (54.7 M ha, Fig. S4) in China. When using both bioenergy crops and agricultural and forestry residues, bioenergy crops contributed over half (52.6%, 0.9 M ha) of the current total biomass supply in China (Fig. S5). The contribution differences in different regions depended on the biomass amount around plants in a maximum capacity-constrained radius (Fig. 1a). The largest contribution of bioenergy crops, 63.8%, occurred in the South region, followed by the Southwest, 63.0%, and the East, 62.4% (Fig. S2, S5). In contrast, the contribution of bioenergy crops in the Northeast region was low (22.9%, Fig. S5).

Constrained by biomass-processing plant capacity, biochar produced from dedicated bioenergy crops (BCBE), traditional agricultural and forestry residues (BCAF), and a combination of these two feedstock types (BCBEAF) can delivered a net CDR potential of 25.8, 29.8, and 29.8 Tg CO_2 year^{-1}, respectively, in China (Fig. 1b). The CDR potential of BCBE was comparable to that of BCAF (Fig. 1b) and thus bioenergy crops can be substituted for agricultural-forestry residues, allowing them to be utilized in other ways. The CDR of BCBE was approximately 6.8 times that of the forest carbon sink (Fang et al. 2018) (3.8 Tg CO_2 year^{-1}) which could be achieved if the abandoned cropland area used for bioenergy crops in BCBE was instead converted into forest. This result underscores the critical importance of properly utilizing abandoned cropland to maximize CDR contributions to the goal of achieving China's carbon neutrality by 2060.

This study also compared the CDR of biochar applications with that of BECCS. In the BECCS scenario, it was assumed that biomass power plants could be retrofitted with CCS systems (Methods) and that the biomass supply was exclusively from dedicated bioenergy crops, consistent with the biomass supply used for BCBE. The CDR of BECCS (27.6 Tg CO_2 year^{-1}) was higher than that of BCBE, but lower than that of BCAF and BCBEAF (Fig. 1b).

The CDR of BCBE came primarily from replacing fossil fuels with energy produced by pyrolysis and increased SOC due to biochar addition. However, the total CDR from energy substitution and SOC increase for BCBE was lower than the total amount of energy substitution and CCS for BECCS, resulting in a lower net CDR for BCBE than for BECCS (Fig. 1b). The life cycle emissions from BCBE reached 4.4 Tg CO_2 year^{-1}, 81.4% of which came from the energy consumption associated with various aspects of feedstock collection, such as fertilization and harvesting (Fig. 1b).

3.2 Costs and benefits of biochar

After excluding carbon income, which depends on the carbon price, from the cost–benefit analysis, the net costs of BCBE, BCAF, and BCBEAF in China were \$9.6, \$12.4, and \$10.7 t^{-1} CO_2, respectively, all lower than the \$90.9 t^{-1} CO_2 of BECCS (Fig. 2a). The greater cost of BECCS was largely attributed to the high costs of biomass and CO_2 transport, and of CO_2 capture and storage, which accounted for 32.0% and 22.3% of the total cost of BECCS, respectively (Fig. 2a). The primary costs of BCBE were from feedstock collection, plant operation and capital investment (Fig. 2a). The main benefit of BCBE was energy income; however, without income from the carbon market, the total income was insufficient to offset the total cost, highlighting the necessity of carbon trading to enable the future cost-effective deployment of biochar.

When carbon income was included in the cost–benefit analysis, the net benefit increased with increasing carbon

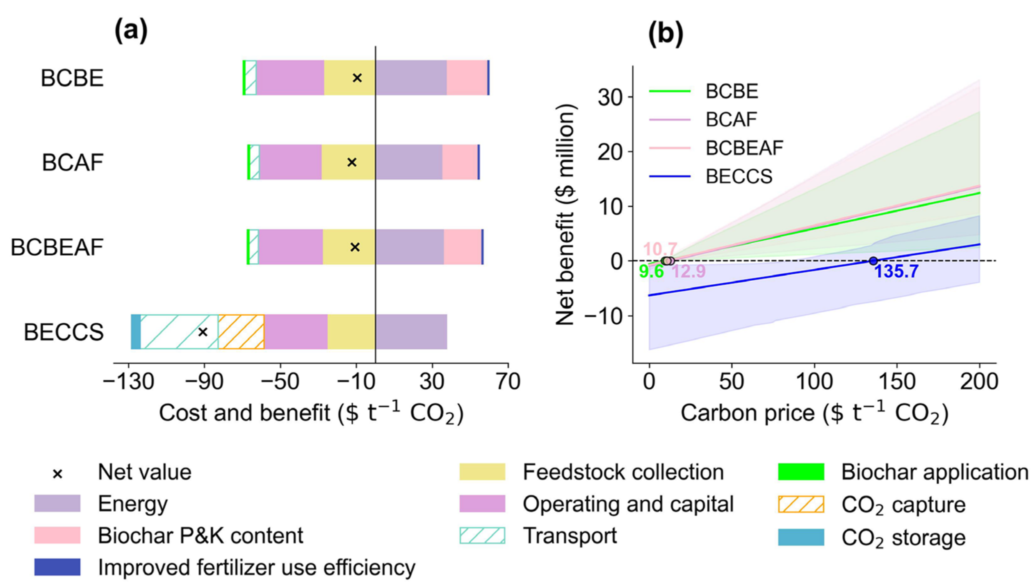


Fig. 2 Costs and benefits of biochar implementation in China. **a** The cost and benefit components of BCBE, BCAF, BCBEAF, and BECCS in China without considering carbon income from the carbon trading market. The average net benefit of existing biomass power plants in China for BCBE, BCAF, BCBEAF, and BECCS at varying carbon prices is shown in (**b**). The shaded areas in **b** represent the 95% confidence intervals of the net benefits from these plants, derived from the 2.5th and 97.5th percentiles of the distribution across all plants. The dots indicate the critical carbon price threshold, above which the net benefit of biochar shifts from negative to positive at the national level

prices (Fig. 2b). BCBE and BCAF were profitable at current carbon price in China (Fig. S6a). This study defines a critical carbon price threshold, beyond which the net benefit of biochar shifts from negative to positive at the national level (i.e., the intersection of the trend lines with the zero benefit line, Fig. 2b). A higher cost of carbon removal thus requires a higher carbon price threshold to balance the cost. Among the CDR technologies, BCBE had the lowest carbon price threshold at \$9.6 t^{-1} CO_2, followed by BCBEAF (\$10.7), BCAF (\$12.9), and BECCS (\$135.7)(Fig. 2b), highlighting the potential of BCBE to generate profits.

3.3 Spatial patterns of CDR potentials and costs

At the regional scale, the largest CDR potentials of BCBE were found in the East (9.5 Tg CO_2 $year^{-1}$), Northeast (4.8 Tg CO_2 $year^{-1}$), and Central regions (4.2 Tg CO_2 $year^{-1}$), while the CDR potential in the Northwest region was the lowest (0.7 Tg CO_2 $year^{-1}$) (Fig. 3, Fig. S2). This pattern was mainly due to the larger number and greater capacity of biomass power plants in the East, Northeast, and Central regions (Fig. S7), associated with the availability of an abundant biomass supply and available land there (Fig. S8b,c).

Although the net CDR potential of BCBE was generally lower than that of BECCS across the seven regions, BCBE had a consistently lower cost than BECCS (Fig. S9). The carbon price threshold also served as an indicator of cost and closely aligned with the cost ranking across the seven regions (Fig. 3, Fig. S9). The lowest (\$9.0 t^{-1} CO_2) and highest (\$11.6 t^{-1} CO_2) carbon price thresholds for BCBE were in the Northeast and Northwest regions, respectively. Regions with the lowest and highest carbon price thresholds for BCAF and BCBEAF were consistent with those for BCBE. In contrast, the lowest carbon price thresholds for BECCS were found in the North (\$106.9 t^{-1} CO_2) and Central regions (\$109.5 t^{-1} CO_2), with the highest threshold occurring in the Southern region (\$199.9 t^{-1} CO_2) due to high transport costs (Fig. 3; Fig. S9).

The carbon price thresholds for BCBE and BCBEAF in each region were lower than the current carbon price in the carbon market of China (\$12.6 t^{-1} CO_2). In contrast, the thresholds for BCAF were higher than the current Chinese carbon price but lower than the European carbon price of \$76.5 t^{-1} CO_2 in all regions except the Northeast. Therefore, biochar is profitable under the current carbon price in most regions, depending on the biomass type collected.

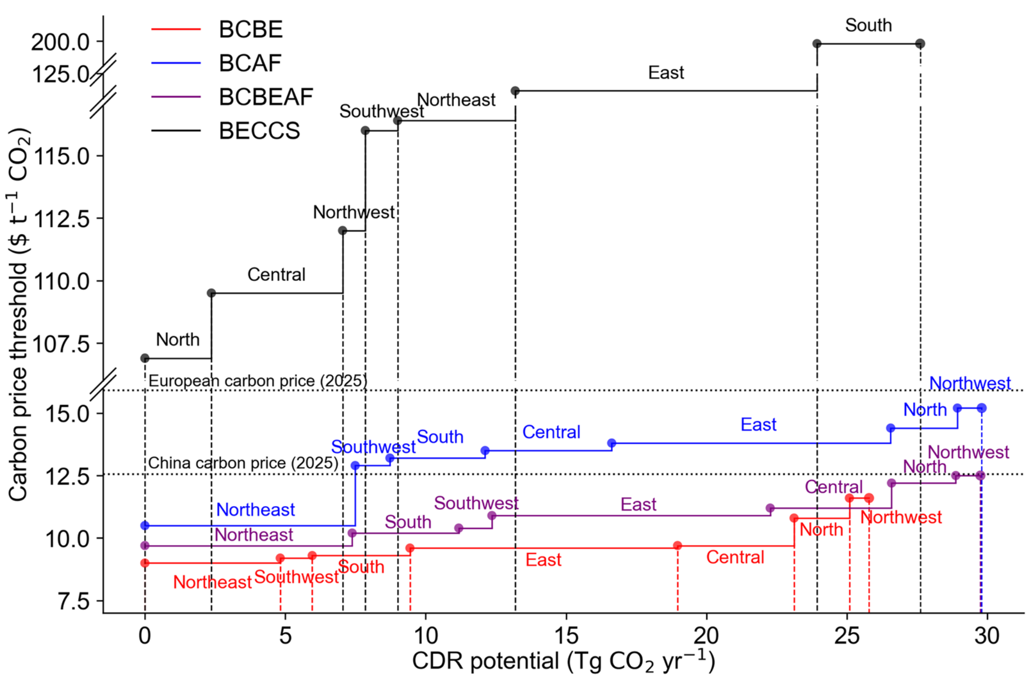


Fig. 3 CDR potential and carbon price threshold for biochar at the regional scale. The seven regions are listed in order of their carbon price thresholds for biochar with biomass supply from bioenergy crops (BCBE), agricultural and forestry residues (BCAF), a combination of both (BCBEAF) and from bioenergy crop cultivation with carbon capture and storage (BECCS). The horizontal distance between two adjacent points represents the CDR potential, and the vertical position of each point represents the carbon price threshold for BCBE, BCAF, BCBEAF and BECCS. The two horizontal dotted lines indicate carbon prices in China (\$12.6 t^{-1} CO_2) and Europe (\$76.5 t^{-1} CO_2) on 20 December 2024

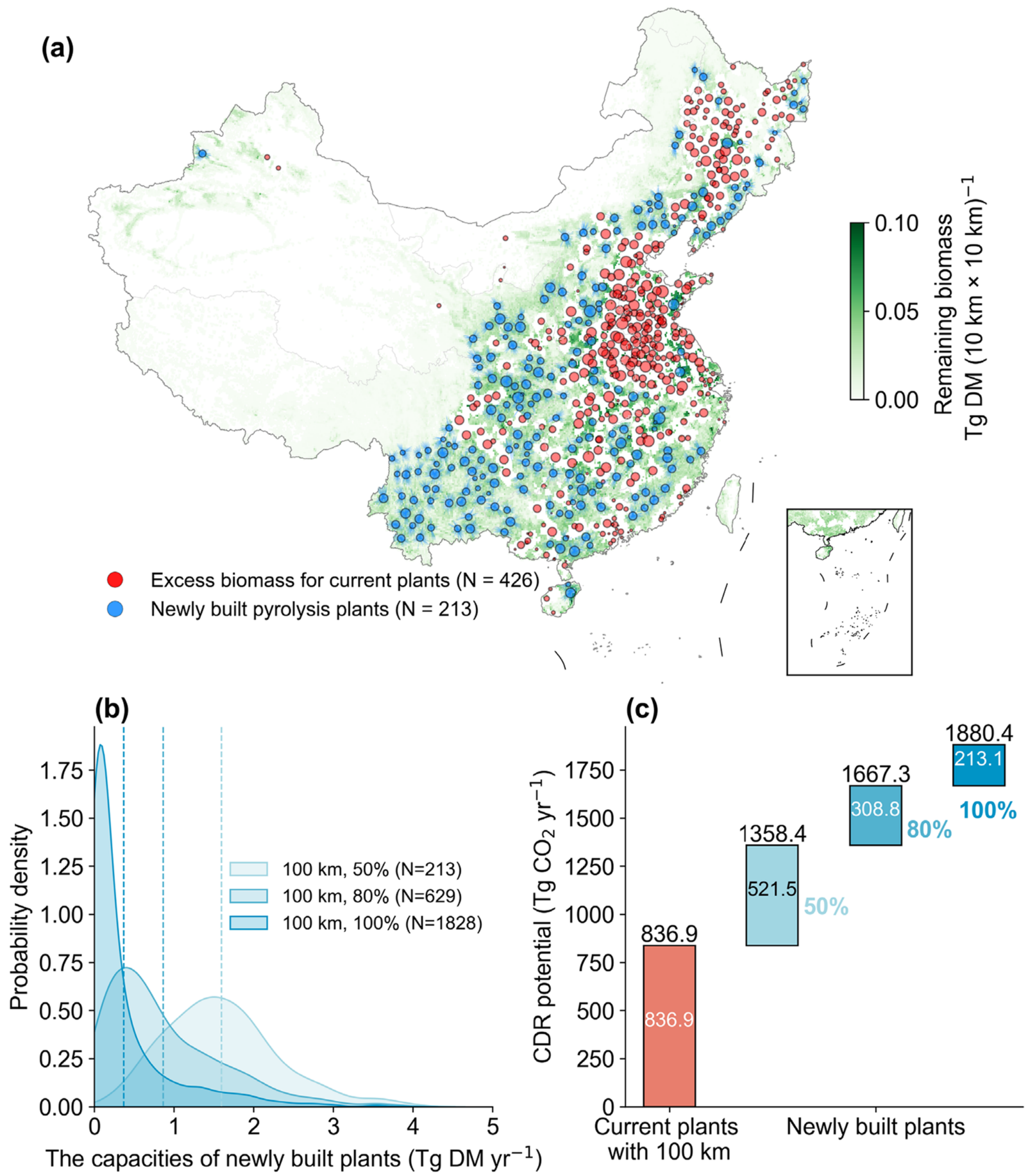


Fig. 4 Spatial distribution, capacity, and CDR potential of current plants (red circles) and newly built pyrolysis plants (blue circles). The size of the red circles in **a** indicates the excess biomass within a 100 km collection radius after satisfying the capacity of current plants with biomass supply from bioenergy crops and agricultural and forestry residues. The size of the blue circles indicates the total biomass collected within an assumed 100 km radius (**a**) in the scenario that 50% of the remaining biomass in China will be used for biochar production at a carbon price of \$20 t^{-1} CO_2. Blue lines emanating from the blue circles represent the routes of biomass supply for a given plant (i.e., from the biomass collection area). The frequency distribution of plant capacities of the newly built plants at different percentages of the collected remaining biomass within a 100 km radius is shown in (**b**). The numbers in the parentheses in **b** are the number of newly built plants, and the dashed lines represent the median capacity of newly built plants. Panel (**c**) displays the potential CDR of biochar with current plants with 100 km collection radii and with new plants assuming 50, 80 and 100% of the remaining biomass is used for biochar production

3.4 Building biomass pyrolysis plants

According to the actual capacity of current biomass power plants ($0.04^{+0.01}_{-0.00}$ Tg DM year^{-1}, median capacity and the interquartile range) and accessibility by road, the biomass collection radius of these plants for biomass supply from both bioenergy crops and agricultural and forestry residues (i.e., BCBEAF) was $17.8^{+5.6}_{-4.3}$ km. Therefore, a substantial amount of excess biomass would remain uncollected within a 100 km radius if bioenergy crops were to be cultivated on current abandoned cropland, particularly in East, Central, and Northeast China (Fig. 4a). Through enlarging the capacity of existing plants to process the biomass available within a 100 km radius (Fig. S3), the CDR potential of biochar, based on the biomass supply routes of these plants (Fig. S3), would reach 836.9 Tg CO_2 year^{-1} (Fig. 4c).

Even assuming plants could fully process biomass within an expanded radius of 100 km (Fig. 4a, Fig. S3), approximately 678.8 Tg DM year^{-1} of biomass (both BE and AF) still remained unused in China, representing roughly 49.3% of the total available biomass (Fig. 4a). There is, therefore, still potential for further biomass utilization by newly built pyrolysis plants in the future. Assuming a plant for biochar production was built in each grid cell (10 km × 10 km) to use the remaining biomass from bioenergy crops and agricultural and forestry residues (Supplementary Text 1), nearly all regions would benefit at a carbon price of \$20 t^{-1} CO_2. It is thus feasible to collect just about all the remaining biomass (Fig. S10).

According to the net benefit map of biochar at \$20 t^{-1} CO_2, the locations of newly built pyrolysis plants were identified. The median capacity of newly built pyrolysis plants expanded as the collected radius increased but decreased as the total biomass collection target increased (Fig. 4b). Because large plants were prioritized in areas with abundant biomass, as collection targets increased, plants had to inevitably be built in regions with lower biomass availability and poor transportation conditions (e.g., Qinghai province). This led to the construction of more small plants, lowering the overall plant capacity (Fig. S11). If 50% or all of the remaining biomass was utilized for biochar production, it would require 213 new plants (median capacity: $1.53^{+0.44}_{-0.46}$ Tg DM year^{-1}) or 1828 plants ($0.12^{+0.28}_{-0.08}$ Tg DM year^{-1}), respectively, based on an assumed collection radius of 100 km (Fig. 4a, b). In contrast, fewer plants would be required with a larger biomass collection radius of 200 km (Fig. S11). The CDR potential of biochar with additional newly built pyrolysis plants that collected 50% and 100% of the remaining biomass could reach 1358.4 Tg CO_2 year^{-1} and 1880.4 Tg CO_2 year^{-1}, respectively (Fig. 4c). Other percentages of the remaining biomass used for biochar were also tested, and the spatial distribution of the newly built plants is shown in Fig. S11.

4 Discussion

4.1 Comparison with previous studies

The current assessment of the future CDR potential of biochar, ranging from 500 to 1280 Tg CO_2 year^{-1}, assumes that 28–100% of residues from agricultural or forestry are used for biochar (Deng et al. 2024; Yang et al. 2021; Zheng et al. 2023)—a figure which vastly exceeds current use of only 0.11% of crop residues and 0.36% of forestry residues (Lu et al. 2022; Xia et al. 2023). The majority of agricultural residues are used for other purposes (for fertilizer, feed, base, fuel and as raw materials) (Huo et al. 2019), while forestry residues are primarily employed in material applications, papermaking, and energy production (Xia et al. 2023). Consequently, to secure sufficient biomass, biomass power plants have to collect residues over long transport distances, which ultimately constrains the CDR potential of BCAF. A sensitivity test using various biomass utilization rates for biochar was conducted (1%–70%, Supplementary Text 5). The results showed that if plants were supplied solely by agricultural and forestry residues at a 1% utilization rate, they met only 31.6% of current plant capacity (Fig. S12a, Table S1). However, when residues (at 1% utilization) and bioenergy crops were combined, they fulfilled 87.9% of plant capacity, with bioenergy crops contributing 20.2% of the total biomass collected (18.46 Tg DM year^{-1}) and covering 1.61 M ha of abandoned cropland (Fig. S12a). These results highlight the necessity of cultivating dedicated bioenergy crops on abandoned cropland to supply feedstock for biochar, particularly given the other anticipated use of agricultural and forestry residues in the future. In particular, the South, Southwest, and East regions have large potential for additional biomass supply from dedicated bioenergy crops (62.4–63.8%, Fig. S2, S5), while the Northeast region contributes a lower percentage (22.9%) due to lower yields of bioenergy crops and limited land area (Fig. 1a).

In this study, 73% of agricultural residues and 50% of forestry residues were assumed available for biochar production (Table S1). The CDR potential of BCAF, based on the existing biomass power plant capacity (29.8 Tg CO_2 year^{-1}, Fig. 1b), was generally lower than estimates based on all agricultural or forestry residues in China being available (Deng et al. 2024; Zheng et al. 2023), because the feedstock for biochar is constrained by the capacity of current plants. The plant-averaged CDR potential of BCAF in this study (0.07 Tg CO_2 year^{-1} for a mean plant capacity of about 50,000 t DM year^{-1}, Fig. S13) fell within the reported range of 0.03–0.13 Tg CO_2 year^{-1} for plants with capacities of 20,000–100,000 t DM year^{-1} in East Asia (Han et al. 2022). The average emission reduction from fossil fuel substitution by syngas and bio-oil in the life cycle analysis (0.04 Tg CO_2 year^{-1}, Fig. S13) was lower than the 0.12–0.14 Tg CO_2 year^{-1} reported for pyrolysis poly-generation pilot projects in Wuhan, Hubei province (OV Bluefire 2023). This difference is primarily due to the smaller size of current biomass power plants compared to the pilot facilities (90,000–110,000 t DM year^{-1}). The average carbon sequestration from biochar in this study (0.03 Tg CO_2 year^{-1}) was also comparable to values of 0.02 Tg CO_2 year^{-1} for a UK biochar facility (PM Today 2024) and 0.01 Tg CO_2 year^{-1} for a Brazilian plant using crop residues (Renewable Carbon News 2023) (Fig. S13).

The estimate of the maximum CDR potential for biochar with additional newly built plants using 100% of the remaining residues and bioenergy crops in China was 1880.4 Tg CO_2 $year^{-1}$ (Fig. 4). This value is comparable to the sustainable technical potential of 1680 Tg CO_2 $year^{-1}$ reported by Deng et al. (2024), which considered residues from agricultural, forestry and grass, and dedicated bioenergy crops on unused lands and shrublands, but did not account for potential plant distribution and biomass utilization via road availability around these plants. However, although comparable, there is still a difference in the values, which is probably due to variations in the definitions of marginal land, and the available biomass amount and types.

It was found in this study that the maximum CDR potential of BCBE was lower than that of BECCS (Fig. 2), consistent with the finding of Løvenskiold et al. (2022) that BECCS exhibits a higher CDR potential due to the substantial contribution of CCS (carbon capture efficiency: 90–92%) across various future scenarios. However, the carbon price threshold for BCBE at \$9.6 t^{-1} CO_2 was much lower than that for BECCS at \$135.7 t^{-1} CO_2 (Fig. 2). This threshold for BCBE is within, but in the lower end of, the carbon price range of < \$30 t^{-1} CO_2 and \$50 t^{-1} CO_2, which are adequate to make biochar applications economically viable (Lomax et al. 2015; Roberts et al. 2010). It may be partly due to the inclusion of increased SOC credits in the carbon market (Fig. S6), which account for both the stable carbon contained in biochar and the changes in native SOC after biochar addition (Han et al. 2022). The estimated net cost of BECCS without considering carbon income (\$90.9 t^{-1} CO_2, Fig. 2a) was also within the wide range from \$15 t^{-1} CO_2 to \$400 t^{-1} CO_2, which varies significantly across different technologies (Fuss et al. 2018). Therefore, biochar presents a more cost-effective solution than BECCS. This is also consistent with the findings of Deng et al. (2025), who compared the CDR potential and costs of biochar and BECCS at the grid level. However, for most regions of China, the implementation of biochar using existing biomass power plants is not profitable for BCAF under the current carbon price (\$12.6 t^{-1} CO_2) (Fig. 3). In addition to biochar production in pyrolysis plants with substantial transport costs, small-scale portable pyrolysis systems, which can latch onto the back of tractors, enables on-site biomass processing and biochar production directly in the field. Such systems can save transport costs and provide a cost-effective solution for the rapid large-scale implementation of biochar.

4.2 Uncertainties and limitations

The decay rate of biochar depends on its characteristics and soil properties (e.g., soil temperature), resulting in about 54–84% of the carbon in biochar being retained over a century (Woolf et al. 2010). This study thus employed spatially explicit effects of biochar addition on SOC (Fig. S14; Supplementary Text 4), but for some other parameters, such as the allocation coefficient of feedstock utilization and the N_2O emission reduction factor in cropland (Woolf et al. 2010), were, in contrast, assumed to be constant at the national scale. By considering the variability of key parameters across the processes of feedstock collection, pyrolysis technology, transportation, and soil greenhouse gas mitigation effects with biochar addition (Table S5), the overall uncertainty ranges (95% CI) were 23.6–32.4 Tg CO_2 $year^{-1}$ for BCBE, 28.2–36.8 Tg CO_2 $year^{-1}$ for BCAF and 27.8–37.4 Tg CO_2 $year^{-1}$ for BCBEAF. Among all parameters, the biochar addition rate and yield exerted the greatest influence, highlighting the critical role of biochar application rate, biochar properties, and pyrolysis technology (Fig. S15). Notably, the addition rate can have opposite effects, reflecting the trade-off between the biochar application rate and SOC sequestration efficiency following biochar addition. Increasing the addition rate reduces CDR potential because the decline in the application area outweighed the per-area SOC sequestration gain. By contrast, sensitivity to biomass availability was relatively low, as biomass supply was constrained by plant capacity. Transport distance, transport emission factor, and the N_2O inhibition rate had comparatively small effects (Fig. S15). In addition to the changes in SOC and N_2O emissions resulting from biochar addition, biochar may also cause reductions in soil CH_4 emissions (Jeffery et al. 2016) and an enhancement of plant growth due to increased nitrogen and phosphorus availability, which can further contribute to additional carbon removal from the atmosphere (Glaser and Lehr 2019; Lehmann et al. 2021; Zhang et al. 2021). Biochar may also reduce the indirect costs of fertilizer use due to environmental damage and water treatment expenses (Xie et al. 2023). These factors, however, were not included in this study due to limited understanding of the processes and scarcity of the data. Biochar production via pyrolysis typically results in nitrogen loss compared to the direct return of raw residues (de Oliveira Paiva et al. 2024), meaning that biochar alone cannot fully replace the nutrient supply and soil fertility maintenance functions of returning residues to soils. This limitation is particularly pronounced in nutrient-poor marginal lands, where the direct residue retention may be more effective for preserving soil nutrients stocks. Future work should integrate biomass allocation strategies with optimization of pyrolysis technologies and other management practices (e.g., fertilization) to balance soil nutrient levels during biochar production and application.

Ideally, a plant-level study should account for the diverse technological characteristics of different biomass power plants. However, due to the lack of detailed information, such as plant lifespan, energy conversion efficiency, etc., the use of fixed plant parameter assumptions may introduce uncertainties in estimating life cycle carbon emissions. Given the limited data from pilot projects and complexity in scaling, which involves quality control during operation, standardization requirements, and high cost of capacity expansion, the retrofit process was simplified by assuming that existing biomass power plants could be readily equipped with pyrolysis and CCS, while neglecting the technical compatibility challenges of the entire engineering system and potential technological upgrades over time. Further engineering assessments and policy research are therefore needed to evaluate the technical feasibility of such retrofits.

Although this study considered competition among plants for biomass in the supply–demand chain, real-world decisions are often driven by economic returns. In practice, facilities may prioritize transporting biomass to established partners or more profitable outlets rather than optimizing for CDR potential. The regional deployment of biochar or BECCS should also depends on the infrastructure development, skilled labor availability, and the maturity of supply chains, all of which rely heavily on financial support and policy incentives. For example, long-distance CO_2 transport for CCS must incorporate economic, technical, and political constraints (Fan et al. 2021). Biomass availability itself fluctuates seasonally, while bioenergy crop cultivation is constrained by water and land resources, which may be further pressured by population growth and rising food demand (Næss et al. 2021; Daioglou et al. 2019). These factors underscore the need for a more comprehensive framework that integrates such dynamics into future assessments of biochar potential.

4.3 Implications

The spatial mismatch between biomass power plants and CO_2 storage sites induces high transport costs for BECCS, particularly in South China (Fig. 1a, Fig. S9). Compared to CO_2 transport by road tanker, pipeline transportation reduces both CO_2 emissions and transport costs; however, the long distances in South China may still result in transport accounting for a significant proportion of BECCS costs (Fig. S16; Supplementary Text 6). Instead, biochar is proposed as a low-cost alternative CDR option. In fact, the low carbon price threshold of biochar is largely driven by the gap between the relatively low carbon price in China and the higher price in Europe, reflecting the less mature state of China's carbon market for biochar. This suggests that biochar can be developed cost-effectively in the short term in developing economies to support global mitigation, although uneven carbon prices may also lead to imbalances in carbon markets and hinder international investment. Currently, only a few pyrolysis plants exist in China, primarily as pilot projects in Henan, Anhui, and Hubei (Deng et al. 2024), with a biomass processing capacity of about 100,000 t year^{-1} (Fig. S2, http://ovbluefire.com/index.php?c=content&a=list&catid=25). Many biomass power plants rely on direct biomass combustion but lack pyrolysis technology related to biochar, syngas, and bio-oil production (Guo et al. 2022; Wu et al. 2010). The capacities of these plants are generally smaller than those of coal power plants (Wang et al. 2022), limiting their ability to process large quantities of biomass. Retrofitting existing biomass power plants with large-scale biomass pyrolysis systems is thus needed to enhance biomass utilization, but this shift may reduce electricity output per unit of biomass by about 30%, as part of the carbon in biomass is stabilized in biochar rather than fully combusted (Gaunt and Lehmann 2008).

Given the spatial heterogeneity of biomass supply, pyrolysis plants should be deployed in regions with an imbalance between biomass supply and demand, such as Yunnan Province (Fig. 1a, Fig. S2, Fig. 4a). Yunnan is rich in biomass resources, but it hosts relatively few biomass power plants (Fig. 1a), resulting in large amounts of unused biomass that could otherwise be applied as biochar. This spatial mismatch increases logistics costs and energy consumption, thereby limiting the economic feasibility of pyrolysis projects. Similar spatial mismatches are also observed in Gansu and Guizhou provinces (Fig. 1a, Fig. S2), where biomass resources are underutilized due to high transport costs and uneven biomass spatial distribution. Moreover, biochar deployment requires high capital investment in pyrolysis facilities and land acquisition, while financing challenges (e.g., limited access to green credit and carbon finance) further constrain project implementation. Establishing small- to medium-scale mobile pyrolysis units near biomass sources and promoting financial incentives through carbon credit mechanisms may offer practical pathways to address these challenges (Zilberman et al. 2023).

Although BECCS offers greater CDR potential than biochar, the high cost of CCS technology poses significant economic barriers. Additionally, BECCS may introduce environmental risks, such as CO_2 leakage during capture, transport, and storage processes, which could harm the nearby environment and affect human safety (Fajardy and Mac Dowell 2017). When storage sites in areas with a population density greater than 100 people km^{-2} were excluded to reduce risks, transport emissions and costs increased due to the longer distances to alternative storage sites, especially in the South region (Fig. S16-17; Supplementary Text 6). CCS also requires additional energy and water consumption, which may induce environmental pollution (Sammarchi et al. 2024; Smith 2016). Biochar, in contrast, is a promising near-term CDR solution with a lower cost and a high capacity with additional biomass supply from bioenergy crops. Similar to the benefits of biochar for biomass and soil carbon sequestration, enhanced rock weathering (ERW), which involves adding basalt dust to soil, presents a highly scalable strategy (Goll et al. 2021). It accelerates CO_2 uptake through silicate reactions in basalt while improving soil fertility and boosting plant growth by releasing nutrients (Goll et al. 2021). Therefore, the co-deployment of biochar and ERW could further enhance CDR potential.

However, the long-term and large-scale effectiveness of biochar still need further investigation. For example, while biochar can initially sequester CO_2, its efficiency in removing CO_2 decreases over time as it gradually decays (Chiquier et al. 2022; Wang et al. 2016). However, biochar characterized by a low H/C ratio exhibits strong stability over a centennial timescale (Leng et al. 2019), and negative priming effects on SOC have also been observed (Zimmerman et al. 2011), suggesting that its CO_2 removal potential may even be enhanced over time. Biochar application may also influence the climate via altering surface albedo, which could offset its mitigation potential (Bozzi et al. 2015). Overall, the large-scale implementation of biochar will require robust policy support, including developing bioenergy crop supply chains and maintaining reasonable carbon prices. The trade-offs among CDR potential, socioeconomic factors, and environmental impacts should be carefully considered to optimize their benefits.

5 Conclusion

The study shows that biochar with biomass supply from bioenergy crops is a viable CDR technology with lower cost and risk than BECCS. Cultivating bioenergy crops on marginal lands is critical to minimizing competition with traditional biomass residues, especially as biomass demand becomes more diversified. The balance between biochar and BECCS should be tailored to regional conditions in China—for example, BECCS may be more appropriate near storage sites. However, uncertainties remain due to literature-based parameters, soil responses to biochar, and the lack of dynamic consideration of land-use and food demand. Addressing these gaps will require integrating local project data, conducting field trials, and employing updated socio-economic scenario. These findings provide scientific evidence and policy-relevant evidence for deploying biochar, with bioenergy crops as an additional feedstock, to support China's carbon neutrality goals. Unlocking its large-scale CDR potential will require improved biomass supply chain, incentives for bioenergy crop cultivation on marginal lands, and clear integration of biochar into carbon credit systems.

Supplementary Information

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Additional file1 (DOCX 14739 kb)

Author contributions

All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Mengjie Han, Wei Li, Chenyi Yuan, Philippe Ciais, and Daniel S. Goll. The first draft of the manuscript was written by Mengjie Han, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability

The datasets used or analyzed during the current study can be found within the main manuscript and the Supplementary Material.

Declarations

Competing interests

The authors declare no conflict of interest.

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