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Key Points:

- Land- and calorie-neutral pyrogenic carbon capture and storage can provide negative emissions of 0.44–2.62 Gt CO_2 yr^{-1} depending on yield increase achieved
- Cumulated until 2100, this amounts to 6%–35% of the negative emission demand in integrated assessment scenarios of climate stabilization
- Land not required compared to alternative deployment of bioenergy with carbon capture and storage could be used for increasing food production or nature restoration

Supporting Information:

Supporting Information may be found in the online version of this article.

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Potential of Land-Neutral Negative Emissions Through Biochar Sequestration

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Abstract Negative emissions (NE) are under discussion as elements of mitigation strategies aiming to achieve the climate targets of the Paris Agreement. However, biomass-based NE technologies such as bioenergy with carbon capture and storage (BECCS) require vast land areas in order to meet the targets projected by climate economic optimization models, thereby competing with food production and ecosystem protection. Here we assess feasible NE contributions of alternative, more sustainable pyrogenic carbon capture and storage (PyCCS) based on land-neutral biomass production using biochar-mediated yield increases to maintain calorie production while realizing net CO_2 extraction from the atmosphere. Simulations with a biosphere model indicate that such a land- and calorie-neutral PyCCS approach could sequester 0.44–2.62 Gt CO_2 yr^{-1} depending on the assumed biochar-mediated yield increase achievable on (sub-)tropical cropland (15%, 20% and 30%, respectively). Cumulatively, by the end of the century, 33–201 Gt CO_2 could be sustainably supplied by such an approach, equaling 6%–35% of the NE demand projected for trajectories likely to limit climate warming to 2°C or lower. Furthermore, additional areas dedicated to BECCS in integrated assessment scenarios could instead be used to increase global calorie production (by 2%–16%), or spared for nature protection (up to ~ 100 Mha). Thus, land- and calorie-neutral PyCCS may, within limits, contribute to lessening the additional land use pressure of biomass-based NE technologies.

Plain Language Summary We assessed a land- and calorie-neutral approach to pyrogenic carbon capture and storage (LCN-PyCCS) as a supply-driven, bottom-up approach to large-scale carbon dioxide removal. LCN-PyCCS relies on the process of biomass pyrolysis, where biomass carbon is transferred into the more stable biochar that can be used as soil amendment enhancing the soil properties and storing carbon in the soil. The approach is based on land-neutral biomass production using biochar-mediated yield increases to maintain calorie production while realizing net CO_2 extraction from the atmosphere. In our analysis building on process-based simulations of biomass growth we find a potential of 0.44–2.62 Gt CO_2 yr^{-1} depending on the yield increase achievable. Furthermore, this approach could substitute negative emissions from other, less sustainable, biomass-based negative emission technologies. Assuming that this could free biomass plantations, we evaluated the potential of alternative uses of this land, showing potential increased calorie production of 2%–16% or land sparing for nature protection of up to ~100 Mha.

1. Introduction

Negative emission technologies (NETs) play a central but controversial role in scenarios of achieving climate neutrality by mid-century as required by the Paris Agreement (Forster et al., 2020; Warszawski et al., 2021). NETs are technologies that remove CO_2 from the atmosphere, allowing decarbonization pathways to remain within the cumulative CO_2 budgets associated with the internationally agreed warming limits. Recently, the 6th assessment report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) stressed once again that deployment of NETs to counterbalance hard-to-abate emissions is unavoidable for achieving net zero CO_2 or greenhouse gas emissions. In addition to the compensation for residual emissions, cost optimization models of climate economics further assume NET deployment to counterbalanceto delays in mitigation and insufficient decarbonization, depending on the scenario, in order to solve the equation for the emission budget of a specific climate target (IPCC, 2022; Kriegler et al., 2018; Rogelj et al., 2015). Integrated assessment models (IAMs) following this rationale project cumulative negative emissions (NE) in the order of 200–1,000 Gt CO_2 required over the 21st century as a condition to limit mean global warming to 2°C or below (IPCC AR6 C1-C3 scenarios, (Byers et al., 2022)), typically relying to a large degree on Bioenergy with Carbon Capture and Storage (BECCS).

While these high NE rates might be most efficient in terms of economic costs, the corresponding scenarios of land and resource use often involve severe pressures on the environment. Realistic and responsible pathways for NET deployment thus require a multi-dimensional assessment of technical, economic and governance barriers combined with environmental constraints. This study aims to contribute to the evaluation of opportunities within the latter by assessing biochar sequestration as a NET system of land-neutral biomass production on (sub-)tropical croplands using biochar-mediated yield increases (YI) to maintain calorie production while realizing net CO_2 extraction from the atmosphere.

Across science, policy, NGOs, business and industry, the high deployment rates for NETs and particularly the large-scale deployment of BECCS are viewed critically (Forster et al., 2020) because the roles of ethics (Anderson & Peters, 2016; Lenzi et al., 2018), financial viability (Bednar et al., 2019) and negative effects on the biosphere (Boysen et al., 2017; Heck et al., 2018; Humpenöder et al., 2018) are largely neglected. As biomass-based NETs compete for land with food production and ecosystem protection, they bear the risk to impede other sustainability goals (Boysen et al., 2017; Humpenöder et al., 2018; Smith et al., 2019) and to lead to further transgressions of planetary boundaries (Heck et al., 2018). The debate around large-scale feasibility of BECCS as a NET for reaching the goals of the Paris Agreement is therefore a debate around unattractive trade-offs between stabilizing the climate system and protecting the biosphere from increasing overexploitation.

In this context, we investigate in this study whether carbon sequestration using biochar applications to agricultural soils in a land- and calorie-neutral manner could alleviate such concerns and what fraction of the demand foreseen in decarbonization scenarios could be supplied without the environmental side effect of expanding intensified land use or increasing pressure on food production systems. In such a scheme of land-as well as calorie-neutral pyrogenic carbon capture and storage (LCN-PyCCS), biomass would be grown on land, processed into biochar through pyrolysis, and applied to fields to increase crop yields, as observed in numerous field studies (Joseph et al., 2021; Lehmann et al., 2021; Schmidt et al., 2021).

PyCCS is based on pyrolysis, the thermochemical decomposition of biomass at 350–900°C in an oxygen-deficient atmosphere. The biochar produced in this process can be used as soil amendment for long-term carbon removal (Lehmann et al., 2021; Schmidt et al., 2019), for which the residence time can be predicted by the biochar's H/C_{org} or O/C ratio or, as a surrogate, the processed feedstock type plus highest-heating temperature that is reached during production (Woolf et al., 2021). Offering market-ready and scalable technologies (UNEP, 2017; Woolf et al., 2010), PyCCS is particularly favorable for early NET deployment. Furthermore, biochar used as soil amendment has been shown to improve agricultural plant and soil parameters (review of meta-studies, Schmidt et al. (2021)) including the significant increase in crop yields in many regions (Jeffery et al., 2017; Ye et al., 2020). This provides another financial benefit and the opportunity to produce biomass input from dedicated fast-growing crops in land-neutrality. With biochar-mediated YI, as reported especially for the (sub-)tropics in the latest meta-analyses (Jeffery et al., 2017; Ye et al., 2020), the same amount of food can be produced on less land. Thus, a fraction of the cropland can be dedicated to fast-growing crops supplying PyCCS without requiring additional land. With this LCN-PyCCS application, farmers may produce the feedstock for their own biochar application resulting in beneficiary soil properties at the same time as they generate NE, but without applying additional pressure on land use. Additional potential carbon capture and storage (CCS)-reinforcing returns of investment of biochar use, such as additional soil organic carbon increases (Blanco-Canqui et al., 2020) or N_2O or fossil carbon emission reductions by application of biochar production systems (Lehmann et al., 2021; Woolf et al., 2021) were not included in our assessment but serve as conservative guardrails.

While unreasonable PyCCS (or otherwise, BECCS) feedstock production may result in a substantial loss of natural vegetation if biomass plantations were to be established on hitherto uncultivated land (Werner et al., 2018), LCN-PyCCS relies on inputs from dedicated crops that do not claim additional land. Further sustainable biomass sources with minimal land footprints are residues from cropland or forestry (Laird et al., 2009; Woolf et al., 2010) as long as it does not diminish existing regional land-based carbon pools (soil organic carbon; carbon stocks in wood etc.). However, the estimates of globally available crop residues include significant uncertainties (Wirsenius, 2000). While studies provide initial estimates of the sustainable potential of PyCCS based on biogenic sources and dedicated feedstock plantations on marginal land (Laird et al., 2009; Woolf et al., 2010), the NE potential of LCN-PyCCS based on purpose-grown crops at constant calorie supply and cropland extent has not been quantified yet.

10.1029/2021EF002583

In this study, we apply the process-based dynamic global vegetation model LPJmL ("Lund-Potsdam-Jena managed Land," (Schaphoff et al., 2018)) to calculate the biogeochemical NE potential of LCN-PyCCS for the time period of 2020–2099 based on different assumptions on the achievable level of biochar-mediated YI (15%–30%). Contrary to demand-driven approaches followed by climate economic pathway models, employing NE to meet a specific climate target, we follow a supply-driven approach and quantify the NE potential within the constraints of calorie- and land-neutrality. Furthermore, we analyze the resulting potential benefits of substituting NE from plantation-based BECCS by NE from LCN-PyCCS for nature restoration or additional food production. Following these two substitution schemes, we quantify the maximum area of conservational interest that could be spared for nature protection and alternatively, the maximum area of additional cropland that could be established instead of biomass plantations dedicated to BECCS.

2. Methods

2.1. LPJmL Model

We apply the LPJmL model to simulate the potential biomass production as feedstock for LCN-PyCCS, realizing net CO_2 extraction from the atmosphere while staying within the global bounds of current (2015) cropland and maintaining current calorie production. LPJmL operates at daily time steps and at a spatial resolution of $0.5° \times 0.5°$ simulating key ecosystem processes in direct coupling of the carbon and hydrological cycle. Detailed descriptions and validations of the biogeochemical dynamics can be found in Schaphoff et al. (2018), hence only a short summary is provided here.

In addition to the representation of vegetation by 11 natural plant functional types, 13 crop functional types and managed grassland (von Bloh et al., 2018), LPJmL includes three types of fast-growing second-generation energy crops parametrized as eucalypt in tropical climates and poplar and willow in temperate climates for woody types and C4 grass for herbaceous energy crops (Beringer et al., 2011; Heck et al., 2016). In this study, only fast-growing grasses are considered for the feedstock of BECCS and PyCCS. In the cost optimization for BECCS, the grasses performed better than tree plantations, while the PyCCS scenarios rely on annual harvest of the grasses for constant biochar supply. Fast-growing grasses are assumed to be harvested once or several times a year in LPJmL (i.e., 85% leaf mass at the annual peak or if aboveground carbon storage >400 g m^{-2}).

Preceding the simulations of future land use, an initial spin-up of 5,000 years was performed to achieve an equilibrium of soil carbon and distribution of natural vegetation, followed by 390 years of a transient spin-up accounting for the influence of agriculture on the carbon balance with historic land use change and irrigation management until 2015 based on the HYDE 3.2 gridded data product (Klein Goldewijk et al., 2017).

The model is driven by climate projections for 2020–2099 from the HadGEM2-ES General Circulation Model ("Hadley Center Global Environment Model version 2—Earth System," (Collins et al., 2008)) contributing to the Inter-Sectoral Impact Model Intercomparison Project ISIMIP2b ensemble representing RCP2.6 SSP2 pathways (Frieler et al., 2017) and corresponding CO_2 concentrations to account for climate change effects in the future. This climate model was chosen here because (a) it was available with bias correction (Lange & Büchner, 2017), (b) the climate responses have largely been evaluated by a wide range of climate impact assessments in ISIMIP2b and (c) HadGEM2-ES temperature and precipitation responses to emission pathways are in the middle range of the climate models in ISIMIP2b (Frieler et al., 2017). Further, the RCP2.6 scenario was the lowest emission pathway in the CMIP5 phase, requiring rapid and stringent decarbonization and/or large-scale deployment of NETs, which is central to our assessment here. The potential role of NE in other RCPs is low or neglectable and thus does not require the evaluation of alternative NET approaches as urgently as RCP2.6 compatible scenarios. In addition, the shared socio-economic pathway SSP2 provides future development assumptions in a middle-of-the-road scenario for this assessment, while more extreme cases would require further evaluations.

2.2. Land Use Scenarios

In the future simulation period, the extent of cropland and biomass plantations vary between a reference scenario representing areas for future BECCS and agriculture and the different LCN-PyCCS scenarios of distinct levels of biochar-mediated YI, leading to different NE potentials. The reference scenario provides future cropland and biomass plantations areas for BECCS, according to a realization of the RCP2.6 SSP2 scenario from the

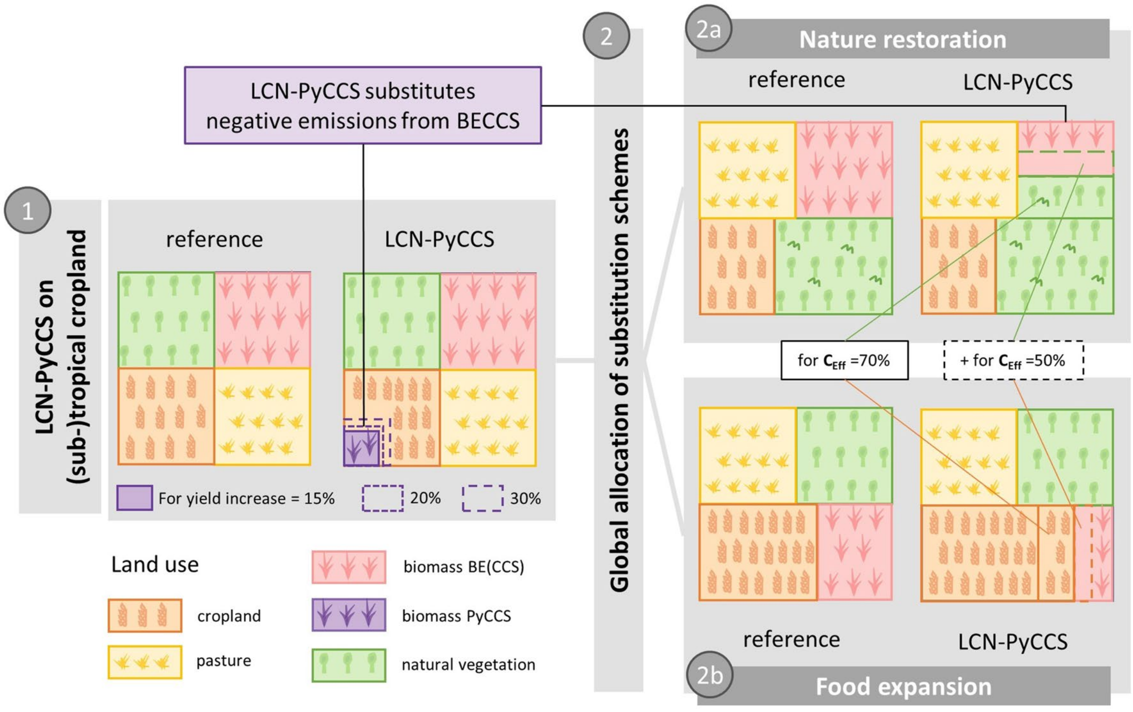

Figure 1. Visualization of land use allocation in generic grid cells of the global pattern for the reference scenario and the land- and calorie-neutral approach to pyrogenic carbon capture and storage (LCN-PyCCS) scenarios of three different levels of biochar-mediated yield increases (15%, 20%, and 30%) resulting in different potentials of LCN-PyCCS negative emissions on (sub-)tropical cropland (1) and two substitution schemes (2) allocating cells globally to replace biomass plantations for bioenergy with carbon capture and storage (BECCS) either (2a) by natural vegetation in areas of conservational interest (see S4, Figure S2 in Supporting Information S1) for nature restoration or (2b) by cropland in the most productive regions for food expansion. The carbon sequestration efficiency of BECCS (C_{Eff} = 50% or 70%) determines the share of biomass plantation area of the reference scenario that is dedicated to BECCS and can be substituted by negative emissions of LCN-PyCCS, while the remaining share contributes to sole bioenergy production. The higher the negative emissions potential of LCN-PyCCS (i.e., with higher biochar-mediated yield increases), the more cells are affected by the substitution.

global land use allocation model MAgPIE (Dietrich et al., 2019) in the ISIMIP2b ensemble consistent with the HadGEM2-ES climate input (see 3.1) and the historic HYDE data set (Frieler et al., 2017).

Based on these projections of future cropland extent, we developed the LCN-PyCCS scenarios. For the three scenarios of distinct YI levels (+15, +20, +30%) we assumed biochar-mediated YI exclusively on cropland within tropical and subtropical regions of the Köppen-Geiger classification as the most significant yield effects were reported for the tropics (Jeffery et al., 2017; Ye et al., 2020). Following the LCN-PyCCS approach, the YI allows to dedicate a fraction of the cropland to PyCCS feedstock production providing self-sufficient biochar supplies plus NE while maintaining calorie production (Figure 1). The fraction of the cropland that could potentially be rededicated to PyCCS depends on the level of YI (S1, Table S1 in Supporting Information S1). For example, if the yield increased by 15%, 115% of the calories could be produced on the same area, while, alternatively, about 87% (1/1.15) of the land could supply 100% of the calories, leaving 13% available for biomass production supplying PyCCS. In the LCN-PyCCS scenario, this land use shift is realized for the cropland in each grid cell of the (sub-)tropics. Emphasizing the advantage of LCN-PyCCS as a decentral application, we model these cells as closed systems of agriculture without trade of biochar. Thus, in order to supply sufficient biochar for the remaining cropland in the system (i.e., 2 t/ha, the upper end of current application rates concluded in Schmidt et al. (2021)), the biochar yield needs to be particularly high if the YI are relatively low (S1).

We tested the extent of suitable land for four different levels of YI: +10, +15, +20, and +30%. As we found that YI of 10% couldn't reach a potential relevant for large-scale interventions for climate stabilization, this scenario was excluded in subsequent analyses (S1). The scenario of 15% YI builds the base scenario which approaches the mean value reported for biochar application on (sub-)tropical cropland (14.8%) in the latest meta-analysis by Ye et al. (2020). We assume another scenario of 20% YI as an advanced application scenario, similar to the higher range of the confidence interval of Ye et al. (2020) (21.8%). Additionally, we explore options of optimized biochar application with a YI level of 30%, accounting for practices in combination with complementary fertilizer adaptation that show significantly higher positive effects on yields (Schmidt et al., 2017; Ye et al., 2020). It can be expected that, as our knowledge in biochar-based fertilization increases, the use of tailored biochars for different soils and crops will shift toward the most effective, return-of-investment strategies of implementation (Joseph et al., 2021; Schmidt et al., 2021). Thus, assuming average YI (as provided by meta-studies) can be seen as a conservative baseline considering the fact that YI have also been reported for temperate soils at or above 10°C annual mean temperature, or that farmers will use the best (highest) YI practices (Pandit et al., 2018; Schmidt et al., 2017; Sutradhar et al., 2021).

2.3. NE Potential

For the quantification of NE potentials, we transformed the biomass carbon potentially produced on the (sub-)tropical cropland rededicated to PyCCS into sequestered carbon of biochar in the soil. The calculation was based on parameters of the standard so-called rotary kiln type slow pyrolysis system with the highest treatment temperature of 450°C and no reactive or inert gas injection (Fagernäs et al., 2012; Peters et al., 2017). With this selection of pyrolysis parameters, we chose a reasonable compromise between a rather high biochar yield (55% of the initial biomass carbon) and extended biochar mean residence times in soils (>750 years, (Camps-Arbestain et al., 2015; Lehmann et al., 2015)) which increase as the pyrolysis temperature increases with the H/C_{org} ratio decreasing accordingly (Lehmann et al., 2021). The potential biomass production is, thus, multiplied with a PyCCS conversion efficiency of 47% to calculate the potential NE in each scenario (see S2 for details of distribution of carbon and assumptions on expenditure and leakage).

2.4. Substitution Schemes

Subsequently, we assess the potential benefits of NE from LCN-PyCCS substituting NE from plantation-based BECCS. Land freed from BECCS due to NE from LCN-PyCCS could be used for a mix of increased food production and restoring nature. Representing the extremes of prioritizing one approach over the other, we quantify the maximum potential for each of the two schemes, "nature restoration" and "food expansion." In both cases, PyCCS replaces the CO_2 removal of BECCS, while the energy fraction is assumed to be compensated through other more cost-efficient regenerative sources (see S3).

The areas dedicated to BECCS are based on distribution of second-generation bioenergy plantations in the reference scenario. However, the NE that could be generated from the harvest of all of these plantations would exceed the NE demand assumed for this RCP2.6 SSP2 scenario, as these areas also supply bioenergy production without CCS (Bauer et al., 2017). Therefore, we only assume a fraction of the plantations to actually be dedicated to BECCS corresponding to the ratio of BECCS to bioenergy without CCS projected in the reference scenario (S4). The biomass production on these BECCS areas is transformed into NE potentials assuming carbon capture efficiencies (C_{Eff}) of, respectively, 50% or 70% for the BECCS technology. The chosen C_{Eff} range represents the uncertainties regarding the realized mix of technologies (i.e., combustion, fermentation, gasification etc.) as well as the actual performance of the BECCS technologies (Cuéllar-Franca & Azapagic, 2015; Gough et al., 2018; Schakel et al., 2014).

The substitution scheme "nature restoration" aims to increase the area of significant conservational interest (ACI) that is being released due to NE substitution by LCN-PyCCS. These areas are here assumed to encompass biodiversity hotspots (Mittermeier et al., 2011), protected areas (IUCN&UNEP-WCMC, 2015), intact forest landscapes (Potapov et al., 2017), and areas of particularly high endemism richness (Kier et al., 2009) (S5, Figure S2 in Supporting Information S1). The allocation algorithm of the "nature restoration" scheme prioritizes the restoration of these particularly vulnerable areas when reallocating areas from biomass plantations for BECCS to nature protection (Figure 1). We refer to nature restoration rather than nature protection, as BECCS plantation are established at the expense of cropland and pastureland in the reference scenario, following the SSP2 narrative (Popp et al., 2017).

For the "food expansion" scheme, we assume that some biomass plantations formerly dedicated to BECCS in the reference scenario will be used for crop production instead (Figure 1). For this case, we aim to maximize the potential calorie production on the land released from BECCS feedstock production. In our assessment, we consider the primary calorie production of crops intended for direct human consumption, animal feed, industrial

10.1029/2021EF002583

Table 1
Area of Feedstock Production, NE Potential and Substitution Potentials for Nature Restoration or Food Production Expansion for Three LCN-PyCCS Scenarios of Different Levels of Biochar-Mediated Yield Increases (15%, 20% and 30%, Rows)

Yield increase scenario	Area feedstock production LCN-PyCCS [Mha]	Annual NE potential LCN-PyCCS [Gt CO_2]	Cumulative NE potential LCN-PyCCS [GtCO_2]	BECCS substitution: Nature restoration—area of restoration [Mha]		BECCS substitution: Food expansion—max. additional calorie production [%]	
				C_{Eff} 50%	C_{Eff} 70%	C_{Eff} 50%	C_{Eff} 70%
15%	13.66	0.44	33.30	19.11	13.69	3.30	2.72
20%	45.39	1.23	93.86	46.90	33.50	8.81	6.59
30%	112.76	2.62	200.92	95.73	68.91	15.71	11.26

Note. BECCS, bioenergy with carbon capture and storage; LCN-PyCCS, land- and calorie-neutral approach to pyrogenic carbon capture and storage; NE, negative emissions; PyCCS, pyrogenic carbon capture and storage. The annual NE potential represents the mean value of calculated annual rates and the cumulative NE potential is calculated as the sum over 2020–2099. The area potentially restored for nature is the maximum area of conservational interest (see Methods and S5) that could be rededicated from biomass plantations to nature restoration when substituting NE from BECCS by LCN-PyCCS, given as the average over 2060–2099. The results for the alternative substitution scheme of food expansion are expressed as relative maximum increase in primary calorie production. Both schemes are calculated for two levels of carbon sequestration efficiency for BECCS: 50% and 70%. For more details see Table S1 and Table S4 in Supporting Information S1.

uses, seeds, and first-generation biofuels, disregarding feed baskets and diets. The carbon production in the storage organs of the crops simulated in LPJmL are converted to fresh matter according to Wirsenius (2000) and subsequently from fresh matter to calories based on FAO balance sheets for unprocessed food (FAO, 2001). We focus on the relative change in potential calorie production comparing the reference scenario and the scenarios of the "food expansion" scheme. For this, we assume the crop composition of each cell to expand proportionally on the land reallocated to food production.

3. Results

We quantified a NE potential of about 0.44 Gt CO_2 yr^{-1} on 14 Mha cropland in the (sub-)tropics for LCN-PyCCS in the base scenario of 15% YI (mean value after an introduction phase of expanding linearly over 5 years, Table 1). This is equivalent to 1.3% of present annual CO_2 emissions. As Figure 2 indicates, the relatively constant extent of cropland during the 21st century in the reference scenario results in relatively stable rates of NE from LCN-PyCCS. The cropland available for reallocation in the (sub-)tropics acts as the main driver for the spatial distribution of NE potentials from LCN-PyCCS (Figure 3). Another crucial factor is the simulated biomass yield: Not only does the biomass harvest provide the PyCCS feedstock and thus defines the overall NE potential, but it also determines whether a region is suitable for LCN-PyCCS, that is, supplying enough biomass for sufficient biochar application on cropland to generate YI that allow for reallocation of land (S1). As lower levels of YI result in lower fractions on cropland available for rededication to feedstock production, the scenario of 15% YI relies on particularly productive regions in the inner tropics to produce sufficient biochar, while the area suitable for LCN-PyCCS expands for 20% YI and 30% YI (Figure 3, Figure S1 in Supporting Information S1).

Until the end of the century, NE potentials of LCN-PyCCS add up to a cumulative sum of 33 Gt CO_2 if full capacity of the approach was followed after 2025. This corresponds to 10% of the NE demand from BECCS and 6% of the total NE demand projected in IAM scenarios likely limiting global warming to 2°C or below in the IPCC AR6 database (respective median NE sums over 2020–2100 across C1-C3 scenarios, (Byers et al., 2022)). For 1.5°C-consistent scenarios with a high overshoot that require a significantly larger amount of NE to draw down the emissions, the respective share of the total NE demand potentially provided by LCN-PyCCS would only be about 5%. In contrast, the annual sequestration rate equals 23% of the annual NE projected for mid-century by the International Energy Agency (IEA) in the scenario of net zero emissions by 2050 (IEA NZE), indicating distinct levels of reliance on NE, and different trajectories, in different approaches to emission scenarios.

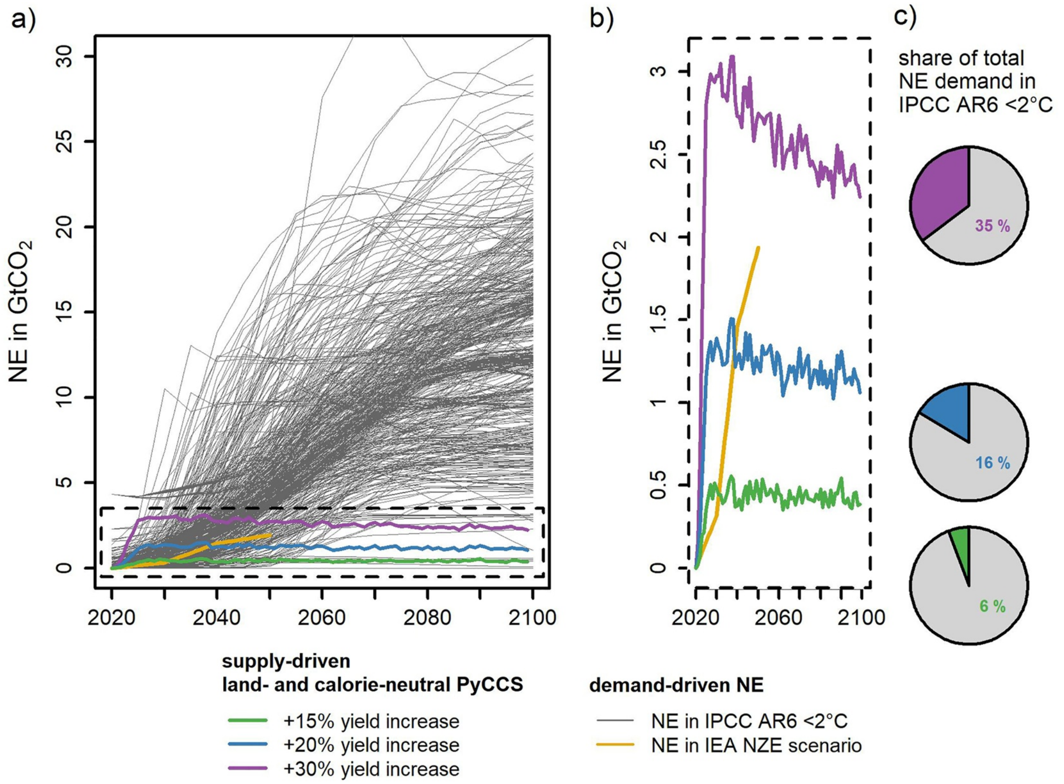

Figure 2. Negative emissions (NE) produced by land- and calorie-neutral approach to pyrogenic carbon capture and storage (LCN-PyCCS) (15% YI green, 20% YI blue, and 30% YI purple lines) compared to trajectories of a scenario of net zero emissions by 2050 International Energy Agency ([IEA] NZE, orange line, IEA, 2021) and the Intergovernmental Panel on Climate Change (IPCC) AR6 database compatible with a maximum warming of 2°C or below (gray lines, C1: limit warming to 1.5°C (>50%) with no or limited overshoot, C2: return to 1.5°C (>50%) after a high overshoot, C3: limit warming to 2°C (>67%), (Byers et al., 2022)). Panel (b) shows the NE rates of the IEA NZE scenario and the LCN-PyCCS scenarios of different levels of yield increase on a larger scale for more details. In panel (c), the cumulative sum of NE produced in the different LCN-PyCCS scenarios until 2100 are represented in relation to the total NE demand in IPCC AR6 scenarios limiting warming to 2°C or below (median).

The cumulative sum of NE from LCN-PyCCS depends on the starting point and length of the employment phase. For example, a delay of 10 years, that is, reaching full capacity of the LCN-PyCCS approach only in 2035, not in 2025, would reduce the total sum of NE over the century to 29 Gt CO_2.

Land spared from BECCS due to NE from LCN-PyCCS could be dedicated to a mix of alternative uses, that is, restoring nature and increased food production. A maximum of 19 Mha (for BECCS C_{Eff} 50%, 14 Mha for C_{Eff} 70%) could be reserved for nature preservation or restoration in areas of conservation interest rather than dedicating these areas to BECCS (Figure 4, Table 1). This area corresponds to about 73% of the extent of Africa's 10 largest national parks (for BECCS C_{Eff} 50%; 54% for BECCS C_{Eff} 70%). Alternatively, a maximum of about 18 Mha could potentially be rededicated to food production and provide an extra ~3% of the global primary calorie production, (Figure S3 in Supporting Information S1, 3.3% for BECCS C_{Eff} 50%; 13 Mha and 2.7% for C_{Eff} 70%, respectively). This alternate use of land for biomass plantations for food production is mainly allocated to particularly fertile cropland in the Yellow River region of China and the Pampas in Argentina, as the most effective contributors in regions planned for biomass production in the reference scenario are prioritized, that is, cells with high kcal/ha values for primary calorie production (Figure S4 in Supporting Information S1). While this substitution scheme aims to indicate maximum potentials for additional food production, another assumption could be the equal distribution of cropland allocation across all areas where existing cropland could be expanded. This alternative scheme would result in ~2% additional primary calorie production (Table S5 in Supporting Information S1, 2.1% for BECCS C_{Eff} 50%; 1.5% for C_{Eff} 70%, respectively).

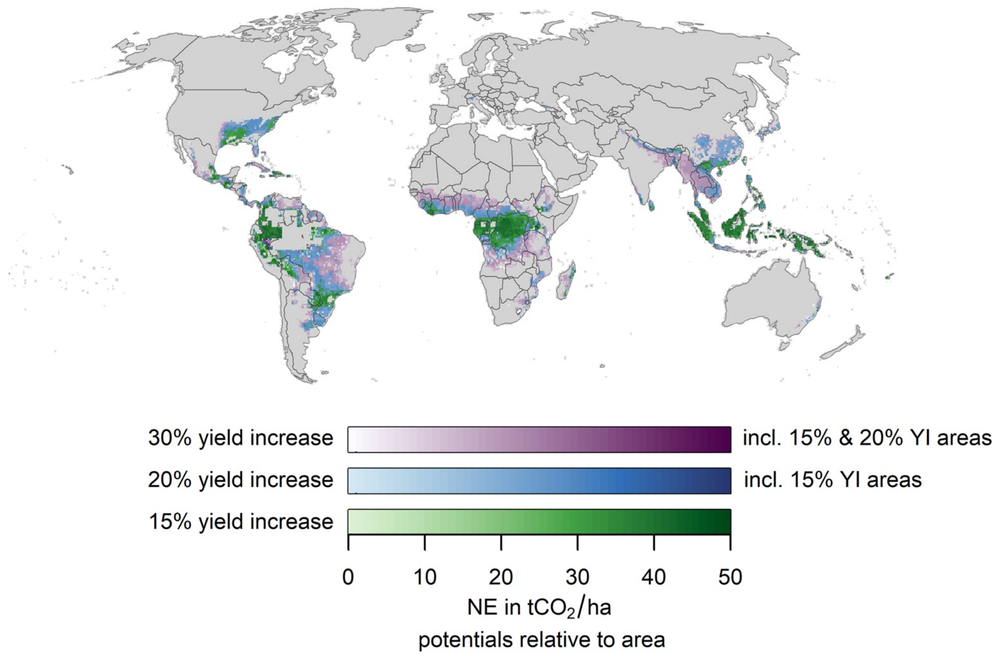

Figure 3. Global distribution of negative emission potentials relative to the area of biomass feedstock production for land- and calorie-neutral approach to pyrogenic carbon capture and storage in the scenarios of 15% yield increase (green), 20% yield increase (blue) and 30% yield increase (purple) for the year 2099. Scenarios of higher yield increase include the areas of the scenarios with lower yield increases.

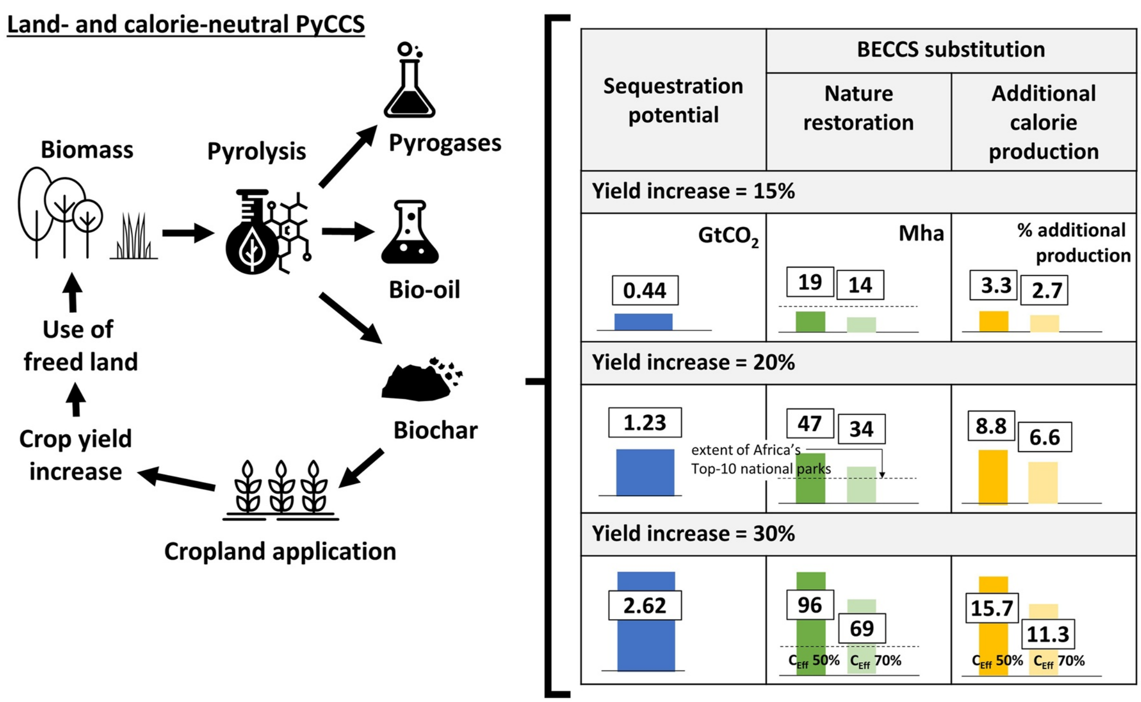

Figure 4. Schematic representation of land- and calorie-neutral PyCCS (LCN-PyCCS) including bar plots (right panel) for the CO_2 sequestration potential (blue bars) and the substitution potentials for nature restoration (green for bioenergy with carbon capture and storage (BECCS) carbon sequestration efficiencies of 50%, light green for 70%, respectively) and food production expansion (orange for BECCS carbon sequestration efficiencies of 50%, yellow for 70%, respectively) for three LCN-PyCCS scenarios of different levels of biochar-mediated yield increases (15%, 20% and 30%, rows). The numbers are based on the same time periods and references as given in Table 1. For comparison of the maximum area of conservational interest that could be rededicated from biomass plantations to nature restoration, the total extent of Africa's 10 largest national parks (~26 Mha, IUCN&UNEP-WCMC (2021)) is indicated as a dashed line.

Higher levels of YI could significantly increase the NE potential (Figure 2) and substitution benefits (Figure 4) of LCN-PyCCS. For the 20% YI scenario, representing an advanced application similar to the higher range of the confidence interval in Ye et al. (2020), we calculated an average annual NE rate of 1.23 Gt CO_2 yr^{-1} by LCN-PyCCS (Table 1). This equals a substantial 63% of the NE projected for the IEA NZE scenario. Until the end of the century, the NE would cumulatively amount to 94 Gt CO_2, corresponding to about 16% of the total NE demand projected in IPCC IAM scenarios compatible with warming below 2°C or 1.5°C (Figure 2). Accordingly, a higher fraction of NE from BECCS could be substituted by LCN-PyCCS, releasing more land for nature restoration or food production, respectively. The maximum area of conservational interest that could potentially be reserved or restored in the 20% YI scenario extends to 47 Mha (for BECCS C_{Eff} 50%; 34 Mha for BECCS C_{Eff} 70%), while maximizing the additional food production in the substitution scheme could result in almost 9% increase in primary calorie production (8.81% for BECCS C_{Eff} 50%; 6.59% for BECCS C_{Eff} 70%). Assuming equal distribution of cropland allocation instead of the optimization would lead to ~6% extra calorie production (Table S5 in Supporting Information S1, 5.66% for BECCS C_{Eff} 50%; 4.05% for BECCS C_{Eff} 70%)

In the assessment of the 30% YI scenario, which represents optimized application doubling the effect in the base scenario as a diagnostic element, we quantified an average annual NE rate of 2.62 Gt CO_2 yr^{-1} for LCN-PyCCS (Table 1). Compared to the IEA NZE scenario, this increased sequestration rate amounts to 135% of the NE projected for the total energy sector. This LCN-PyCCS potential could sum up to 201 Gt CO_2 until 2099, comparing to 35% of the overall NE demand in IPCC IAM scenarios limiting global warming to 2°C or below (IPCC C1-C3) and, if evaluated separately, about 31% of the NE demand in 1.5°C-consistent scenarios with high overshoot (C2). When releasing land from BECCS to nature restoration due to NE from LCN-PyCCS in the 30% YI scenario, up to 96 Mha of ACI could be restored, comparing to more than 3.5 times the extent of Africa's 10 largest national parks (for BECCS C_{Eff} 50%; 69 Mha for BECCS C_{Eff} 70%). Alternatively, a maximum of about 16% additional primary calories could be produced (15.71% for BECCS C_{Eff} 50%; 11.26% for BECCS C_{Eff} 70%). With higher NE potential, the land rededicated from biomass production to food supply increases in the Yellow River region and the Pampas and further expands to Northeast China, Europe and moderately in India, Pakistan and the USA (Figure S5 in Supporting Information S1). Aiming at the equal distribution of additional cropland across suitable areas would however affect all these regions equally, even at lower NE levels, and sum up to a ~12% increase of primary calories in the 30% YI scenario (11.55% for BECCS C_{Eff} 50%; 8.25% for BECCS C_{Eff} 70%).

4. Discussion

This study quantifies the global NE potential of land- and calorie-neutral PyCCS (LCN-PyCCS) as a system of land-neutral biomass production on (sub-)tropical croplands using biochar-mediated YI to maintain calorie production. In spatially detailed simulations of biomass production as a function of climatic conditions, we found that 33–210 Gt CO_2 can be sequestered from the atmosphere as pyrogenic carbon in soils until the end of the century, depending on the level of biochar-mediated YI achieved, pointing toward the necessity of research and development of effective, soil- and crop-tailored biochar-based fertilizers (Joseph et al., 2021). The NE produced by LCN-PyCCS could further be used to replace NE from BECCS and alleviate the problematic additional land use pressure of biomass-based NETs, as demonstrated in the substitution schemes of this study. The comparably low contribution to overall NE demands calculated by IAMs (Figure 2) originates from the distinct rationales: the here presented supply-driven biogeochemical potential assessment of LCN-PyCCS as a low-pressure approach versus demand-driven IAM scenarios of cost optimization relying mainly on large-scale BECCS to reach a certain climate target.

We assess LCN-PyCCS as one particular sustainable application of a specific NET that aims to produce NE while staying within the bounds of cropland area and maintaining calorie production. In contrast, integration of large-scale BECCS into the global land use system is not possible without substantially increasing environmental pressures and contributing to further transgression of terrestrial planetary boundaries (Heck et al., 2018). Accordingly, we found that only a fraction of NE demand projected in IAM scenarios compatible with the 1.5°C or 2°C target can be met by more environmentally sustainably LCN-PyCCS (Figure 2), while the remaining demand for meeting these trajectories likely implies substantial conflict with non-climatic dimensions of the Earth system.

However, a new generation of IAM scenarios with NET deployment rates reduced by ~40% is expected to emerge due to alternative carbon pricing schemes, that is, carbon price trajectories that start high and rise only moderately after emission neutrality instead of following the hoteling rule (Strefler et al., 2021). This could increase the relative contributions of LCN-PyCCS to the total NE demand up to roughly 7%–46%, depending on the YI achieved. Further, as the trade-offs for large-scale NET deployment and especially BECCS became widely recognized, IAM scenarios of limited NET deployment were increasingly explored and implications for carbon pricing, timing of climate policies and stringency of measures were further assessed (Grubler et al., 2018; Kriegler et al., 2018; Strefler et al., 2018; van Vuuren et al., 2018). Drawing a corridor for realistic assumptions on mitigation options, Warszawski et al. (2021) describe global NE levels of below 3 Gt CO_2 as "reasonable," 3-7 Gt CO_2 as "challenging" and >7 Gt CO_2 as "speculative" (sum of NE from BECCS, direct air capture and enhanced weathering) and, thus, would rate most IPCC scenarios compatible with a maximum warming 1.5°C or 2°C as unreasonable. Assuming "reasonable" NE rates of maximally 3 Gt CO_2, LCN-PyCCS could satisfy 15%, 41% or 87% of the NE demand with YI of 15%, 20%, or 30%, respectively. Yet, the definition of "reasonable" remains subject to debate; for example, in contrast to the findings of Heck et al. (2018) showing that merely any expansion of biomass plantations would be possible if further transgression of planetary boundaries were to be avoided.

The IEA scenario designed to reach net zero CO_2 emission from energy and industry by 2050 (NZE IEA) presents a different approach to NE deployment than followed by IAMs shaping the scenarios in previous IPCC reports. The roadmap for the energy and industry sector excludes any offsets from land use or forestry and restricts bioenergy to around 100 EJ limiting the expansion of plantations for feedstock production to 80 Mha and the overall NE supply from BECCS to 1.3 Gt CO_2 in 2050 (IEA, 2021). While the balancing in the NZE IEA scenario focuses on what is achievable within the energy and industry sector (i.e., compensating residual emissions through NE from direct air capture and BECCS), the report further debates contributions to a net zero balance in the AFOLU (agriculture, forestry and other land use) sector, concluding that especially the non-CO_2 greenhouse gases (5-6 Gt CO_2-eq yr^{-1}) are hard to abate and would require NET deployment. Considering LCN-PyCCS in this balance could entirely unfold the potential of the approach by compensating a minimum of about 7%–9% of the current non-CO_2 greenhouse gas emissions (for 15% YI; 21%–25% for 20% YI; 44%–52% of 30% YI) on the one hand and reducing agricultural emissions through biochar use as soil amendment on the other hand (see below), while staying within the bounds of cropland and maintaining calorie production.

We assessed a range of YI levels to account for uncertainties regarding the effect of biochar application on crop yields, such as soil properties, biochar characteristics and management practices. Over the last decade, the meta-analyses on biochar-mediated YI have first reported a grand mean of 10% YI in Jeffery et al. (2011) and 11% in Liu et al. (2013); then, in general no effect on temperate crops, but 25% YI in the (sub-)tropics in Jeffery et al. (2017) and, lately, responses separated by fertilization effects showing 1.4%–16.3% YI in temperate and 14.8%–40.6% YI in (sub-)tropical regions when compared to the fertilized and the non-fertilized controls, respectively, in Ye et al. (2020). Whereas the body of studies recording further details of biochar properties and application conditions is constantly growing and will allow meta-analyses to further differentiate between the factors influencing biochar-mediated YI, isolating the effects in the diverse applications will remain challenging. Yet, one of the most significant differences could still be identified for climate zones in Ye et al. (2020), originating from more strongly weathered soils in the tropics (Sattari et al., 2012; Schoumans et al., 2015) and historically larger loads of fertilizers applied to soils in temperate regions, positioning them closer to their maximum potential (Mueller et al., 2012), as already pointed out by Jeffery et al. (2017) and Ye et al. (2020).

In this diagnostic assessment of LCN-PyCCS, we, thus, analyzed a range of YI levels on (sub-)tropical cropland to provide results for a rather conservative case similar to the median response on fertilized cropland in the (sub-)tropics (15% YI) as well as for an advanced application representing the higher range of the confidence interval of these responses (20% YI). Further, we explore options of optimized biochar application with a YI level of 30%, considering practices in combination with complementary fertilizer adaptation resulting in significantly higher yields. Charging the biochar with organic fertilizers is already common practice, as practitioners aim for the largest benefit (Kammann et al., 2016; Schmidt et al., 2021). However, the yield response will depend on the management intensity before the biochar amendment. Consequently, when planned reasonably, realizing a biochar program on scarcely managed cropland would include charging the biochar with additional or previously unused organic fertilizers (such as cow urine, Schmidt et al. (2017) and Sutradhar et al. (2021): average YI of 50%–100% within a large number of practitioner field trials), leading to high YI levels as represented in our 30% YI scenario.

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However, when considering future biochar-mediated YI for LCN-PyCCS, further uncertainties are introduced by the YI assumptions already incorporated in the reference scenario (see the documentation for land use intensity in the MAgPIE model in Dietrich et al. (2012) for details). While some of the assumed benefits can be considered additive to the effects of biochar applications (i.e., new breeds, advances for agricultural machinery, and sowing dates), others might result from processes that can also be caused by biochar amendment (i.e., liming, improved synchronization of nutrient supply, and increased efficiency of fertilizers). Yet, most of the (sub-)tropical regions that are assumed for LCN-PyCCS deployment in this study are currently showing the largest yield gaps (Mueller et al., 2012). Kätterer et al. (2019) demonstrated persisting yield-improving effects of +1.2 Mg ha^{-1} for maize and +0.4 Mg ha^{-1} for soybean in the longest-running sub-Saharan field experiments in Kenya after two doses of biochar application over more than 10 years where "biochar addition" and "fertilizer application" were additive in increasing yields. Thus, additive methods are more likely to be applied in those regions in order to get closer to the yield potential.

While this analysis only accounts for biochar-mediated YI, further beneficiary effects induced by biochar amendment to agricultural soils will additionally promote large-scale application (Schmidt et al., 2021). Water holding capacities (Edeh et al., 2020; Gao et al., 2020; Omondi et al., 2016), root growth (Xiang et al., 2017), and the build-up of soil organic carbon (Bai et al., 2019; Blanco-Canqui et al., 2020; Weng et al., 2017) were observed to increase in soils enriched with biochar. Furthermore, it may reduce soil acidity (Chintala et al., 2014; Yuan et al., 2011), nitrate leaching (Borchard et al., 2019; Hagemann et al., 2017) as well as N_2O and CH_4 emissions (Borchard et al., 2019; He et al., 2017; Jeffery et al., 2016), which in total enhances soil quality, cuts down management costs and lowers agricultural greenhouse gas emissions (Kammann et al., 2017; Lehmann et al., 2021). Thus, the potential overall contribution of PyCCS to the challenge of shifting the land use sector from a greenhouse gas source into a sink is not represented in this study which solely assesses the sequestration potential of the pyrogenic carbon.

Estimates of global NE potentials of PyCCS range from 0.65 to 35 CO_2-eq $year^{-1}$ and vary significantly in their assumptions on feedstock and accounting for emission avoidance (Tisserant & Cherubini, 2019). The lower range is characterized by biogenic sources, while higher potentials (and thus environmental pressures) emerge from dedicated plantations for biochar production. Diverse feedstock options of low environmental impact are explored for residues from landscape management, hedgerow pruning, street-wood management and municipal waste (Randolph et al., 2017), but not assessed on a global scale yet.

Besides the feedstock availability, the overall NE potential is further largely dependent on the sequestration efficiency assumed for the pyrolysis process. While we base our assumptions on Schmidt et al. (2019) relying on mostly optimal, and thus preferred, process configurations from observations reported in (Neves et al., 2011), others follow a more conservative approaches based on mean observed values and derivations from related processes (Woolf et al., 2021). However, as we assess future PyCCS deployment, we assume that the configurations known for the best outcome (i.e., maximum carbon sequestration), as presented in Schmidt et al. (2019), will be implemented.

In addition, the sequestration potential can be increased significantly by storing further carbonaceous pyrolysis products in addition to the biochar: the bio-oil potentially pumped into depleted fossil oil repositories for long-term storage, and permanent-pyrogases that may also be transferred as CO_2 to geological storages with advanced techniques such as solar-power driven electrical pyrolysis (Schmidt et al., 2019). Moreover, alternative utility and storage options emerge for PyCCS and extend its application to carbon sinks in further sectors, that is, building or composite materials (Bartoli et al., 2020; Schmidt et al., 2019). The LCN-PyCCS scenarios assessed in this study, however, assume basic PyCCS with biochar as soil amendment aiming to represent a market-ready bottom-up implementation of large-scale NE for agricultural systems with self-sufficient biochar production. LCN-PyCCS is proposed as a scalable approach that can be integrated into diverse agricultural systems around the world and potentially contributes to the UN Sustainable Development Goals (SDGs), that is, through reducing dependencies on external resources, higher agroecosystem resilience, water purification, and clean cooking technology with pyrolyzers, as reported for biochar in Smith et al. (2019).

5. Conclusions

Climate stabilization is a top priority goal of Earth stabilization but runs the risk of considerably undermining the integrity of Earth's biosphere if supported by extensive plantation-based BECCS. In contrast, PyCCS deployment could be land-neutral if restricted to small-scale carbon farming on cropland while maintaining the calories supply of the remaining cropland through biochar-mediated yields increases, as observed in field experiments. We find a substantial gap between the NE required by demand-driven climate stabilization BECCS scenarios and the potential of supply-side, land- and calories-neutral PyCCS. These differences need to be made transparent in discussions of the feasibility and trade-offs of large-scale NE deployment on land. However, we quantified a substantial potential of land- and calories-neutral PyCCS to contribute to climate stabilization. While biomass-based NETs risk an evolution toward being a major driver of detrimental future land use change, adding to a continued deterioration of the Earth's biosphere, the LCN-PyCCS substitution scheme quantified in this study demonstrates how the approach may, within limits, contribute to lessening this problematic additional land use pressure and thereby to safeguarding a safe operating space for humanity.

Data Availability Statement

Data supporting the main findings of this study are available via https://doi.org/10.5281/zenodo.6595002. Land use and climate input data can be downloaded from the ISIMIP repository, https://data.isimip.org/ (Frieler et al., 2017) and https://doi.org/10.48364/ISIMIP.208515 (Lange & Büchner, 2017).

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