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ORIGINAL ARTICLE

Land-neutral negative emissions through biochar-based fertilization—assessing global potentials under varied management and pyrolysis conditions

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Abstract

Climate stabilization is crucial for restabilizing the Earth system but should not undermine biosphere integrity, a second pillar of Earth system functioning. This is of particular concern if it is to be achieved through biomass-based negative emission (NE) technologies that compete for land with food production and ecosystem protection. We assess the NE contribution of land- and calorie-neutral pyrogenic carbon capture and storage (LCN-PyCCS) facilitated by biochar-based fertilization, which sequesters carbon and reduces land demand by increasing crop yields. Applying the global biosphere model LPJmL with an enhanced representation of fast-growing species for PyCCS feedstock production, we calculated a land-neutral global NE potential of 0.20–1.10 $GtCO_2$ $year^{-1}$ assuming 74% of the biochar carbon remaining in the soil after 100 years (for + 10% yield increase; no potential for + 5%; 0.61–1.88 $GtCO_2$ $year^{-1}$ for + 15%). The potential is primarily driven by the achievable yield increase and the management intensity of the biomass producing systems. NE production is estimated to be enhanced by + 200–270% if management intensity increases from a marginal to a moderate level. Furthermore, our results show sensitivity to process-specific biochar yields and carbon contents, producing a difference of + 40–75% between conservative assumptions and an optimized setting. Despite these challenges for making world-wide assumptions on LCN-PyCCS systems in modeling, our findings point to discrepancies between the large NE volumes calculated in demand-driven and economically optimized mitigation scenarios and the potentials from analyses focusing on supply-driven approaches that meet environmental and socioeconomic preconditions as delivered by LCN-PyCCS.

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1 Introduction

Negative emissions (NE; see Table 1 for a list of abbreviations) pose a significant and complex challenge to science and policy searching for feasible pathways to achieve the climate targets of the Paris Agreement. In addition to deep emission reductions, NEs are being considered to offset residual hard-to-abate emissions, but also to compensate for delays in stringent decarbonization. Yet, while especially biomass-based negative emissions technologies (NETs) like bioenergy with carbon capture and storage (BECCS) are considered feasible in economic optimization, land-based options require vast areas, thereby competing with food production and ecosystem protection (Boysen et al. 2017; Heck et al. 2018; Humpenöder et al. 2018). As an alternative to land-demanding BECCS, we here assess feasible NE contributions of more sustainable pyrogenic carbon capture and storage (PyCCS) based on land- and calorie-neutral biomass production, capitalizing on yield increases induced by biochar-based fertilization (BBF) to maintain calorie production while realizing net CO_2 removal from the atmosphere.

In climate economic models with cost optimization (Integrated assessment models, IAMs), scenarios compatible with a maximum warming of below 1.5 °C or 2 °C frequently rely on extensive BECCS deployment. They project required rates of up to more than 9 $GtCO_2$ $year^{-1}$ around the year 2050 (median: 2.75 $GtCO_2$ $year^{-1}$), reaching maximum levels of more than 16 $GtCO_2$ $year^{-1}$ by 2100 (median: 8.96 $GtCO_2$ $year^{-1}$, 15th–85th percentile: 2.63–16.15 $GtCO_2$ $year^{-1}$) (IPCC 2022). However, there is large skepticism whether these simulated high deployment volumes of BECCS can realistically be achieved given economic, political, and technological constraints on the assumed rapid scale-up of NETs (Bednar et al. 2019; Lenzi et al. 2018; Nemet et al. 2018). Also, serious concerns have been raised regarding substantial environmental and social side effects: Large-scale deployment of BECCS from dedicated bioenergy crops would lead to additional land degradation, competition for land with both food production and biodiversity protection, and could cause strong increases in human water and fertilization use, among others (Boysen et al. 2017; Stenzel et al. 2019). All of these contribute to planetary destabilization by further increasing the pressure on planetary boundaries characterizing humanity's safe operating space (Heck et al. 2018).

PyCCS is proposed as an alternative biomass-based NET and scalable approach with a high level of technological readiness and applicability across a broad spectrum of usages

Table 1 List of abbreviations

BBF	Biochar-based fertilization	LCN-PyCCS	Land- and calorie-neutral PyCCS
BC_{100}	Biochar carbon remaining after 100 years	NE	Negative emissions
BECCS	Bioenergy with carbon capture and storage	NET	Negative emission technology
BFT	Biomass functional type	PBIAS	Percent bias after Moriasi et al. (2007)
DACCS	Direct air carbon capture and storage	PyCCS	Pyrogenic carbon capture and storage
IAM	Integrated assessment model	YI	Biochar-mediated yield increases
la/sa	Ratio of leaf area to sapwood area		

including diverse agricultural systems, waste management, and material production (Osman et al. 2022). This NET is based on pyrolysis, the thermochemical decomposition of biomass at high temperatures (350–900 °C) in an oxygen-deficient atmosphere. The three main carbonaceous pyrolysis products can subsequently be stored in different ways to produce NE: as solid biochar in soils or building material, as bio-oil in depleted fossil oil repositories, and as CO_2 after combustion of permanent-pyrogas in geological storages in very advanced technological settings (Schmidt et al. 2019).

The term PyCCS has been introduced to cover the whole range of sequestration options arising from the pyrolysis process, which however differ in their level of technological readiness and storage permanence (Schmidt et al. 2019; Werner et al. 2018). This is essentially different to the terminology of BECCS and DACCS (direct air carbon capture and storage), where CCS exclusively refers to processing and storing CO_2 (IPCC 2018). While biochar applications to soil have been practiced for centuries and researched for more than one decade, the combination of chemical looping combustion and pyrolysis, which would result in the most efficient way for the geological storage of combustion products of permanent-pyrogases, has not been tested widely yet (Schmidt et al. 2019). Once deployed, the geological storage of processed pyrogases can be considered permanent (unless leaked through permeable faults or fractures in the seal) according to the assumptions for the same processes for BECCS and DACCS.

In case of carbon sequestration through biochar, however, the fate of carbon differs between applications. High durability of biochar carbon storage in soils can be attributed to the development of fused aromatic structures during biomass pyrolysis (Wang et al. 2016). These structures render biochar considerably less susceptible to microbial decomposition in comparison to fresh biomass. To ensure biochars exhibit high durability, production must occur at elevated temperatures with extended residence times, promoting complete carbonization and the formation of fused aromatic structures, indicated by low H/C ratios (Ippolito et al. 2020; Spokas 2010). Established methodologies quantifying 100-year biochar persistence (e.g., IPCC (2019)) mainly extrapolate short-term decomposition of biochar components with a lower degree of aromaticity observed under laboratory conditions. Yet, uncertainties remain as this falls short of capturing processes explaining millennial persistence and dynamics in the open environment (Leng et al. 2019). Following these quantification methods, the fraction of biochar carbon remaining in the soil after 100 years is estimated to be around 70–80% for H/C ratios below 0.5 and pyrolysis temperatures above 450 °C (Camps-Arbestain et al. 2015; IPCC 2019; Lehmann et al. 2021). Yet, the permanence of pyrogenic carbon sequestration would be significantly increased when the biochar is used in building materials.

In this study, we solely account for biochar sequestration in soils and its particular co-benefit in agriculture, as applying biochar to arable soils potentially leads to significant increases in agricultural yields as well as reduced water and nutrient demand (Schmidt et al. (2021) and metastudies therein; Bai et al. (2022)), reducing the pressure on land, water, and fertilizer resources. Furthermore, large-scale ubiquitous biochar sequestration in soils might be favored over industrial-scale top-down approaches to NETs because it can be deployed from small-scale to the large-scale (subsistence to industrial) and therefore might support the UN Sustainable Development Goals (SDGs). This might be achieved by reducing dependencies on external resources, realizing higher agroecosystem resilience and water purification, as well as delivering clean cooking technology with pyrolyzers that can reduce biomass demand, as reported for biochar in Smith et al. (2019).

Yet, as holds true for all biomass-based NETs, the source of the feedstock is the most critical factor for the environmental impact of PyCCS. The land and water footprints of PyCCS feedstock production are thus minimal if based on residues from cropland or forestry (Woolf et al. 2010) but can be more substantial if based on dedicated plantations (Werner et al. 2018). Unfortunately, the global availability of crop residues not already used for other purposes is highly uncertain (Hanssen et al. 2020). An intriguing additional option for sustainable feedstock production is unique to PyCCS: biomass input from dedicated fast-growing stocks produced in land-neutrality. If significant levels of biochar-mediated yield increases (YI) were achieved, the same amount of food could be produced on less land. Thus, a fraction of the cropland could be dedicated to fast-growing biomass supplying PyCCS feedstocks without requiring additional land (Fig. 1).

Werner et al. (2022) estimated the NE potential of LCN-PyCCS (land- and calorie-neutral PyCCS) as 0.44–2.62 Gt CO_2 year^{-1} depending on the achievable degree of YI above present levels on (sub-)tropical cropland (15–30%) assuming an application rate of 2 t ha^{-1}. Note that the higher end of the range requires very optimistic assumptions such as the development of optimized biochar applications adapted to specific soils and crops (see below) and/or the increase of soil-crop system resilience against extreme weather/climatic events that strongly reduce agricultural production.

However, recent studies and meta-analyses indicate that significant YI can still be reached with lower application rates (such as < 1 t ha^{-1}) if operated as BBF instead of as a general soil amendment. Bulk soil amendment with biochar is the incorporation of pure, untreated biochar to agricultural land where it is ploughed or drilled into the soil.

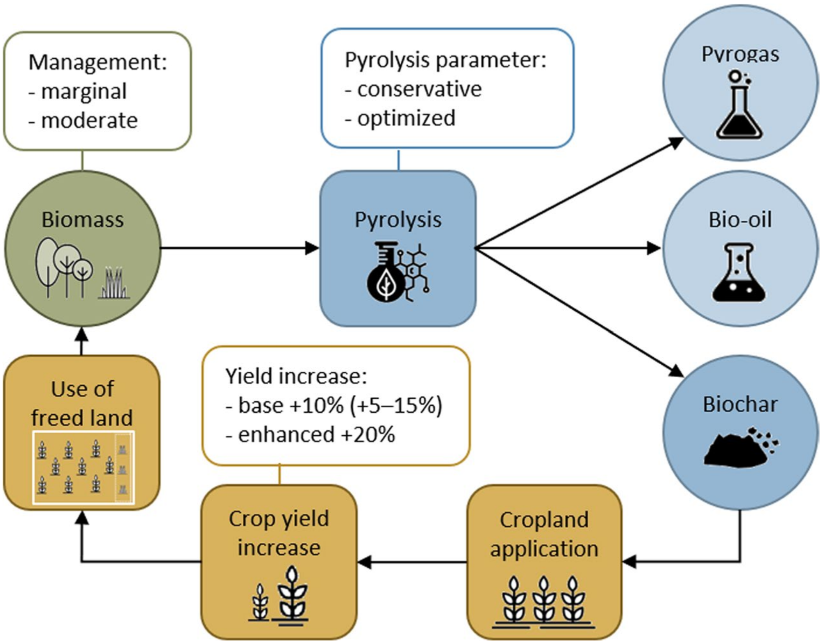

Fig. 1 Schematic representation of land- and calorie-neutral PyCCS (LCN-PyCCS) indicating the ranges of the operation space assessed in this study (white boxes; green frame: ranges for feedstock management, blue frame: ranges for pyrolysis process, brown frame: ranges for crop yield response to biochar-based fertilization). Details on the assessment ranges are given in Table S1

In contrast, BBF refers to either biochar-fertilizer mixtures (mineral or organic) placed concentrated in the root zone (Schmidt et al. 2017; Sutradhar et al. 2021), or granular/pelletized biochar fertilizers that often consist of clay/silicate minerals, (mineral) fertilizers containing nitrogen, phosphorus and potassium, and other nutrients, plus an untreated, pre- or post-treated (functionalized) biochar component (Joseph et al. 2021). With BBFs, comparably low biochar additions of < 1 t ha^{-1} can have considerable effects (Grafmüller et al. 2022; Qian et al. 2014). The meta-analysis of Melo et al. (2022) reported a grand mean effect of 10% YI in comparison to the fertilized control at an average application rate of 0.8 t ha^{-1} and even 17% for chars with a carbon content of > 30%.

In comparison to bulk amendment with biochar, tailored BBF could extend the geographic applicability of LCN-PyCCS for two reasons: (i) the positive yield effects of BBF could also be observed in temperate regions whereas the amendment approach increases yields mostly only in the (sub-)tropics; (ii) the lower application rates of BBF decrease the biochar demand and thereby the yield requirements for LCN-feedstock production.

To investigate the potentially extended applicability of LCN-PyCCS based on BBF, we quantify its global NE potential by applying the biogeochemical biosphere process model LPJmL to simulate the biomass that can potentially be produced as pyrolysis feedstock under this land- and calorie-neutral approach. We extend the analysis further by addressing the sensitivity of LCN-PyCCS potentials to assumptions about (i) pyrolysis process parameters, (ii) the management intensity of the feedstock producing system, and (iii) biochar durability in soils. In the case of (i), we consider a range between two sets of parameters representing a conservative assumption and an optimized setting to account for the calculation's sensitivity towards assumed process-specific biochar yields and carbon contents in the char. Regarding (ii), we account for two levels of management of feedstock-producing systems to reflect on the potential of management intensification. For (iii), we assess a range of biochar residence times in soils centered around a base assumption to reflect the uncertainty in regard to durability. Furthermore, as the extent and overall NE potential of LCN-PyCCS strongly depends on the biomass yields, the analysis is preceded by adapting the most important parameters for the representation of fast-growing plants potentially used as pyrolysis feedstock based on comparisons of simulated yields and observations.

2 Methods

LCN-PyCCS is a system of land-neutral biomass production on croplands using biochar-mediated YI to maintain calorie production while realizing net CO_2 extraction from the atmosphere. Through the YI, a fraction of the cropland can be dedicated to PyCCS feedstock production to provide self-sufficient biochar supplies and NE while preserving levels of food production (Fig. 1). Assuming + 10% YI, for example, would allow 110% calorie production on the same area or 100% production on 91% of the area, leaving 9% for PyCCS feedstock production. Whether cropland is suitable for the LCN-PyCCS approach therefore depends on the potential biomass production on the rededicated land. Only if the biomass yield provided enough feedstock to supply the remaining cropland with sufficient biochar (i.e., 0.8 t ha^{-1} year^{-1} mean in Melo et al. (2022)) for maintaining the calories produced, a fraction of the land would be considered for biochar feedstock production. Yet, this is a conservative assumption, because it does not include (a fraction of) the crop residues, which are in practice often added to biochar production, e.g., by smallholder farmers (Schmidt et al. 2017).

2.1 The global biosphere model LPJmL

A spatially explicit estimate of potential biomass production is required for an assessment of global theoretical potentials of the LCN-PyCCS approach. In this study, we apply the process-based global biogeochemical vegetation model LPJmL (version 4.0) to simulate the growth of dedicated PyCCS feedstocks (lignocellulosic grasses and fast-growing tree species) with a daily time step and a spatial resolution of 0.5° × 0.5°. Simulating key ecosystem processes in direct coupling of the carbon and hydrological cycle, the model estimates the vegetation dynamics of 11 natural plant functional types (Sitch et al. 2003) and 12 crop functional types and managed grassland (Bondeau et al. 2007); for detailed descriptions and validations of the biogeochemical dynamics, see Schaphoff et al. (2018a) and Schaphoff et al. (2018b). Additionally, three types of second generation energy crops are included (biomass functional types; BFTs) to estimate potential feedstock production for biomass-based NETs: two fast-growing tree species for woody biomass parameterized as eucalypt in tropical climates and poplar and willow in temperate climates and lignocellulosic C4 grass for herbaceous energy crops (Beringer et al. 2011; Heck et al. 2016).

2.2 Sensitivity analysis of parameters for simulating biomass production

We primarily calculate the LCN-PyCCS potential based on herbaceous feedstock to ensure annual biomass supply. This focus has been established in prior studies on global estimates, i.e., Werner et al. (2018) and Werner et al. (2022), because the grassy BFT shows higher yields in LPJmL, and biochars from herbaceous feedstock often have better yield-increasing properties than woody biochars; see meta-studies compiled in Schmidt et al. (2021). Systems of wood harvest and short rotation coppice are typically harvested in a multi-annual cycle (Li et al. 2018), which could cause a biochar deficit in the LCN-PyCCS approach (if not supplemented by residues or other biomass sources). However, the implementation of LCN-PyCCS can be diverse depending on the farm's conditions and needs, where the rededication of cropland to woody species (e.g., hedgerows) might be preferred for ecological reasons and the biomass deficit might be balanced through annual pruning or selective logging, which is not represented in the model. To provide a first estimate of the LCN-PyCCS potential of these woody feedstocks, we additionally applied our calculations to the biomass harvest simulated for the two woody BFTs in LPJmL, averaged over the plantation lifetime.

To ensure a robust representation of BFTs, we investigate the sensitivity of the simulated yields to variations of selected parameters characterizing plant physiology and management, which are most relevant for the simulation of biomass production in the model.

The grassy BFT follows growth dynamics of tropical C4 grass in LPJmL, representing fast-growing species like Miscanthus and switchgrass. While the lignin-rich supportive tissue enabling annual harvests through continuous growth that is characteristic for, i.e., Miscanthus, is not represented in the model, it can still represent a highly productive grass functional type optimized towards biomass production through multiple harvests per year. In LPJmL, the grassy BFT is harvested whenever aboveground biomass reaches a certain threshold and when senescence is reached. The harvest threshold controls the intervals between harvests and regrowth dynamics and thereby significantly impacts simulated yield levels. Low values result in longer growing periods with stagnating productivity and thereby lower yields. Furthermore, the yields depend on the harvest index, i.e., the fraction of biomass removed. To best match reported annual harvest sums, we revisit these parameters (harvest threshold of 400 gC m^2 and harvest index of 0.75 selected in Heck et al. (2016)) based on a comparison of simulated biomass yields with a new extensive observational dataset on bioenergy crop yields (Li et al. 2018). For this, we vary the harvest threshold and harvest index in a literature-based range (150–450 gC m^{-2} and 0.7–0.9, respectively; S1) and compare simulated yields to observations from 90 sites in Li et al. (2018). We exclude switchgrass observations because the biomass production of Miscanthus is significantly higher (Li et al. 2018; Li et al. 2020), which makes a combined representation of both species less relevant (Ai et al. 2020) and decisions to grow the more productive crop more likely (Zhuang et al. 2013).

In case of the woody BFTs, we assess the response to varying the ratio of the characteristic areas of leaves and sapwood (la:sa). The parameter la:sa has been identified by Zaehle et al. (2005) as one of the parameters of plant growth that influence the productivity of trees most significantly. However, it has not been adapted for the woody biomass plantations yet (while the other important parameters were adjusted, see S2). As lower la:sa values increase the amount of carbon required for leaves and associated transport tissue, thereby reducing the leaf area but enhancing the carbon storage in wood, lower la:sa values can be expected for species chosen for their enhanced biomass production. Here, we assess the sensitivity of simulated biomass production in LPJmL to a literature-based range of la:sa values (tropical: 2500–5000, temperate: 2000–5500; see S1) and evaluate the respective model performance according to observations.

While the management of biomass plantations can vary widely in practice (i.e., fertilization, pest control, soil preparation, irrigation, etc.), variation in plantation management for BFTs in LPJmL is represented by cell-specific irrigation (representing management intensity) and for woody BFTs by a BFT-specific rotation length, i.e., the years of growth before coppice. While irrigation can be used to spatially vary management intensity levels for different scenarios, the rotation length is predefined for each woody BFT and has been set to 8 years for both types in the original parameterization (Beringer et al. 2011). However, the rotation length can be quite variable in practice with a median of 3 years for short rotation coppice systems of willow or poplar and 6 years for eucalypt plantations reported in the Li et al. (2018) database. In combination with the range of la:sa, we assess the model's response to varying this parameter for a range of 1–12 and 2–10 for the rotation length of tropical and temperate trees, respectively, covering the 10th to 90th percentile of plantation age (including all experiments, temperate $n = 1068$, tropical $n = 439$) and rotation length (reported as common practice, temperate $n = 678$, tropical $n = 96$).

The global yield dataset for major lignocellulosic bioenergy crops reported for field measurements compiled by Li et al. (2018) provides an extensive database for evaluation of simulated biomass yields and thereby provides a suitable reference for parameter selection based on the performed sensitivity analyses. We simulate the growth and harvest of irrigated and rainfed plants under climate conditions of 1985–2014 and calculate the mean yields over five rotations for woody types and over 30 years for the herbaceous type. These LPJmL-computed mid-range yields between rainfed (no irrigation) and intensified (full irrigation) are then compared to the mean of the minimum and maximum reported yields of experimental test sites located in the respective grid cell (varying in observations periods (1968–2016), mean sampling year: 1999). The model performance is assessed by the metric of percent bias (PBIAS), the sum of biases divided by the sum of observed values (Moriasi et al. 2007) excluding outliers of the relative difference between observed and simulated yields, defined as values below the 25th percentile minus 1.5*interquartile range or above the 75th percentile plus 1.5*interquartile range.

2.3 Simulation set-up for LCN-PyCCS scenarios

For the assessment of the theoretical NE potential of LCN-PyCCS, we apply LPJmL to simulate the growth of the BFTs under a parameter selection that is based on the sensitivity analysis and evaluation of model performance described above.

The model is driven by climate input from the general circulation climate model HadGEM2-ES as contributed to the ISIMIP2b ensemble for the RCP2.6 SSP2 pathways (Frieler et al. 2017) and corresponding CO_2 concentrations as well as data on soil texture based on the Harmonized World Soil Database (FAO et al. 2012). Preceding the simulations from 2025 to 2099, an initial spin-up of 5000 years is performed to achieve an equilibrium of soil carbon and distribution of natural vegetation followed by 390 years of a transient spin-up introducing the influence of agriculture on the carbon balance with historic land use change until 2015 based on HYDE 3.2 (Klein Goldewijk et al. 2017).

The reallocation of cropland to biomass production for PyCCS is based on the land use projections of a RCP2.6 SSP2 scenario realization of the land allocation model MAgPIE (Dietrich et al. 2019), provided in the ISIMIP2b ensemble that is consistent with the HadGEM2-ES climate input (Frieler et al. 2017). The fraction of cropland dedicated to biochar feedstock production (9%) is based on the assumption of 10% YI achievable through BBF, corresponding to the grand mean of yield responses reported in Melo et al. (2022). In the assessment, we draw a range of 5% and 15% YI around this base assumption (according to the respective confidence interval in Melo et al. (2022)) to account for uncertainties and dependencies in the yield response. In addition, we test for a scenario of biochar application optimized towards carbon sequestration and yield responses with 20% YI (Fig. 1, S1), which is within the range of the confidence interval for biochar with a carbon content > 30% (CI 11–24%) in Melo et al. (2022).

2.4 Management intensities

To analyze the effect of management of feedstock production and resulting yields on NE potentials, we assess two management intensities on the rededicated cropland (Fig. 1, S1). First, we assume minimal management, reflecting a case where the farmer's management efforts focus on the remaining cropland. The feedstock is then simulated as rainfed biomass yields in LPJmL. In the sensitivity analysis, irrigation meeting the total water demand of the plantation represents the upper end of the range of agricultural management. In line with this, we assess a second scenario assuming moderate management as the mid-range yield between rainfed (no irrigation) and intensified (full irrigation).

2.5 Pyrolysis parameters and sequestration efficiencies

For the pyrolysis process transforming the harvested biomass into biochar, we assume parameters for slow pyrolysis with a highest heating temperature of 500 °C to ensure relatively high biochar yields at the same time as high fractions of recalcitrant biochar. As NE potentials of simulated biochar applications strongly depend on the assumed process- and feedstock-specific biochar yields and carbon contents in the char, we study two sets of parameters representing a conservative and an optimized setting, setting a range (Fig. 1, S1). The first set shown in Table 2 is based on Woolf et al. (2021) by averaging over a large number of different pyrolysis technologies, while the second set represents settings that are optimized towards biochar production for carbon sequestration following the biochar yield equations of Schmidt et al. (2019)

and an enhanced carbon conversion efficiency through ash amendment based on Grafmüller et al. (2022).

Regarding the permanence of biochar, our base assumption applies a conservative estimate of 74% carbon remaining in the soil after 100 years ($BC_{100} = 74\%$) based on an annual decay rate of 0.3% per year for biochar with H/C ratios < 0.4 based on the findings of Camps-Arbestain et al. (2015). Acknowledging the uncertainties associated with biochar durability in soils, we have additionally computed the sequestration potential under both a lower and a higher estimate for biochar durability to establish a range that envelopes this base assumption. The lower range presumes a 70% retention of biochar carbon in the soil after a century, which aligns with the estimate derived from the linear regression in Lehmann et al. (2021) based on observational data for pyrolysis temperatures of 500 °C. On the contrary, the upper range operates with an assumption of 80% biochar carbon remaining in the soil after 100 years, as suggested in the Refinement to the IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2019).

To finally account for net carbon capture efficiency (Table 2), we consider a carbon expenditure of about 18% of the sequestered biomass carbon including upstream CO_2 emissions from biomass cultivation, harvest, processing, and transport and downstream CO_2 emissions associated with the conversion of biomass into biochar at the pyrolysis plant, as well as the transport and application of biochar on soil (S3, Chiquier et al. (2022)). Yet, it has to be noted that with biochar production and use by subsistence farmers, such expenditures may be close to zero.

3 Results

3.1 Sensitivity analysis and selection of parameters for simulating biomass production

Preceding the evaluation of global NE potentials for LCN-PyCCS, we assessed the sensitivity of the model representation of biomass growth for dedicated stocks to the most critical parameters (see "Methods") and used this as a basis for a final parameter selection.

For the herbaceous BFT, higher fractions of harvested biomass lead to lower yields because of smaller leaf area and therefore decreased photosynthetic activity after harvest. However, the decrease in biomass yields is much stronger for larger harvest thresholds. Higher thresholds show lower average productivity because of productivity stagnation over time, while lower values benefit from shorter intervals of regrowth, except for the very low value of 150 gC m^{-2} where the productivity is limited due to relatively low leaf area after harvest (Figure S1). Considering these two parameter responses, the PBIAS (percent bias, see "Methods") could be reduced from 18.73 to 2.74% with a harvest threshold of 450 gC m^{-2} and a harvest index of 0.7. Thus, the overall overestimation of herbaceous BFT yields in the model could be reduced significantly (Figure S3).

For the woody types, we find that biomass production is significantly enhanced for lower la:sa values, as these lead to more allocation of carbon to the wood. In case of the tropical BFT, the biomass yields (averaged over growing years) further increase with longer rotation cycles. Yet, this dynamic is divergent for the temperate tree, where the yields decline again for rotation lengths > 5 years, because here, the biomass increment is lower than the production averaged over the preceding years, as more carbon is lost via respiration of the living tissue.

Table 2 Pyrolysis parameters with numbers in brackets indicating the values for the lower (70%) and upper (80%) range for the biochar durability in soils after 100 years

Feedstock type	Biochar yield [% ash-free dry matter]	Carbon conversion efficiency [% biomass carbon in biochar]	Carbon capture over 100 years [% biomass carbon]	Net carbon capture efficiency [% biomass carbon]
Conservative				
Herbaceous	23.13	38.66	28.61 (27.06–30.93)	23.51 (22.24–25.42)
Woody	26.67	42.97	31.80 (30.08–34.38)	26.14 (24.72–28.26)
Optimized				
Herbaceous	30.89	52.99	39.21 (37.09–42.39)	32.22 (30.49–34.85)
Woody	35.05	61.21	45.30 (42.85–48.97)	37.24 (35.22–40.25)

For the tropical BFT, the parameter combination leading to the best fit with observation data considering PBIAS is the extremes of the assessed ranges, i.e., la:sa = 2500 and rotation length = 12 years with a PBIAS of − 2.45% (Figure S2). This indicates that other processes and parameters beyond the selected parameters for biomass production are likely relevant and might also have to be calibrated for the representation of eucalypt wood yields. However, as we are dealing here with a global biosphere model for generalized global-scale simulations rather than a dedicated crop model for plantation dynamics of a specific type, we consider performance with a PBIAS of − 2.45% sufficient for representing biomass production on a global scale. Compared to the PBIAS of −27.06% of the original parameterization (la:sa = 4000, rotation length = 8 years), the new parameter selection could significantly reduce the underestimation of yields for this BFT in the model (Figure S4).

For the temperate BFT, we find a number of combinations that result in an acceptable fit of simulated yields with observed yields: the best performing 10% of parameter combinations (considering PBIAS) lie between ± 2% PBIAS with la:sa between 2000 and 3500 and rotations ranging between 3 and 10 years (Figure S2). Given the similar fits for different parameter combinations, we additionally base the parameter selection on the median of reported rotation lengths in Li et al. (2018) while prioritizing a parameterization of la:sa that results in a better fit across all rotation lengths, strengthening the role of plant physiology compared to primarily management-driven dynamics. Based on these arguments, we chose the parameters of la:sa = 3500 and rotation length = 4 years with a PBIAS of − 1.97% for our simulations. The representation could thus be enhanced by reducing the overall underestimation in comparison to the old parameterization with a PBIAS of − 10.83% (Figure S4).

While the parameter selection based on model performance in comparison to observed yields could improve the overall representation in the regions covered by test sites (Figure S3, Figure S4), there is limited evidence for the compatibility of the global biosphere model in the rest of the world. As shown for Miscanthus in Fig. 1b, there is a clear focus of test sites in the northern temperate zone. Here, LPJmL-computed rainfed yields range from approximately 10 to 20 t dry matter ha^{-1}, whereas some tropical regions exceed 30 t dry matter ha^{-1} even without irrigation (Fig. 2a). Yet, as no suitable reference data is available, the higher productivity simulated in the tropics is based on process-based modeling, matching other findings on enhanced plant productivity in the tropics (Cramer et al. 1999; Turner et al. 2006), rather than parameters fitted to observations. However, the upper end of reported yields in the temperate zone is comparable to the simulated yields in the tropics, indicating that the plant physiology of Miscanthus has the potential for yields of such magnitude. For the LCN-PyCCS analysis, robustness of simulated yields is particularly relevant, as a certain level of biomass production has to be reached on the rededicated land in order to produce sufficient biochar for the remaining cropland (yield thresholds in Fig. 2b). Yet, our assessment assumes marginal management (represented as rainfed plants in LPJmL) and moderate management (represented by the mean of irrigated and rainfed yields), while the simulated maximum of irrigated yields would represent highly intensified agriculture that is typically not considered for the management of pyrolysis feedstock production systems.

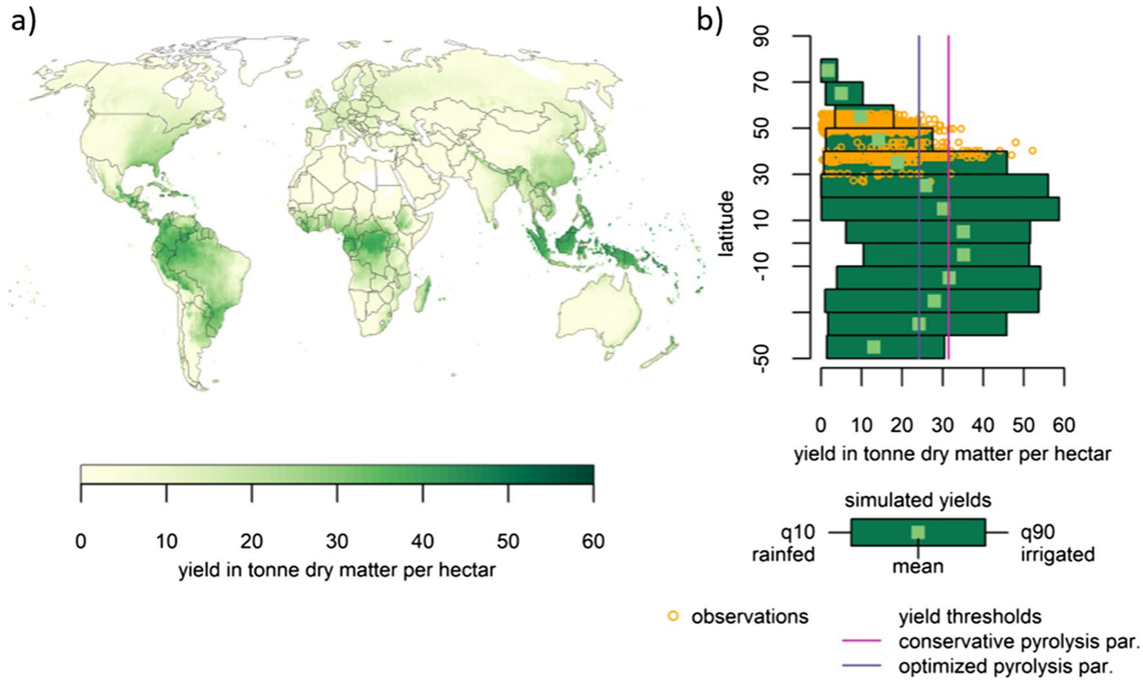

Fig. 2 Yields of LPJmL-simulated herbaceous biomass stock shown as global distribution of rainfed yields (**a**) and as a range between the 10^{th} percentile of rainfed yields and 90^{th} percentile of irrigated yields grouped by latitude and compared to observations (orange circles) of corresponding location (**b**). The light green boxes in **b** indicate the mean values of rainfed and irrigated yields (mid-range) averaged over the latitude group; the vertical purple and pink lines show the thresholds of biomass yields on rededicated land required to supply the remaining cropland with sufficient biochar under the assumption of optimized and conservative pyrolysis parameters, respectively

3.2 Negative emission potential

Based on the enhanced simulation of feedstock yields, we quantified the global NE potential of the LCN-PyCCS approach for parameters and geographical extents representing the findings for BBF in the literature. We found that the results strongly depend on the accomplishable YI, as previously indicated in Werner et al. (2022), but additionally also on the pyrolysis parameters, biochar durability in soils, and management intensity of the feedstock production systems assumed. For the main analysis, we follow the base assumption of herbaceous biomass input (see above). The calculated NE potentials under the assumption of BC_{100} = 74% and marginal management of the feedstock production range from 0.20 $GtCO_2$ $year^{-1}$ based on conservative assumptions for pyrolysis parameters (for 10% YI; 0–0.61 $GtCO_2$ $year^{-1}$ for 5% and 15%, respectively) to 0.37 $GtCO_2$ $year^{-1}$ for the optimized pyrolysis case (0–0.82 $GtCO_2$ $year^{-1}$, Table 3; Fig. 3b). As the biochar yield is lower for conservative pyrolysis parameters (Table 2), more biomass and thereby particularly productive regions are required to supply the corresponding cropland with the sufficient rate of biochar. Thus, the suitable area is restricted to the most productive regions in the tropics resulting in a relatively low global NE potential (Fig. 3). Furthermore, in addition to the limited extent, the lower biochar yield and carbon content in the conservative parameter set lead to lower overall carbon sequestration per biomass carbon input.

If only + 5% YI was accomplished through BBF, the feedstock yield requirements would rise significantly, because a smaller area dedicated to PyCCS feedstock production would need to supply biochar for a larger area of remaining cropland. As our simulations barely reach this yield level, no NE potential can be quantified here. Accordingly, land- and calorie-neutral biochar sequestration can only be realized under such low yield responses if the feedstock production of the LCN-PyCCS approach (i.e., land rededication) was largely supplemented by other land- and calorie-neutral sources.

For the base assumption of 10% YI, the productivity and thus the NE supply could potentially be increased by intensifying the management of the biomass production systems. With higher yields due to enhanced management, more areas produce sufficient biochar to supply the corresponding cropland and become suitable for the LCN-PyCCS approach (Fig. 3). While the LCN-PyCCS applicability shows a strong focus on tropical regions under marginal management, the moderate intensification expands the suitability into the subtropics and even into the temperate zone in wide areas of Eastern USA. Based on the conservative pyrolysis parameters, moderate intensification may sequester up to 0.74 $GtCO_2$ $year^{-1}$ (for +10% YI and BC_{100} = 74%; 1,64 $GtCO_2$ $year^{-1}$ for + 15% YI), while the optimized pyrolysis case might even reach NE rates of about 1.10 $GtCO_2$ $year^{-1}$ (for + 10% YI and BC_{100} = 74%; 1.88 $GtCO_2$ $year^{-1}$ for + 15% YI).

Accordingly, the cumulative NE sums from 2025 to 2100 could be increased by feedstock production management from 15.09 and 28.07 $GtCO_2$ $year^{-1}$ to 55.49 and 82.59 $GtCO_2$ $year^{-1}$ for conservative and optimized pyrolysis parameters under BC_{100} = 74%, respectively. Comparing these results to IAM scenarios, the cumulative sums for marginally managed feedstock systems correspond to 3–6% of the total NE demand until the end of the century in scenarios compatible with 1.5 °C or 2 °C in the 6th Assessment Report of the IPCC (IPCC 2022), while the numbers for moderately managed systems compare to 10–16%, respectively.

Yet, while the LCN-PyCCS potentials that we quantified lie at the lower end of projected NE demands for Paris-compatible IAM scenarios, their potential for moderate management is comparable to the separate mid-century NE supply by BECCS required in the

Table 3 Negative emission potentials of land- and calorie-neutral PyCCS calculated for 10% yield increase achieved by biochar-based fertilization given as a mean annual potential and sums over 2025–2100 with results for 5% and 15% yield increases in brackets. The base assumption of a biochar durability of 74% of the biochar carbon remaining in the soil after 100 years is given in bold, whereas the lower range of 70% is shown in plain and 80% in italic font

Management	Annual NE potential [$GtCO_2$]			Cumulative NE potential 2025–2100 [$GtCO_2$]		
Conservative pyrolysis parameters						
Marginal	0.19 (0–0.57)	**0.20 (0–0.61)**	*0.22 (0–0.65)*	14.27 (0–43.01)	**15.09 (0–45.47)**	*16.31 (0–49.16)*
Moderate	0.70 (0–1.55)	**0.74 (0–1.64)**	*0.80 (0–1.78)*	52.49 (0–116.59)	**55.49 (0–123.26)**	*59.98 (0–133.25)*
Optimized pyrolysis parameters						
Marginal	0.35 (0.01–0.78)	**0.37 (0.01–0.82)**	*0.40 (0.01–0.89)*	26.55 (0.87–57.89)	**28.07 (0.92–61.20)**	*30.35 (0.99–66.16)*
Moderate	1.04 (0.01–1.78)	**1.10 (0.01–1.88)**	*1.19 (0.01–2.03)*	78.13 (0.94–134.08)	**82.59 (0.99–141.74)**	*89.29 (1.07–153.23)*
	70%	**74% biochar C after 100 years**	*80%*	70%	**74% biochar C after 100 years**	*80%*

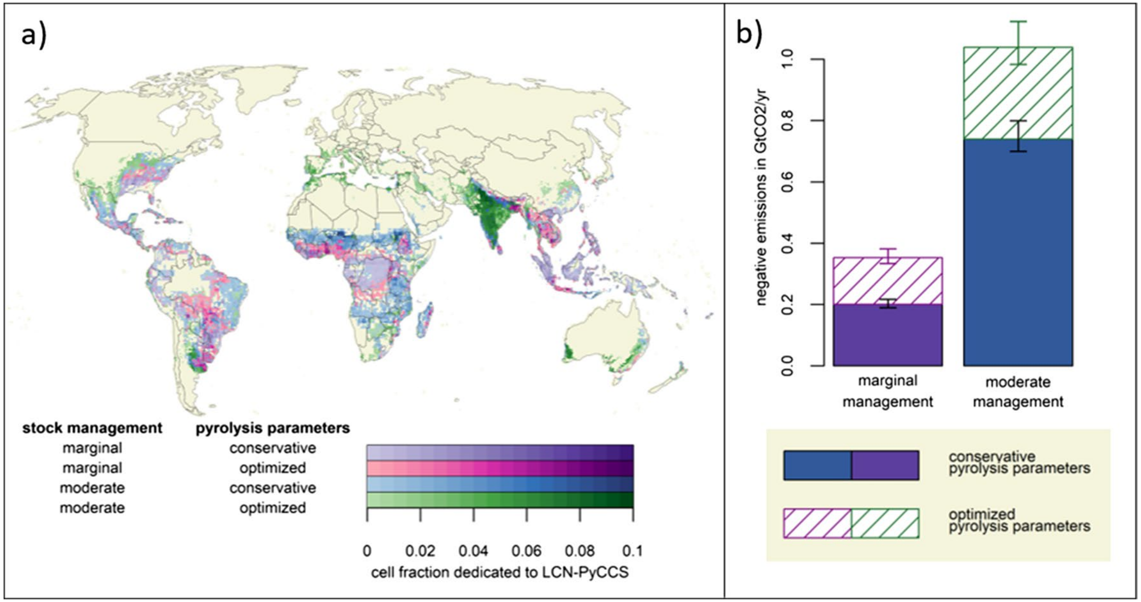

Fig. 3 Cell fractions dedicated to LCN-PyCCS in 2099 (**a**) and annual global sums of negative emissions averaged over 2025–2099 (**b**) based on different assumptions of pyrolysis parameters and management of the feedstock-producing systems, assuming 10% biochar-mediated yield increase. Combinations of higher potential (highest: moderate stock management plus optimized pyrolysis parameters, green) include the area of combinations with lower potential (lowest: marginal stock management plus conservative pyrolysis parameters, purple). The segments of the bar plots in **b** represent the potential under the assumption of 74% biochar carbon remaining in the soil after 100 years, while the error bars show the range for the lower (70%) and higher (80%) durability tested

illustrative mitigation pathway of Shifting Pathways which assumes far-reaching transformations in society and economy (IPCC 2022; Soergel et al. 2021). The annual PyCCS rates based on moderate management correspond to 82–115% (conservative to optimized assumptions for pyrolysis under BC_{100} = 74%) of the BECCS demand in this illustrative mitigation pathway with a focus on shifting transition towards Sustainable Development Goals, including poverty reduction and broader environmental protection in addition to deep GHG emissions cuts. Consequently, there is evidence from IAM assessments that NE rates of the magnitude quantified in this study could support the climate targets of the Paris Agreement. This is the case, however, only if the stringent decarbonization measures in combination with the comprehensive socioeconomic transformations (e.g., diet changes, minimized food waste, and improved distribution of goods) assumed in these scenarios are successful, and not for the mainstream collection of IAM pathways beyond the illustrative pathway mentioned.

In addition to enhancing the pyrolysis processes and the productivity of the feedstock supply, we tested a case of improved BBF application leading to 20% yield increases, i.e., as observed for chars with particularly high carbon content in Melo et al. (2022) (17% for > 30% carbon content) and expected for tailored biochars (Joseph et al. 2021). This optimization on the application side may increase the NE production to up to 2.45 $GtCO_2$ year^{-1} under the assumption of optimized pyrolysis parameters, moderate feedstock management, and BC_{100} = 74%.

While pyrolysis parameters and feedstock production impact the suitable area for the LCN-PyCCS approach (Fig. 3a), the presumed biochar carbon durability in soils drives the depiction of carbon losses over 100 years, ultimately affecting the final sequestration potential (Fig. 3b). A biochar carbon retention rate as low as 70% of the initial biochar carbon input would result in sequestration potentials of 0.19 $GtCO_2$ year^{-1} for marginal and 0.70 $GtCO_2$ year^{-1} for moderate feedstock management intensity, considering 10% YI and conservative pyrolysis parameters (Table 3). Under optimized pyrolysis conditions, with this lower BC_{100} of 70%, potential sequestration could reach 0.35 $GtCO_2$ year^{-1} for marginal and 1.04 $GtCO_2$ year^{-1} for moderate feedstock management intensity. Assuming a higher fraction of biochar carbon remaining in soil with BC_{100} = 80% would significantly increase the overall sequestration potential to 0.22 $GtCO_2$ year^{-1} for marginal and 0.80 $GtCO_2$ year^{-1} for moderate feedstock management intensity, given 10% YI and conservative pyrolysis parameters. Optimizing the pyrolysis process in this case could raise the potentials up to 0.40 $GtCO_2$ year^{-1} for marginal and 1.19 $GtCO_2$ year^{-1} for moderate feedstock management intensity.

As feedstock types for pyrolysis can be very diverse and woody inputs are also widely considered for biochar production (Ye et al. 2020), we additionally tested woody feedstock for the LCN-PyCCS approach considering the fast-growing tree functional types represented in LPJmL and parameterized in this study. We find that the NE potentials are significantly lower than quantified for the grassy feedstock because the required biomass yields for sufficient biochar supply are barely reached with the woody functional types in the model. Only if these biomass production systems are moderately managed, woody feedstock as represented in this study may become suitable for LCN-PyCCS in a few highly productive regions, resulting in relatively low NE potentials of 0.10 $GtCO_2$ year^{-1} and 0.15 $GtCO_2$ year^{-1} for conservative and optimized pyrolysis parameters, respectively.

4 Discussion

Climate stabilization is crucial for Earth system stability, but when biomass-based NETs that compete for land with food production and ecosystem protection are implemented without consideration of the environmental (e.g. land required) and societal (e.g. calories produced) repercussions, stabilization measures may at the same time threaten earth system stability by undermining biosphere integrity. Instead of expanding NET deployment in order to reach a certain NE target as in optimization models of climate economics, this assessment quantified the NE supply achievable "bottom-up" under the constraints of land- and calorie-neutrality. While staying within the bounds of cropland and maintaining calorie production, LCN-PyCCS based on BBF may produce 0 to 2.03 $GtCO_2$ year^{-1} (0.19–1.19 $GtCO_2$ year^{-1} for the base assumption of + 10% YI; 0–0.01 $GtCO_2$ year^{-1} for + 5%; 0.57–2.03 $GtCO_2$ year^{-1} for +15%) depending on (i) the YI achieved through BBF, (ii) the pyrolysis parameters assumed, (iii) the management intensity of the biomass producing system, and (iv) the biochar durability in soils. We argue that in order to estimate realistic potentials of NE, the discrepancy found between the demand-driven NE volumes calculated in economic optimization models (IAMs) for paths reaching ambitious climate targets and the results of supply-driven approaches as assessed here needs to be transparently discussed.

Our results support the findings in Werner et al. (2022) that global LCN-PyCCS potentials are driven by the biochar-mediated YI that can be accomplished. At the lower range, we find that a level of + 5% YI is not sufficient for the LCN-PyCCS approach based on BBF. Besides the high feedstock yield requirements or large biomass substitution demand, such low yield responses are not likely to encourage rededication of land to feedstock production. In cases where biochar application is still preferred despite low YI (i.e., for enhanced soil resilience), feedstock would thus need to be supplied by other (sustainable) sources.

In our assessment, we employed the insights from Melo et al. (2022) to substantiate universal YI levels in the adoption of a systematic methodology. However, the actual yield improvement achievable across diverse locations might surpass or fall short of this value, because the response to BBF exhibits considerable variability, as evidenced by the data compiled by Melo et al. (2022). A more precise, spatially explicit computation of YI under current conditions would necessitate the integration of diverse factors, among others encompassing soil category, fertilizer type, and crop variety. Yet, the currently available data is not sufficient for a statistical model of that kind. In the Melo et al. (2022) dataset, the observations associated with one category of an explanatory variable can show a substantial range in BBF response; for instance, the category of "weakly developed soils" exhibits a confidence interval spanning from 1 to 25% YI. Additionally, responses across categories within a variable, like "weakly developed soils" and "highly weathered soils," might not exhibit significant differences. While a comprehensive statistical model for deriving BBF-induced yield increase through multiple explanatory variables is presently absent, our study follows a systematic approach with theoretically universal levels of YI to reflect on magnitudes of the sequestration potential of LCN-PyCCS and its sensitivity to achievable YI, management intensity, pyrolysis parameters, and storage durability. Yet, as areas identified as suitable for LCN-PyCCS are not distributed equally, we have verified that the designated regions for LCN-PyCCS predominantly coincide with soil orders that have shown significant response to BBF (S4). Beyond the evaluated distribution of LCN-PyCCS, other regions of agricultural production are largely marked by more pronounced responses to fertilization and/or soils different from highly weathered and weakly developed soils. It needs to be noted that these distinct soil characteristics exhibited less significant to no yield responses to biochar addition in the meta-analysis by Melo et al. (2022). Thus, if BBF applications were assumed to concentrate on these less responsive soils, the overall net impact could be significantly reduced.

In addition to a focus on responsive soils, we assume feedstock treatment during pyrolysis that maximizes carbon storage via biochar. Consequently, the envisioned BBF involves biochar characterized by elevated carbon content (conservative estimate: 63% and optimized estimate: 67%). This aligns with the subset of chars in the > 30% carbon content category, which demonstrated notably elevated yield responses in the Melo et al. dataset (mean YI: 17%).

Enhancing the biochar application in terms of stronger responses to BBF in plant productivity (also by combining it with another land-based NET such as enhanced weathering) may significantly increase the NE potential. Research and development on BBFs are picking up pace, alongside with a growing understanding of biochar-surface interactions with major nutrients such as nitrogen and pre- and post-production treatment options to increase desired effects for crop yields, increased nitrogen use efficiency, and reduced environmental nitrogen pollution (state of knowledge reviewed in Rasse et al. (2022)). An example is the infiltration of the porous biochar structure with molten urea, providing a slow-release compound biochar fertilizer (Wang et al. 2021; Xiang et al. 2020), the coating of conventional fertilizers with biochar to increase the nitrogen use efficiency (Jia et al. 2021), biochar surface oxygenation to increase ammonia (NH_3) sorption or acid treatments, and organic coating to increase nitrate capture (Rasse et al. 2022) and other strategies. It can hence be expected that the upper ceiling of YI achieved with tailored BBFs has not yet been reached.

Beyond the impact of accomplishable YI, our results indicate a strong sensitivity of the NE potentials to the assumed pyrolysis parameters. Basing the calculations on the optimized parameter set instead of the conservative assumption increased the NE potential by 40–75%. Thus, practitioners aiming for carbon sequestration should follow settings for their pyrolysis plant/kiln that enhance the biochar yield and consider ash or rock powder supplements (Buss et al. 2022; Mašek et al. 2019); rock powder (enhanced weathering) represents another NET that can also increase yields (Beerling et al. 2020; Kantzas et al. 2022).

Furthermore, we identified the management of the biomass supplying systems as another factor driving the NE potentials in this assessment. The NE production could be increased by + 200–270% if the management of biomass production was assumed to be intensified from marginal to moderate levels. Elevated yields do not only increase the NE production per hectare, but also expand the area that is suitable for the approach because more regions meet the biomass production on rededicated land required to supply sufficient biochar for the cropland. This is particularly relevant for the expansion in the subtropics or even temperate regions that only become suitable for the LCN-PyCCS approach investigated in this assessment when moderate management is assumed. Yet, in most of the subtropical and temperate regions, such a degree of intensification is also more likely because the agronomic development in these countries already provides the infrastructure and resources required.

At the same time, the temperate regions are also best represented in the observational dataset that was used for the comparison with simulated yields, driving the parameter selection in this analysis. While the PBIAS could be increased significantly with the new parameterization for all BFTs, we also identified shortcomings in representing plant physiology. Furthermore, the model performance could only be assessed where observation data was provided. Yet, for the tropics, there is a significant lack of data on lignocellulosic energy crops in the literature (Fig. 2, Li et al. 2018). We therefore conclude that in order to extent the robustness of the representation of such crops in global modeling, both, the simulated processes of plant physiology and the geographic coverage of validation data, would need to be enhanced.

As we tested the quantification of LCN-PyCCS for woody biomass by applying fast-growing tree functional types as represented in LPJmL for the feedstock supply, we calculated NE potentials that were significantly lower than for the assessment of grassy feedstock. However, these functional types fail to represent all possible wood-like feedstocks that could be used for LCN-PyCCS (e.g., coffee, tea, cocoa, or fruit/nut tree pruning wood). Moreover, depending on the climatic, soil, and management conditions of the cropland, fast-growing tree species (e.g. agroforestry systems) can be more beneficial for plant growth, soil resilience, and intermediate-term landscape carbon sequestration (Dollinger and Jose 2018; Lorenz and Lal 2018) and might thus be preferred over grassy species, or be combined with them. Resulting potential benefits and site-specific effects like nutrient cycling, shade cover, increasing relative air humidity, and root growth preventing soil erosion (Fahad et al. 2022; Torralba et al. 2016) are not represented in our model and thus did not contribute to this assessment, but would reinforce rather than compromise our findings.

In addition to feedstock production and the pivotal role of pyrolysis conditions in determining the input of biochar carbon into the soil, we also assessed a range of alternative assumptions for the biochar durability in soils to account for the uncertainty associated with this aspect. It is known that biochar durability is enhanced by a greater proportion of fused aromatic structures, which form at higher temperatures and with extended residence times (Ippolito et al. 2020; Wang et al. 2016). However, estimating the portion that remains after, for instance, 100 years is reliant on estimations, given the absence of long-term experiments (Leng et al. 2019). Current methodologies for quantifying 100-year biochar persistence, such as those used in IPCC inventory guidelines, primarily extrapolate short-term soil decomposition processes. These methods fail to entirely encompass the mechanisms contributing to millennial persistence. Consequently, the actual biochar carbon residence time might exceed these estimations. Concurrently, future research should focus on biochar incubation in field conditions, aiming to highlight distinctions from laboratory settings (Leng et al. 2019). This field research may uncover factors that could intensify decomposition compared to laboratory experiments.

Furthermore, the study is limited to pyrogenic carbon sequestration and does not consider other biochar-mediated processes in the soils that could potentially contribute to shifting the land use sector from a greenhouse gas source into a sink. Biochar-enriched soils have been shown to enhance the build-up of soil organic carbon (Bai et al. 2019; Blanco-Canqui et al. 2020; Weng et al. 2017) and reduce soil acidity (Singh et al. 2017), nitrate leaching (Borchard et al. 2019; Hagemann et al. 2017), and N_2O and CH_4 emissions (Borchard et al. 2019; He et al. 2017; Jeffery et al. 2016). In total, biochar treatments can thus enhance soil quality, cut down management costs, and lower agricultural greenhouse gas emissions (Kammann et al. 2017; Lehmann et al. 2021).

While we assessed the potential for purpose-grown pyrolysis feedstock in the LCN-PyCCS approach, it needs to be emphasized that harvest residues and waste can provide additional sustainable biomass inputs, particularly because of the avoided land competition with food and nature. These additional sources for biochar production may even expand the area of LCN-PyCCS applicability as they could supplement the biochar supply in regions where the production by purpose-grown feedstock on rededicated land falls below the threshold of sufficient biochar application. Yet, the availability of residues and waste is uncertain and limited (Hanssen et al. 2020; IPCC 2022), and they cannot be considered freely available in the light of competing uses or benefits, such as soil carbon built-up against land degradation or the replacement of animal feed (Kalt et al. 2020; van Zanten et al. 2018). Another source that should receive more attention as the biomass market comes under increasing pressure is feedstocks that are often overlooked, for example, annual pruning wood or trunk and root weeding wood (at replanting cycles) of subtropical or tropical annual and perennial crops such as coffee, tea, cocoa, palm oil trees, banana, or fruit/nut trees. For example, waste stream and heat demand of the work flow at coffee production sites would favor pyrolysis (i) for drying coffee beans in a controlled manner to increase product quality and reduce the danger of fungal contamination and (ii) to compost coffee cherry pulp with biochar. Using such a product as a soil amendment at replanting has been shown to accelerate young tree growth and shorten the time until the first harvest is gained (Neumann Coffee Group, H. Faessler, practical trials, pers. comm.); biochar-composts can improve soil fertility for demanding crops such as coffee in particular in tropical soils (Zhao et al. 2020).

This global assessment aims to illustrate potential magnitudes of NE achievable through LCN-PyCCS, along with its sensitivity to specific influencing factors. We acknowledge however that broad-scale generalizations cannot fully encapsulate the unique local conditions that ultimately drive the sequestration process. Established methodologies employed to evaluate the sequestration potential within specific systems are lifecycle assessments (LCAs) integrating all information about inputs and outputs along the particular production and storage chain (Tisserant and Cherubini 2019). The NE outcome is contingent upon a multitude of variables across the lifecycle stages, including feedstock selection, pyrolysis conditions, transportation distances, and energy/fuel mix (Azzi et al. 2021). While LCAs serve as valuable tools for assessing the CDR potential of particular systems and their economic viability, often, the specific assumptions they entail are not extrapolatable to large-scale global scenarios. Consequently, they may focus on refining carbon sequestration within biochar production under specific circumstances. For instance, Fawzy et al. (2022) demonstrated this by optimizing the pyrolysis of olive tree pruning residue, yielding a total sequestration of 2.69 tCO_2-equivalent per ton of biochar. Compared to our study, the NE potential per unit biochar is thus approximately 1.7- to 1.9-fold higher and can be attributed to their optimized pyrolysis process, tailored for maximum carbon sequestration from a lignin-rich feedstock. Notably, the composition of biochar in the Fawzy et al. study, characterized by a carbon content of 84.9%, BC_{100} of 92%, and CO_2-equivalent expenditures along the lifecycle of 7%, stands in contrast to our assessment, where these figures are 62.7%, 74%, and 18%, respectively. Yet, to estimate the magnitude of global potentials, more generalized assumptions—albeit not aligned with the tenets of LCA—become necessary. Consequently, we assessed pyrolysis parameter ranges following functions based on observations for the broader category of grassy (and woody) feedstock (Grafmüller et al. 2022; Schmidt et al. 2019; Woolf et al. 2021). More generic assumptions were also made for the carbon expenditure throughout the lifecycle which corresponds to a moderately decarbonized energy and fuel blend, considering an average global transport distance of 55 km (see S3).

As described above, our global assessment reveals several limitations across various dimensions: In terms of feedstock supply, the availability of observational data for lignocellulosic grass growth in tropical regions remains sparse. Additionally, LPJmL currently lacks representation of most suitable wood-like feedstocks, especially those derived from integrated systems like agroforestry. Furthermore, this assessment does not incorporate other land-neutral resources, such as residues and waste, as biomass inputs. Moreover, the global assumptions concerning yield increase and carbon expenditure rely on global averages rather than accounting for the specific efficiencies of individual systems. Regarding the NE potential, the assessment does not incorporate other benefits linked to carbon sequestration that may arise from the application of biochar to soils. Yet, despite these constraints, systematic approaches like this study can contribute to advancing the discourse on negative emissions strategies, as they offer a means to assess the magnitude and responsiveness of global LCN-PyCCS potentials concerning diverse parameters.

Building on the first global quantification of LCN-PyCCS potentials based on biochar soil amendments of 2 t ha^{-1}, this study does not only add results for the promising practice of BBF at lower application rates (around 0.8 t ha^{-1}), but also insights on the sensitivity of the results towards assumptions on pyrolysis parameters and the management intensity of feedstock-producing systems. While the annual rate of 0.44 $GtCO_2$ $year^{-1}$ reported for + 15% YI at 2 t ha^{-1} biochar application in Werner et al. (2022) was solely based on optimized pyrolysis parameters and marginal management, this analysis illustrates an operation space for different pyrolysis processes and management intensities. Our calculation of the BBF-based NE potential following optimized pyrolysis parameters and marginal management results in 0.37 $GtCO_2$ $year^{-1}$ as we assume a YI of + 10% according to the grand mean reported in the BBF meta-analysis by Melo et al. (2022). Assuming + 15% YI in the BBF setting however shows higher NE potential (0.82 $GtCO_2$ $year^{-1}$, Table 3) than in Werner et al. (2022). This can be explained by the lower application rate that leads to a lower yield threshold of biomass production on the rededicated land required for sufficient biochar supply on the remaining cropland. Consequently, the application can be expanded into less productive regions that only then become suitable for LCN-PyCCS. Furthermore, the assumptions on the pyrolysis process were revised, now referring to 500 °C instead of 450 °C for the highest heating temperature. This is closer to practice and leads to a lower biochar yield but longer residence times in the soil, which we consider a more reasonable balance for long-term carbon sequestration. To increase the robustness of the assumptions about pyrogenic carbon residence time in the soil, we additionally adjusted the fraction of carbon that remains after 100 years from 90% (Werner et al. 2022) to 74% based on findings by Camps-Arbestain et al. (2015). In light of the latest analyses and new evidence on the recalcitrant nature of biochar produced at this temperature, the assumed fraction can be considered conservative (Azzi et al. 2024; Sanei et al. 2024).

Yet, addressing the differences between biochar used as soil amendment or BBF and the sensitivity towards pyrolysis parameters und management intensities of the biomass supply, we conclude that biogeochemical evaluations of the global LCN-PyCCS potential can only provide a range of estimates that mark the outer bounds of the maximum potential under the given assumptions. It is highly unlikely that a universally uniform level of YI will be achieved at a global scale. Such a concept is employed herein solely as a theoretical assumption, facilitating an exploration of sequestration potentials and parameter sensitivities. The usage and design of the pyrolysis plant/kiln as well as the biochar application methods and yield responses will always be specific for the explicit needs and conditions at the respective producer. Our findings of significantly higher NE potentials with optimized pyrolysis parameters and biochar application show that applying the constantly expanding knowledge on optimal carbon sequestration and yield response in practice can increase the global potential to a large degree. These scenarios are largely theoretical by assuming global applications; in that sense, they are purely analytical. Achievable real-world potentials depend on the feasibility of implementation (e.g., cultural, social, or political uptake or resistance), sufficient incentives for integrating PyCCS into agricultural practices worldwide, and established proof of successful operation for NE certification. Addressing potential resistance can be facilitated through adherence to robust accounting regulations, integrated within comprehensive measurement, reporting, and verification frameworks, which PyCCS already exhibits promising entry points for (Lehmann et al. 2021). A compelling illustration of stringent quality control of the chemical composition of biochar is, for example, already practiced with the European Biochar Certificate (EBC 2023; Fawzy et al. 2021). Furthermore, to circumvent competition for land and resources, the implementation of PyCCS should concentrate on accounting for the wide spectrum of co-benefits, particularly within the agricultural sector (see above), while concurrently integrating it within cross-sectoral planning rather than considering it an isolated climate change mitigation measure. Furthermore, one should not consider findings as found here to be yet a sufficient basis for planning on mitigation paths that assume these potentials will be available. However, it is a particular strength of LCN-PyCCS that this NET can (and already is) adopted by diverse agricultural systems and contributes to NE in a bottom-up dynamic, rather than top-down approaches like BECCS that likely rely on centralized markets and massive investments for costly infrastructure.

While it is therefore challenging to make global assumptions on the NE production potential of LCN-PyCCS systems, we still consider it illuminating to place the global estimates quantified in our analyses within the ongoing discussion of the large-scale implementation of NETs for climate stabilization—even with the large ranges we find. Only through such comparisons, at the same scale, can the discrepancies be identified between the large NE volumes calculated in demand-driven optimization models and the potentials from analyses focusing on supply-driven approaches, characterized by preconditions like minimizing the pressure on land resources and calorie production.

The argument of comparability holds true for the time scale of technological development: while PyCCS and particularly biochar assessments are usually based on parameters and process understanding that is directly derived from operating plants and real-world applications, the evaluations of BECCS and DACCS typically follow assumptions of future development based on only scarce evidence at commercial scale (Chatterjee and Huang 2020; Haikola et al. 2019). The Orca facility in Iceland is the first DACCS plant to operate at a commercial scale with a capacity of 4000 t CO_2 year^{-1} (Carbfix 2021). In contrast to this, the European Biochar Industry Consortium (EBI 2022) reports about 53,000 t biochar production capacity built in 2022 (i.e., PyCCS) in Central Europe alone (EBI 2023), potentially sequestering about 90,000–110,000 t CO_2 based on the sequestration efficiencies used for soil applications in this study. Plant construction was projected to increase the European biochar production to above 90,000 t in 2023 (EBI 2023). For BECCS, the development is focused on North America that counts four BECCS plants capturing $\geq$ 100,000 t CO_2 plus the Decatur plant with potentially one million t CO_2 capture per year. In Europe, the DRAX facility in the UK, with a capacity of 330 t CO_2 capture per year, is currently the only BECCS plant in operation, yet several projects are planned (Fajardy 2022; Shahbaz et al. 2021). Thus, the real-world carbon sequestration of PyCCS in Europe exceeds that of DACCS and BECCS at the moment. Also, on a global scale, PyCCS (particularly biochar sequestration) is showing the highest number of operating plants and catches up in regard to capacity, when compared to BECCS and DACCS (note that a global quantification of biochar production is still lacking and would result in much higher numbers).

Our analysis integrating biochar-mediated yield increases in the scenario development for global NET deployment identifies a potential for land- and calorie-neutral NE production. The LCN-PyCCS approach could thus contribute to a broader NET assessment considering critical additional limitations in environmental, social, and policy dimensions. Furthermore, as biochar application to soils potentially enhances soil properties in diverse ways (see above), the role of PyCCS could be enhanced in such impact-sensitive analyses if more biochar-mediated processes (i.e., liming, water-holding capacity, enhanced microbial activity, increased nutrient retention) were represented in the models. Yet, in parallel to those efforts in process representation within vegetation models, more elaborate models and databases for residue and waste availability (or beneficial waste-stream management strategies involving biochar) should be developed, as estimates and projections for sustainable biomass sources are crucial. While the LCN-PyCCS approach assessed here may contribute to some degree to global (more sustainable) NE production, a much higher potential could be unlocked if the outstanding feature of PyCCS that a variety of materials can be processed were to be exploited at a larger scale, particularly using residues and wastes that are of no other use (or where biochar production and use in organic waste management offer further SDG-supporting benefits).

In exploring various alternatives, it is crucial to prevent biomass-based NETs—exclusively intended for climate stabilization—from becoming a major driver of detrimental future land use change. This concern is particularly pertinent considering the already substantial degradation of the Earth's biosphere. In this study, we specifically highlight BBF-based LCN-PyCCS as one potential avenue but underscore the sensitivity of potential global NE production to factors such as achievable YI, pyrolysis settings, and the management intensity of feedstock production. While our assessment addresses the need of strict preconditions for large-scale NET deployment (i.e., land and calorie neutrality), the findings reveal that the resulting potentials are subject to large remaining uncertainties. Given these uncertainties, the study reinforces the imperative for prioritizing deep emission reductions as the foremost strategy in climate stabilization efforts.

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Data availability Data supporting the main findings of this study are available via 10.5281/zenodo.7116841. Land use and climate input data can be downloaded from the ISIMIP repository, https://data.isimip.org/ (Frieler et al. 2017) and 10.48364/ISIMIP.208515 (Lange and Büchner 2017).

Declarations

Competing Interest The authors declare that they have no conflict of interest.

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