



Climate impact of bioenergy with or without carbon dioxide removal: influence of functional unit and parameter variability

Lisa Zakrisson¹ · Elias S. Azzi¹ · Cecilia Sundberg¹

Received: 28 June 2022 / Accepted: 2 February 2023 / Published online: 3 March 2023
© The Author(s) 2023

Abstract

Purpose Bioenergy with carbon dioxide removal (CDR) is increasingly proposed as an efficient way to mitigate climate change. This study examined the circumstances and methodological choices in which two CDR bioenergy systems were preferable to a reference bioenergy system from a climate change mitigation perspective. The CDR systems were also compared.

Methods Three systems were modelled: two CDR systems (Biochar, bioenergy with carbon capture and storage (BECCS)), with a combined heat and power (CHP) system as reference. A parameterised life cycle inventory (LCI) model was developed and computed for all systems and four different functional units (FUs), resulting in different distributions of climate impacts. Contribution analysis was performed, followed by pair-wise comparison of all scenarios to establish their ranking. First-order Sobol indices were computed to assess the contribution of each parameter to total variance. When ranking of scenarios was strongly dependent on parameter values, decision tree analysis was applied.

Results and discussion The CDR systems had a lower climate impact than CHP in most computations, across all FUs. On comparing the two CDR systems, the preferable system changed with FU. With heat or carbon sequestration as FU the Biochar system was preferable in general, while with electricity or biomass use as FU, the BECCS system had the lowest climate impact in most computations. For most system configurations, energy substitutions had a large influence and contributed most to the variance in results. The system ranking also depended on the reference activities in the background energy system.

Conclusions The Biochar and BECCS systems were generally preferable to the reference CHP system from a climate mitigation perspective, particularly when the reference energy systems had a relatively low climate impact. However, FU and parameters affected the system ranking. For comparing BECCS and biochar, case-specific climate impacts will be decisive, but not always conclusive, as the choice of FU has such large impact on the results.

Recommendations When conducting LCA of multi-functional systems, the use of several FUs, parameterised LCI, and contribution analysis allows for deeper investigation than conventional sensitivity analyses. When analysing the climate impact of bioenergy with or without carbon removal, it is especially important to perform sensitivity analysis on the energy background system, since it strongly affects the results.

Keywords Climate change · Environmental assessment · Carbon capture and storage · Biochar · Negative emission technologies · Functional unit · System expansion · Substitution · BECCS

1 Introduction

To achieve climate goals stated in the Paris Agreement, humanity must succeed in reducing greenhouse gas emissions. In addition, it is likely that carbon dioxide removal (CDR) technologies will be needed to reach net zero emissions and compensate for any overshoot of the carbon budget (IPCC 2021). Required carbon dioxide (CO₂) removal from the atmosphere during the twenty-first century is estimated to range from 150 to 1200 GtCO₂ depending on future development pathway (Minx 2018). The total annual

Communicated by Vanessa Bach.

✉ Lisa Zakrisson
lisa.zakrisson@slu.se

¹ Swedish University of Agricultural Sciences, Department of Energy and Technology, Uppsala, Sweden

anthropogenic CO₂ emissions in 2019 were approximately 42.2 Gt (Friedlingstein et al. 2020).

Biochar and bioenergy with carbon capture and storage (BECCS) are two CDR technologies that exploit the ability of biomass to capture CO₂ from the atmosphere via photosynthesis. Biochar is the carbon-rich solid produced from biomass pyrolysis (thermal degradation in partial or total absence of oxygen) (Woolf et al. 2010). Biochar produced under suitable conditions can remain stable in soil for centuries, thereby providing long-term carbon sequestration (Spokas 2010; Woolf et al. 2021). Biochar is also a product with economic value in various sectors (Oni et al. 2019; Sakhiya et al. 2020). Moreover, electricity and heat can be obtained from combustion of the gases and tars co-produced during pyrolysis. The BECCS process involves burning biomass for bioenergy generation, combined with capturing the CO₂ from flue gases and transporting it to a permanent geological storage site (Kemper 2015). Electricity and heat can be produced from the BECCS process in the same way as in a combined heat and power (CHP) bioenergy plant, but the carbon capture and storage (CCS) process consumes some of the electricity produced (Gustafsson et al. 2021; Levihn et al. 2019).

Previous CDR research highlights the importance of carbon accounting and often recommends the use of life cycle assessment (LCA) to guarantee that supply-chain emissions do not outweigh the amount of CO₂ captured (Tanzer and Ramirez 2019; Brander et al. 2021). CDR research also reckons that only system-wide changes in greenhouse gas emissions and sinks actually lead to climate change mitigation (Tanzer and Ramirez 2019; Brander et al. 2021). However, determining supply-chain emissions and system-wide emissions changes requires delimitation of system boundaries in LCA, which is not always straightforward for multi-functional bio-based systems such as Biochar and BECCS that deliver several products sharing supply-chain burdens and benefits. The environmental impacts of each product cannot always be distinguished, and the results may depend on the choice of functional unit (FU) (Ahlgren et al. 2015). Bio-based systems rely on biogenic resources, thus involving the short cycle of carbon and various stocks of biogenic matter. Changes in these stocks are assessed relative to a reference biomass form or land use and often make large contributions to the estimated climate impact (Cherubini and Strømman 2011; Koponen et al. 2018).

LCA can be used to compare the environmental performance of several CDR technologies and to inform decision-making. However, results from comparative LCA studies of bioenergy systems are affected by the methodological choices made, and comparing results from multiple studies is therefore difficult (Cherubini and Strømman 2011). On reviewing the biochar LCA literature, Terlouw et al. (2021) found that the calculated climate impacts from the studies were not comparable, partly due to the use of different FUs,

leading those authors to conclude that LCA results for CDR technologies must not be compared without further harmonisation, due to lack of consistency in methodological choices. These inconsistencies in methodological choices indicate a need to determine the extent to which different FUs lead to different conclusions in otherwise identical LCA. LCA results for bioenergy systems and CDR systems can also differ depending on choice of reference activity when performing substitutions (Koponen et al. 2018; Terlouw et al. 2021). Specifically, Matuščík et al. (2020) found that LCA results for biochar systems are difficult to compare, partly due to methodological inconsistencies, but also to contextual differences. Therefore, parameters should be defined when modelling a system, allowing parameter uncertainty and variability to be taken into account.

Considering the methodological difficulties (choice of FU, multi-functionality, parameter uncertainty, and variability) in comparative LCA of CDR technologies, the aim of this study was to determine the circumstances in which implementation of CDR in bioenergy systems is beneficial for climate change mitigation. An additional aim was to compare the climate impacts of Biochar and BECCS systems by conducting LCA with different methodological choices, such as parameter uncertainty and variability and choice of FU.

2 Methods

2.1 Goal and scope definition

2.1.1 Studied systems and products

Three systems (CHP, Biochar, BECCS) were modelled, and their climate impacts were calculated in LCA (Fig. 1). The CHP system was based on a bioenergy plant without CCS that produces heat and power. The Biochar system involved pyrolysis instead of combustion, and the system produced heat, power, and biochar. The BECCS system was based on a bioenergy plant similar to that in the CHP scenario, but with CCS technology separating CO₂ from the flue gas. These systems are multi-functional and deliver the following functions: electricity production, heat production, biomass use, carbon sequestration (Biochar and BECCS only), and biochar use (Biochar system only). In order to account for this multi-functionality, the substitution method was applied (see Sect. 2.2).

The biomass feedstock for all systems was assumed to be woodchips from logging residues (tops and branches) produced in close proximity to the power plant. The residues were assumed to be forwarded to a roadside storage site, stored for 8 months and then chipped. The woodchips were assumed to be transported by lorry to the power plant,

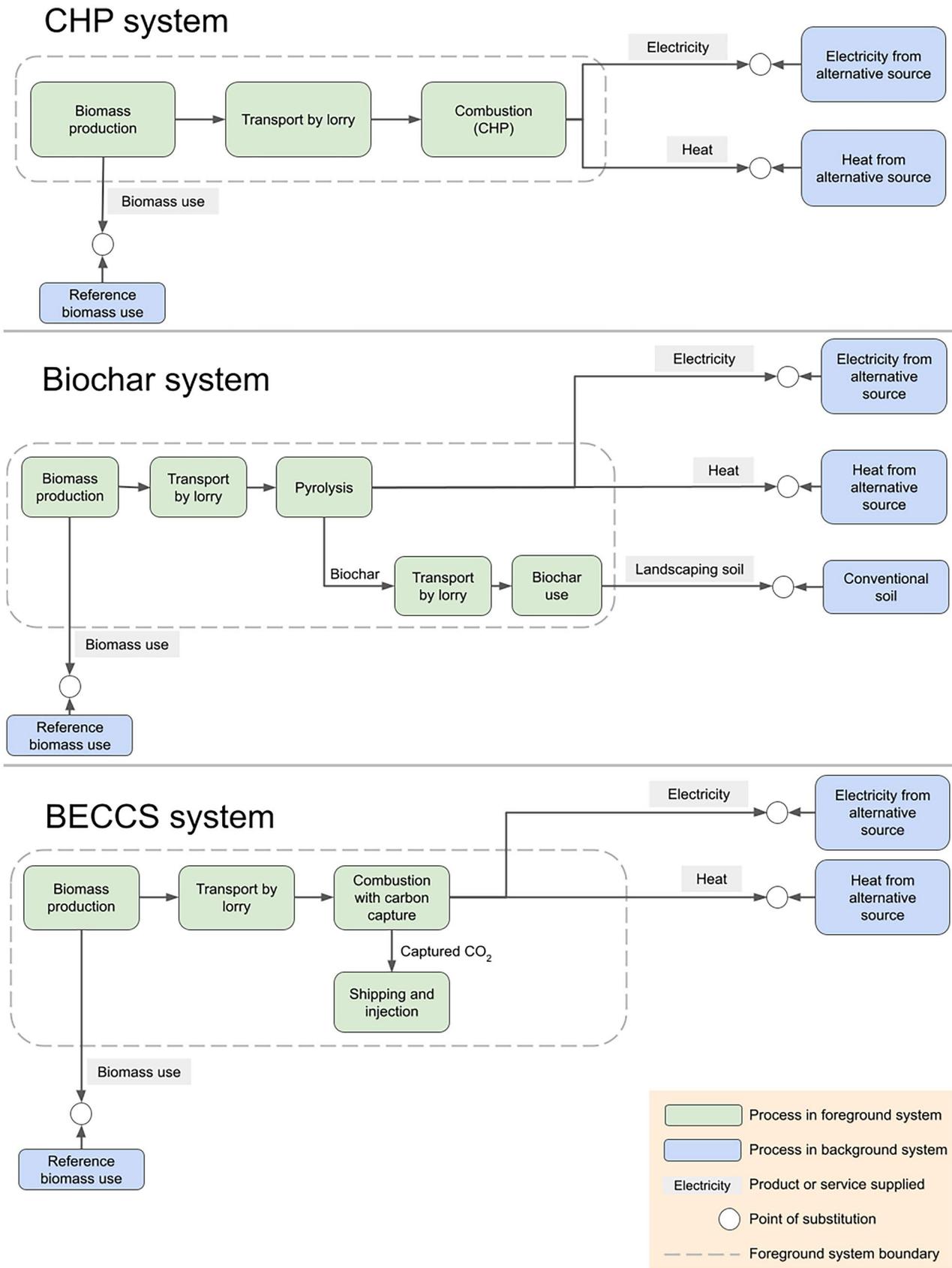


Fig. 1 Flowcharts of the three systems: Combined heat and power (CHP), Biochar, and Bioenergy with carbon capture and storage (BECCS)

and the ash remaining after combustion was assumed to be returned to the forest. All biochar produced from the Biochar system was assumed to be applied to soil. The CO₂ captured from the BECCS system was assumed to be shipped to an intermediate storage and then transported through a pipeline and injected into a permanent geological storage. More details and data can be found in the Supplementary Material.

2.1.2 Goal, impact categories, database, and software

The goals of the LCA were to determine whether the bioenergy systems implementing CDR technologies have lower climate impacts than the reference bioenergy system without CDR and to identify the CDR-based system with the lowest climate impact. Climate change was the only impact category used to evaluate the systems, characterised by global warming potential with a time horizon of 100 years (GWP₁₀₀). The greenhouse gas emissions modelled were carbon dioxide (CO₂), nitrous oxide (N₂O; GWP₁₀₀ = 265), and methane (CH₄; GWP₁₀₀ = 29.7), using data from the Ecoinvent database, version 3.6 (cut-off system-model) (Wernet et al. 2016). The model was developed and implemented using the Python framework for LCA, brightway2 (Mutel 2017), its graphical user interface, the activity browser (Steubing et al. 2020), and the algebraic extension *lca_algebraic* (Jolivet et al. 2021). In addition, several Python scripts were developed to automate comparative LCA of several systems with multiple FUs, multiple choices of reference activities, and defined parameters.

2.1.3 Functional units

The functional unit, i.e. the reference flow on which the results of an LCA are based, is usually chosen based on the aim of the study (Ahlgren et al. 2015), and in general, only one FU is chosen. In this study, we considered all FUs that could lead to different results, although the number of FUs relevant to compare was limited to the number of functions delivered by all three systems studied (for reasoning, see Supplementary Material). When analysing all three systems, the FUs for the case study were the individual products delivered by all systems (heat, electricity, or biomass use). When analysing the CDR systems, CO₂ sequestration was defined as an additional FU (Table 1). According to

Terlouw et al. (2021), the recommended FU for comparing CDR systems is impact per tonne of CO₂-removal, where CO₂-removal is sequestration only, excluding any avoided burdens. When comparing only CDR systems, it could be argued that CO₂-removal is the most relevant FU, since carbon sequestration is (probably) the primary reason for implementing these systems.

2.1.4 Limitations and cut-offs

There were some limitations and generalisations in the model; e.g. parts of the systems were excluded, such as biochar effects on soil, pre-treatment of biomass before combustion, and production of necessary infrastructure.

2.2 Parameterisation of life cycle inventories

In order to account for uncertain or ambiguous data, parameters were defined for some data entries in the life cycle inventory (LCI), which allowed multiple possible values of the same exchange to be considered in the results and analysis (Table 2). All parameter values were based on literature sources with the exception of transport distances, which were all simply modelled based on assumptions. The purpose of the LCI was to portray a general scenario, not a specific local case, although data selection was based on Swedish/Nordic case studies. More details and data can be found in Supplementary Material.

2.2.1 Thermochemical conversion

Electricity (E) and heat (H) outputs from the CHP system were calculated as:

$$E = LHV \times \eta \text{ [GJ tonne}^{-1} \text{ biomass]} \quad (1)$$

$$H = LHV \times \theta \text{ [GJ tonne}^{-1} \text{ biomass]} \quad (2)$$

where E is electricity produced, H is heat produced, LHV is the lower heating value of the woodchips, η is the power efficiency of the combustion process, and θ is the thermal efficiency.

Table 1 Functional units selected for case studies and potential interpretation of the results

Function	Input/output	Amount	Interpretation
Biomass used	Input	1 tonne	How to use biomass resources in a climate efficient way
Electricity generated	Output	1 MWh	How to produce electricity with the least climate impact
Heat produced	Output	1 GJ	How to produce heat with the least climate impact
Carbon dioxide sequestered	Output	1 kg	How to sequester carbon dioxide with the least climate impact

Table 2 Definitions of parameters used in case studies on combined heat and power (CHP), Biochar, and bioenergy with carbon capture and storage (BECCS)

Name, symbol	System	Definition	Uncertainty distribution	Parameter range	Units	Source
Biochar decay, D	Biochar	Decay of biochar over 100 years after application to soil, measured as mass percentage	Uniform	Min = 0.10 Max = 0.50	Fraction of decay over 100 years	Azzi et al. (2019)
Biochar yield, β	Biochar	Yield of biochar from the pyrolysis process, measured as mass percentage compared with biomass	Uniform	Min = 0.21 Max = 0.36	kg biochar kg ⁻¹ biomass	Azzi et al. (2019)
Carbon capture percentage, C	BECCS	Ratio of CO ₂ captured to total CO ₂ emissions from the combustion process	Uniform	Min = 0.70 Max = 0.90	-	Gustafsson et al. (2021)*
CCS electricity efficiency, η_{CCS}	BECCS	Ratio of electricity produced by the BECCS plant, compared with electricity production from the CHP plant. See Eq. 5 in Sect. 2.2	Uniform	Min = 0.3273 Max = 0.4546	-	Gustafsson et al. (2021)
CCS heat efficiency, θ_{CCS}	BECCS	Ratio of heat produced by the BECCS plant to heat produced by the CHP plant. See Eq. 6 in Sect. 2.2	Uniform	Min = 1.2162 Max = 1.2534	-	Gustafsson et al. (2021)
CO ₂ long-term storage losses, L_2	BECCS	Fraction of CO ₂ lost from long-term storage	Normal	$\mu = 0.0050$ $\sigma = 0.0010$	-	Erlandsson and Tannoury (2020)
CO ₂ pipeline losses, L_1	BECCS	Fraction of CO ₂ lost from pipeline transport	Normal	$\mu = 0.00032$ $\sigma = 0.000050$	-	Erlandsson and Tannoury (2020)
Electricity for CO ₂ discharge from ship	BECCS		Uniform	Min = 0.10 Max = 0.13	kWh tonne ⁻¹ CO ₂	Erlandsson and Tannoury (2020)
Electricity for CO ₂ liquefaction	BECCS		Uniform	Min = 110 Max = 140	kWh tonne ⁻¹ CO ₂	Erlandsson and Tannoury (2020)
Electricity for CO ₂ loading to ship	BECCS		Uniform	Min = 0.099 Max = 0.12	kWh tonne ⁻¹ CO ₂	Erlandsson and Tannoury (2020)
Electricity for CO ₂ storage 1	BECCS	Storage of CO ₂ at power plant	Uniform	Min = 0.0 Max = 15	kWh tonne ⁻¹ CO ₂	Erlandsson and Tannoury (2020)
Electricity for CO ₂ storage 2	BECCS	Storage of CO ₂ in intermediate storage	Uniform	Min = 8.0 Max = 15	kWh tonne ⁻¹ CO ₂	Erlandsson and Tannoury (2020)
LHV woodchips (dry weight), LHV	All		Uniform	Min = 17 Max = 19	GJ tonne ⁻¹	Azzi et al. (2019)**
Power efficiency, η	CHP and BECCS	Share of electricity recovered from the combustion in the CHP plant, expressed as ratio of the LHV value. See Eq. 1 in Sect. 2.2. Electricity from the BECCS plant was further multiplied by η_{CCS}	Normal	$\mu = 0.33$ $\sigma = 0.033$	-	Azzi et al. (2019)

Table 2 (continued)

Name, symbol	System	Definition	Uncertainty distribution	Parameter range	Units	Source
Pyrolysis power-to-heat ratio, R	Biochar	The ratio of electricity to total energy produced from the biochar plant (the rest is heat)	Uniform	Min = 0.20 Max = 0.40	-	Azzi et al. (2019)
Thermal efficiency, θ	CHP and BECCS	Share of heat recovered from the combustion in the CHP plant, expressed as ratio of the LHV value. See Eq. 2 in Sect. 2.2. Electricity from the BECCS plant was further multiplied by θ_{CCS}	Normal	$\mu = 0.70$ $\sigma = 0.070$	-	Azzi et al. (2019)
Transport distance biochar	Biochar	Transport of biochar from power plant to manufacturer of landscaping soil	Normal	$\mu = 250$ $\sigma = 75$	km	-
Transport distance biomass	All		Normal	$\mu = 500$ $\sigma = 100$	km	-
Transport distance carbon dioxide	BECCS		Normal	$\mu = 1800$ $\sigma = 180$	km	-
Transport distance soil	Biochar	Transport of landscaping soil from manufacturer to location of usage	Normal	$\mu = 100$ $\sigma = 10$	km	-

For parameters with normal uncertainty distribution, μ is the mean value and σ is the standard deviation

*Maximum value taken from source, minimum value based on assumption; **Source gave one value, range assumed based on this value

Electricity and heat outputs from the Biochar system were calculated as (Azzi et al. 2019):

$$E = r \times 234.95 \times e^{-6.56\beta} \times \beta \text{ [GJ tonne}^{-1} \text{ biomass]} \quad (3)$$

$$H = (1 - r) \times 234.95 \times e^{-6.56\beta} \times \beta \text{ [GJ tonne}^{-1} \text{ biomass]} \quad (4)$$

where r is the ratio of electricity to total energy output and β is the biochar yield in weight percentage relative to weight of biomass (Azzi et al. 2019).

Finally, electricity and heat outputs from the BECCS system were calculated as:

$$LHV \times \eta \times \eta_{CCS} \text{ [GJ tonne}^{-1} \text{ biomass]} \quad (5)$$

$$LHV \times \theta \times \theta_{CCS} \text{ [GJ tonne}^{-1} \text{ biomass]} \quad (6)$$

Thus, production of electricity and heat in the BECCS system was calculated in a similar way as for the CHP system, using the same parameters η and θ , but further multiplied by η_{CCS} and θ_{CCS} , respectively, where η_{CCS} and θ_{CCS} are the relative electricity efficiency and heat efficiency, respectively, of the BECCS system compared with the CHP system. All reported values for θ_{CCS} are greater than 1, meaning that the CCS process actually allows the BECCS system to produce more heat than the CHP system (Gustafsson et al. 2021).

2.2.2 Carbon dioxide sequestration

The amount of carbon sequestered in the Biochar system was calculated as:

$$C_S = \beta \times C_{BC} \times \frac{44}{12} \times (1 - D) \text{ [kg CO}_2 \text{ kg biomass}^{-1}] \quad (7)$$

where C_S is the amount of carbon sequestered, β is the biochar yield, C_{BC} is the percentage of carbon in the biochar, and D is the fraction of biochar decaying over 100 years.

Carbon sequestration in the BECCS system was calculated as:

$$C_S = C_B \times \frac{44}{12} \times C \times (1 - L_1) \times (1 - L_2) \text{ [kg CO}_2 \text{ kg biomass}^{-1}] \quad (8)$$

where C_B is the carbon content in the biomass, C is the percentage of carbon captured from the CCS process, L_1 is losses from the pipeline, and L_2 is losses from long-term storage.

2.2.3 Reference activities

In order to account for multi-functionality, the substitution method was applied (with substitution as defined by Heijungs et al. 2021). In order to perform this allocation, a reference system consisting of reference activities was defined where each function delivered from the foreground system had at least one corresponding reference activity that fulfilled the same function (Table 3). Emissions from the reference activities were viewed as so-called avoided burdens and were subtracted from the total system impact during allocation. The reference activity defined for the biomass use product was leaving the biomass in the forest for continued carbon sequestration, as an alternative to harvesting and removal. Several alternative reference activities were chosen for the electricity and heat products, and the choices were defined as discrete parameters in the LCI with equal probability. For electricity, these were production from natural gas, wind power, and coal, while for heat, they were production from natural gas, oil, and wood chip combustion. The electricity consumed by each system was modelled as the same entry in the Ecoinvent database as the reference activity for electricity production. The biochar from the pyrolysis plant was assumed to be used as a component in landscaping soil, and therefore, the corresponding reference activity was the same amount of the conventional landscaping soil.

Table 3 Reference activities defined for every function delivered by the three systems studied

Function	Reference activity	Impact of reference activity	Source
Biomass use	Biomass decay in forest (no harvesting)	−89.1 kg CO ₂ -eq tonne ^{−1}	Hammar et al. (2019)
Electricity generated	Electricity from wind power	0.015 kg CO ₂ -eq kWh ^{−1}	Ecoinvent
	Electricity from natural gas	0.750 kg CO ₂ -eq kWh ^{−1}	Ecoinvent
	Electricity from coal	1.10 kg CO ₂ -eq kWh ^{−1}	Ecoinvent
Heat produced	Heat from woodchips	0.011 kg CO ₂ -eq MJ ^{−1}	Ecoinvent
	Heat from natural gas	0.070 kg CO ₂ -eq MJ ^{−1}	Ecoinvent
	Heat from oil	0.093 kg CO ₂ -eq MJ ^{−1}	Ecoinvent
Landscaping soil	Conventional landscaping soil	84 kg CO ₂ -eq (m ³) ^{−1}	Azzi et al. (2022)

The reference activity for biomass use had a negative impact since carbon was sequestered, in contrast to emissions of carbon dioxide in all other reference activities

2.3 Analysis of results

Climate impacts of the three individual systems were calculated, and pair-wise comparisons of the systems were performed, allowing them to be ranked according to performance. Rather than calculating impacts for a single set of parameters, global sensitivity analysis was used to generate distribution of impacts, with 460,000 iterations. These distributions were then interpreted using contribution analysis, Sobol indices, and decision trees. Analyses were conducted for each system (CHP, Biochar, BECCS) and FU (heat, electricity, biomass use, carbon sequestration); i.e. a total of 11 different scenarios were analysed and compared.

Contribution analysis In order to identify parts of the life cycle contributing to a relatively high share of the total impact, i.e. hot-spots, contribution analysis was performed on the distribution of impacts with the total impact divided into the following groups: carbon sequestration (only for CDR systems), supply-chain emissions (all impacts which were not part of the other groups), avoided burdens due to substitutions for heat and electricity production (one group for each), avoided burdens due to biochar use (only for Biochar system), and additional impacts due to the reference biomass use (see Table 3). Identifying the avoided burdens due to substitutions and permanent carbon sequestration made it possible to distinguish between avoided emissions and actual negative emissions, as recommended by Terlouw et al. (2021).

Pair-wise comparison When conducting comparative LCA on two systems, it is of specific interest to calculate the differences in impacts. These differences were calculated for each computation of impacts; i.e. with the same parameter values for both systems, and for each FU, the systems had in common. Based on observed differences, the number of computations in which each system had a lower impact, and was therefore preferable from a climate mitigation perspective, was calculated.

Sobol indices Sobol indices are suitable for use in sensitivity analysis of complex environmental models with high numbers of parameters (Nossent et al. 2011), in order to determine the variance contribution for the parameters. If Y is the output of a system which depends on several parameters, then the first-order Sobol index for parameter i (S_i) is defined as:

$$S_i = \frac{V_i}{V(Y)} \quad (9)$$

where V_i is the variance in Y due to uncertainty in i and $V(Y)$ is the variation in the output Y (Nossent et al. 2011). The

sum of all Sobol indices is 1, taking into account the total variability and all indices of all orders (Sobol 2001).

Sobol indices can be computed for different parameters in order to determine their contribution to the overall variance in the results, individually (first-order indices) or through interactions of multiple parameters (higher-order indices) (Sobol 2001). This approach is especially useful for parameters defined according to a continuous uncertainty distribution, since the number of combinations to be analysed is infinite. Sobol indices can also be computed for choices of reference activities if they have been defined as parameters (as described above). Here, Sobol indices were calculated for all 11 individual scenarios, but also for algebraic expressions of the differences in impacts obtained from the pair-wise comparisons. Only first-order Sobol indices were calculated; i.e. only the contributions of individual parameters were taken into account. Higher-order Sobol indices were not deemed relevant, as all sums of first-order Sobol indices were close to 1 (0.84–0.99) (Tables 4 and 5), meaning that the majority of the variance was attributable to individual parameters.

Decision trees Decision trees were generated for pair-wise comparisons where the results were ambiguous, i.e. where it was unclear which system was (generally) preferable. Decision trees can be used to classify data according to known attributes and predefined classes (Quinlan 1993). They take the form of top-down flowcharts, where each so-called *decision node* represents a test for a given attribute on the data, dividing the data into several branches. Decision trees in this study were generated in order to identify the parameter values that were most influential when calculating the difference between two systems, i.e. to identify the system configurations where one system was preferable to the other. In order to generate the decision trees, the Scikit-learn Python module was used (Pedregosa et al. 2011).

3 Results

3.1 Stand-alone climate impact distributions and contribution analysis

The overall impact of the CDR systems was always negative; i.e. the avoided emissions and carbon sequestration outweighed the positive emissions from the systems (Fig. 2). The CHP system had net positive emissions in some cases when the electricity reference activity was wind power, or when the heat reference activity was wood chips, i.e. when the energy reference activity had a relatively low climate impact. Otherwise, the total impact of the CHP system was negative, meaning that the avoided emissions were larger

Table 4 First-order Sobol indices for the calculated impacts of each system (combined heat and power (CHP), Biochar, bioenergy with carbon capture and storage (BECCS)) and each functional unit (FU)

FU System	Heat			Electricity			Biomass use			CO ₂ seq.	
	CHP	Biochar	BECCS	CHP	Biochar	BECCS	CHP	Biochar	BECCS	Biochar	BECCS
Parameter name											
Biochar decay, <i>D</i>	-	0.04	-	-	0.05	-	-	0.04	-	0.10	-
Biochar yield, <i>β</i>	-	0.23	-	-	0.28	-	-	0.00	-	0.16	-
Carbon capture percentage, <i>C</i>	-	-	0.12	-	-	0.02	-	-	0.03	-	0.02
CCS electricity efficiency, η_{CCS}	-	-	0.02	-	-	0.09	-	-	0.00	-	0.00
Electricity source	0.95	0.54	0.49	0.00	0.00	0.02	0.71	0.62	0.11	0.44	0.11
Heat source	-	-	-	0.94	0.29	0.71	0.26	0.27	0.81	0.19	0.81
LHV woodchips, LHV	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Power efficiency, η	0.02	-	0.02	0.02	-	0.11	0.01	-	0.00	-	0.00
Pyrolysis power-to-heat ratio, <i>R</i>	-	0.16	-	-	0.34	-	-	0.02	-	0.01	-
Thermal efficiency, θ	0.01	-	0.30	0.03	-	0.02	0.01	-	0.02	-	0.02
Sum	0.98	0.97	0.97	0.99	0.96	0.97	0.99	0.95	0.97	0.90	0.96

Values shown express the contribution of an individual parameter to the total variance in the results. The three highest values of Sobol indices in each column are marked in bold. If the parameter was not present in the algebraic expression of the impact, the corresponding Sobol index is marked with ‘-’. Parameters with a Sobol index value of zero for all scenarios are not included in the table

than the positive emissions. For both CDR systems, carbon sequestration contributed significantly to the total impact, especially for the BECCS system, where the relative contribution from carbon sequestration varied across the impact distribution and was the largest contributor when the impact was relatively high. For the Biochar system, the reference activity for biochar usage was a significant contributor across the entire impact distribution (Fig. 2b, e, h and j). The substitutions for electricity and heat were in general dominant contributors to the total impact, and their contribution increased drastically with a lower impact, meaning that the avoided burdens were the main reasons for the low negative impacts. The contribution of other sources of emissions, such as supply-chain impact and substitution for biomass use, was more constant (relative to each other), regardless of their variance.

For all impact distributions, a high total impact was always associated with an energy system with a low climate impact (wind power and/or woodchips), and the lowest total impact occurred in an energy setting with a high climate impact (oil and/or coal). This was an expected finding, since a high-impact energy reference system resulted in a larger impact being subtracted from the total impact of the foreground system.

The Sobol indices for each system and FU (Table 4) indicated that much of the variance in the impact distributions was due to differences in impacts of the multiple energy reference activities. In fact, for nine out of the 11 scenarios (including all three CHP scenarios), most of the variance in results was attributable to these parameters. For the Biochar system, the parameters such as biochar decay, biochar yield,

and power-to-heat ratio also made high contributions to the variance. The parameters making high contributions to variance for the BECCS system were the electricity percentage for CCS and percentage of carbon captured. Some parameters, e.g. transport distances, did not significantly affect the variance of the results of any system or FU, for example, the transport distances.

3.2 Pair-wise comparisons of climate impact

When the systems were compared pair-wise for each FU, it emerged that the preferable system depended on the FU (Fig. 3). When the CDR systems were compared with the reference system (CHP), the CDR systems were preferable in the majority of cases. However, the CHP scenario scored somewhat better than the BECCS system with heat as FU (preferable in 25.9% of all cases) and also than the Biochar system with biomass as FU (preferable in 39.7% of all cases). For all other FUs and pair-wise comparisons involving the CHP system, that system was preferable in less than 1% of all cases. In fact, when compared with the BECCS system with electricity as FU, CHP was the least preferable system in all scenarios.

Comparing the CDR systems with each other, it was found that the preferable system changed with FU (Fig. 3). The BECCS system was preferable to the Biochar system with electricity generation or biomass usage as FU (preferable for 98.7% and 97% of all scenarios, respectively), while the Biochar system was preferable when the FU was heat generated or carbon sequestered (performed better in 89% and 99.7% of all scenarios, respectively).

Table 5 First order Sobol indices for the calculated differences in impacts between each pair of systems (combined heat and power (CHP), Biochar, bioenergy with carbon capture and storage (BECCS)) and each functional unit (FU)

FU	Heat				Electricity				Biomass use				CO ₂ seq.	
	Biochar vs CHP		BECCS vs CHP		Biochar vs CHP		BECCS vs CHP		Biochar vs CHP		BECCS vs CHP		Biochar vs Biochar	
	Biochar	BECCS	Biochar	BECCS	Biochar	BECCS	Biochar	BECCS	Biochar	BECCS	Biochar	BECCS	Biochar	BECCS
Parameter name														
Biochar decay, <i>D</i>	0.07	-	0.05	-	0.06	-	0.02	-	0.05	-	0.06	-	0.15	
Biochar yield, <i>β</i>	0.45	-	0.28	-	0.38	-	0.11	-	0.00	-	0.00	-	0.24	
Carbon capture percentage, <i>C</i>	-	0.02	0.01	0.04	-	0.04	0.03	-	-	0.03	0.06	-	0.00	
CCS electricity efficiency, η_{CCS}	-	0.00	0.00	0.16	-	0.16	0.12	-	-	0.00	0.01	-	0.00	
Electricity source	0.01	0.93	0.38	0.03	0.00	0.03	0.02	0.58	0.17	0.90	0.19	0.42	0.01	
Heat source	-	-	-	0.57	0.01	0.36	0.36	0.50	0.03	0.50	0.50	0.01	0.01	
LHV woodchips, LHV	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.02	0.02	0.00	0.01	0.00	0.00	
Power efficiency, η	0.02	0.01	0.00	0.15	0.00	0.13	0.13	0.06	0.06	0.01	0.01	0.00	0.00	
Pyrolysis power-to-heat ratio, <i>R</i>	0.31	-	0.20	-	0.47	-	0.14	0.02	0.02	-	0.03	0.02	0.02	
Thermal efficiency, θ	0.02	0.01	0.02	0.02	0.01	0.02	0.03	0.03	0.03	0.00	0.05	0.01	0.01	
Sum	0.88	0.97	0.94	0.98	0.93	0.98	0.96	0.93	0.93	0.97	0.92	0.85	0.85	

The three highest values of Sobol indices for each case are marked in bold. If the parameter was not present in the algebraic expression of the impact, the corresponding Sobol index is marked with '-'. Parameters with a Sobol index value of zero for all differences are not included in the table

Choice of background energy system significantly affected the Sobol indices calculated for the differences in results (Table 5), although it was generally somewhat less influential than for the individual systems. The differences in impacts in comparisons involving the Biochar system also made a relatively high contribution to variance for the parameters such as biochar decay, biochar yield, and power-to-heat ratio.

In pair-wise comparisons where the better-performing system was not clear, sensitive parameters were identified with decision tree analysis. When the Biochar system and CHP were compared with biomass as FU (Fig. 3g), the Biochar system was preferable in 99.8% of all cases if the reference electricity supply was wind power (Fig. S2 in Supplementary Material). When the BECCS system and the CHP system were compared with heat as FU (Fig. 3b), BECCS was preferable for most cases (99.3%) if the reference electricity supply was wind power or natural gas (Fig. S3 in Supplementary Material). Lastly, when the BECCS and Biochar systems were compared with heat as FU (Fig. 3c), the Biochar system was preferable in 99.1% of all cases when the reference electricity supply was natural gas or coal (Fig. S4).

4 Discussion

4.1 Interpretation of results

In general, both CDR systems had a lower climate impact than the reference CHP system, with a clear majority of pair-wise comparisons showing that the CDR systems were preferable (Fig. 3). However, in system configurations where the CHP system scored better, primarily when the background energy system had a high climate impact due to combustion of fossil fuels, the climate benefit of the greater fossil fuel replacement caused by the higher energy efficiency of the CHP outweighed the climate benefits of CDR.

Choice of functional unit Biomass can be used as FU in order to assess how biomass resources can be most efficiently used for climate change mitigation (Ahlgren et al. 2015). Identifying the most efficient use of biomass is important as demand for biomass will increase in a future transition from fossil fuels to biofuels (Berndes et al. 2016). This is especially important in contexts where biomass and land are limited resources. BECCS was preferable to both Biochar and CHP with biomass as FU (Fig. 3), indicating that it is a more climate-efficient use of biomass.

With electricity or heat as FU, LCA results can be used to identify a system which provides electricity or heat with relatively low climate impact. Electricity with low climate impact is important when planning national electricity

supply, particularly in a future energy context that includes growing demand for electricity and simultaneous phase-out of fossil fuels (Luderer et al. 2022). Heat with low climate impact is relevant for large-scale heat supply systems, e.g. industrial or district heat systems, especially in countries with colder climates and high demand for heat.

Using carbon sequestration as FU can be relevant when assessing CDR systems, to ensure that emission reductions are not outweighed by supply-chain emissions (i.e. total net emissions are negative). According to Terlouw et al. (2021), carbon sequestration is an appropriate FU when comparing different CDR systems. Comparing different CDR systems is relevant when designing future climate pathways that include CDR techniques to reach climate goals (Fuss et al. 2018).

Comparison of CDR systems The ranking of the CDR systems depended on the FU. This means that the better CDR system to implement will depend on the indicator of most interest. In our analysis, Biochar was preferable to BECCS with CDR as FU (Fig. 3), indicating that the supply-chain and side effects of Biochar have more climate benefits than those of BECCS. With CDR as FU, Biochar always yielded negative climate impacts and those of BECCS were negative or close to zero, showing that most configurations of both CDR technologies have overall beneficial climate effects considering their total lifecycle impact.

Implications of results The results allow general conclusions to be drawn regarding whether CHP or CDR systems are preferable, since both CDR systems outperformed CHP in most scenarios (although not all) for all FUs. However, the better of the two CDR systems depended on FU, making it difficult to rank them in terms of climate impact. Most previous LCAs of Biochar and BECCS systems have only considered one FU (Terlouw et al. 2021), but our study showed that analysis based on one FU insufficient when comparing the climate impact of these systems.. Whether BECCS or Biochar has the lowest climate impact will depend not just on the specific scenario, but also on the FU deemed most relevant. In a specific real-world scenario, other factors such as scale, policies, and economics would also be significant for decision-making.

4.2 Biomass use as a resource indicator

For bioenergy systems, it is of particular interest to assess biomass use, since biomass for energy is often in competition with other forms of land use, e.g. agriculture. For all FUs in this study except biomass use, the systems were penalised by higher use of biomass since the reference activity was carbon sequestration from biomass residues left in forests (see Table 3). Even if a system has a net negative impact

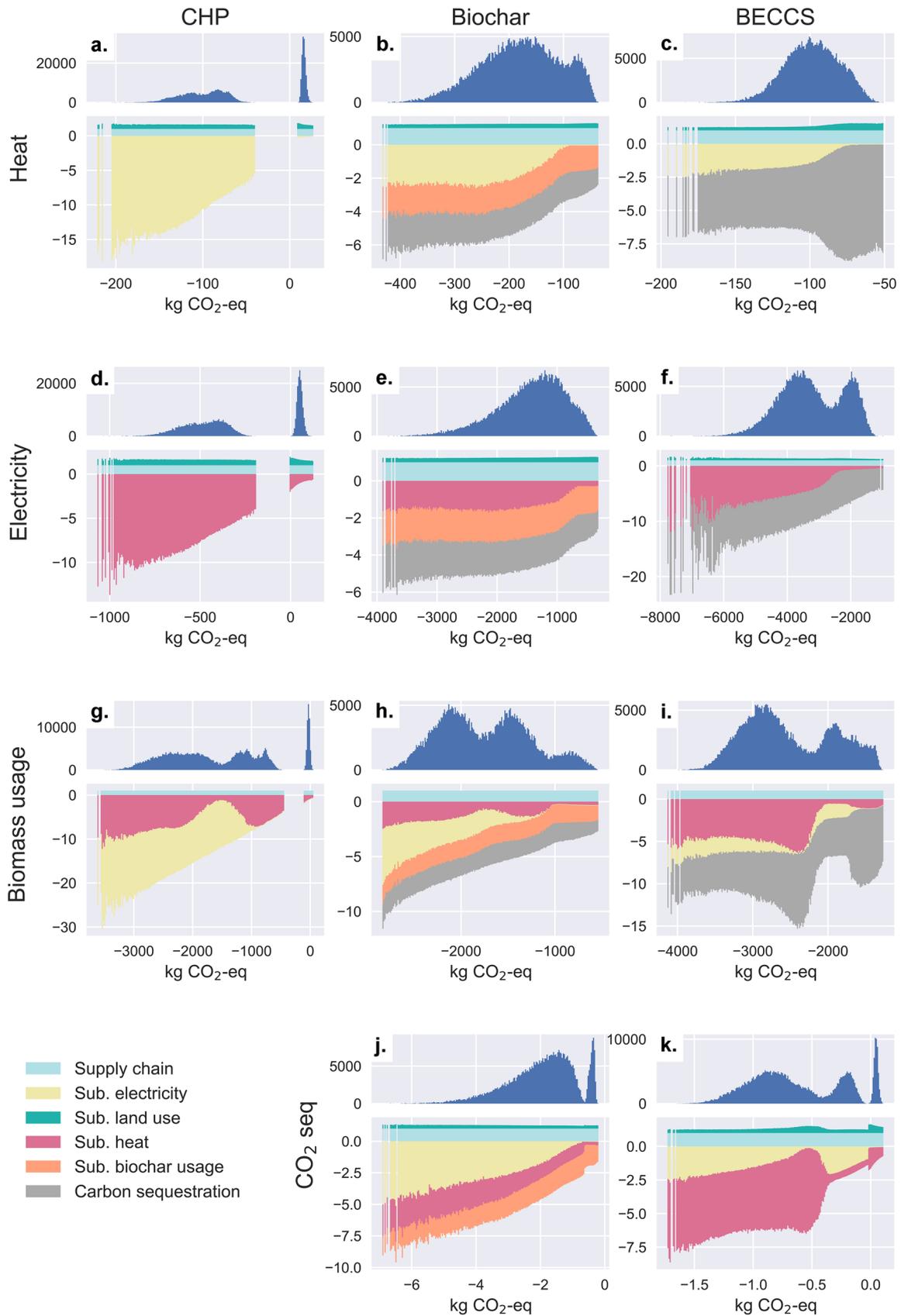


Fig. 2 Contribution analysis. For each scenario **a–k**, the distribution of climate impacts is shown in the upper half and the relative contribution to the total impact for each category of emissions in the lower half. The contributions are normalised to supply-chain emissions (= 1). The *x*-axis shows the climate impact, expressed in kg CO₂-eq, and the scale is the same for the upper and lower part of each graph. The specific system configurations corresponding to each graph are as follows: **a** Combined heat and power (CHP), heat as FU; **b** Biochar, heat as FU; **c** Bioenergy with carbon capture and storage (BECCS), heat as FU; **d** CHP, electricity as FU; **e** Biochar, electricity as FU; **f** BECCS, electricity as FU; **g** CHP, biomass usage as FU; **h** Biochar, biomass usage as FU; **i** BECCS, biomass usage as FU; **j** Biochar, carbon sequestration as FU; **k** BECCS, carbon sequestration as FU. Sub. = substitution

with biomass as FU, i.e. a climate benefit for each tonne biomass consumed, biomass is still a limited resource, and there are constraints on the amount that can be used. In addition, there are sustainable and non-sustainable ways to produce and harvest biomass, depending on the type and amounts extracted. This resource limitation is not reflected in LCA, which assumes linear relationships between resource use and environmental impact and does not take into account, e.g. the concept of tipping points (Rockström et al. 2009).

Biomass harvesting thus raises sustainability issues above and beyond its climate impact. An interesting indicator is then the amount of biomass used per unit of product, e.g. kg of biomass per kWh of electricity. The BECCS system will produce more heat, but less electricity than the CHP system per kg biomass, since parameter η_{CCS} in Eqs. (1, 2, 5, and 6) is always lower than 1 and parameter θ_{CCS} is always higher than 1. Hence, in a local scenario where biomass is a limited resource, BECCS or CHP will be the most suitable system to implement, depending on whether the product of particular interest is heat or electricity. The amount of biomass required for producing electricity will vary with the parameters defined. However, when the mean and median amount of biomass required for producing 1 MWh of electricity were compared for all three systems (Table S3), BECCS required the highest amount of biomass and CHP the lowest (less than half that in the BECCS system). For production of 1 GJ of heat, Biochar required the highest amount of biomass and BECCS the lowest (about half that in the Biochar system). For 1 kg of sequestration of carbon, the Biochar system required about three times as much biomass as the BECCS system.

Another indicator to compare CDR technologies used by Chiquier et al. (2022) is CO₂ removal efficiency, defined as (CO₂ stored—CO₂ emitted in supply chain) / CO₂ stored. This indicator is similar to our climate impact with FU per tonne of CO₂ removal, but without substitution effects. There is thus an important difference between CO₂ removal efficiency and climate change mitigation efficiency. The Biochar system has lower CO₂ removal efficiency (–5 to 39%) than BECCS (69–85%) (Chiquier et al. 2022), since Biochar

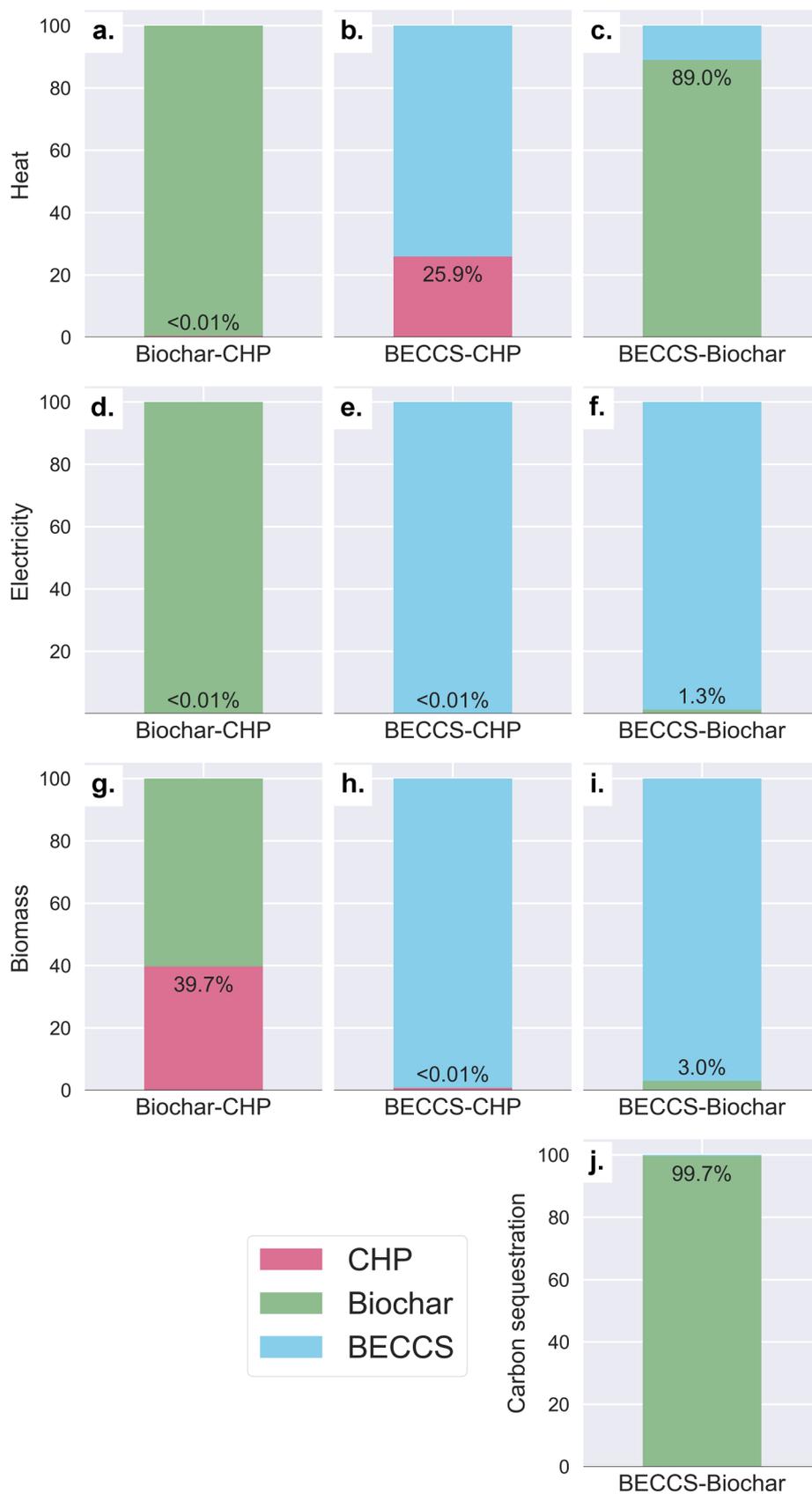
stores less CO₂ than BECCS per unit of biomass. However, our results indicated that Biochar is still a viable technology in terms of climate mitigation efficiency (Fig. 3), because it has additional potential to mitigate climate change through material substitution (Azzi et al. 2022) and other reductions in GHG emissions during its life cycle (Woolf et al. 2021).

4.3 Limitations

In this study, we only analysed biomass systems with low climate impact, which is presumably the primary interest from a policy perspective, and feedstock with higher climate impact might affect the (relative) performance of the systems. The BECCS system studied was a CHP system, producing both electricity and heat, as that is of most relevance from a Nordic perspective. The results are not directly applicable to bioenergy systems that produce electricity only, where heat is not considered a valuable product. Further, some parts of the LCI were omitted from this study; e.g. infrastructure and side effects such as albedo were not considered, though these could potentially affect the results (Terlouw et al. 2021). Finally, the only biochar use modelled was landscaping soil, with biochar replacing horticultural peat. There are several alternative uses for biochar, but for landscaping soil usage, the climate benefits of substitution are relatively high, but also widely applicable (Azzi et al. 2022). Biochar use could potentially have greater benefits in agriculture, e.g. when leading to reduction in N₂O emissions from soil, CH₄ emissions from animal production (Azzi et al. 2019), or increased plant growth (Lehmann et al. 2021). However these effects are complex to model and are strongly dependent on context (Woolf et al. 2021) and were not modelled in this study.

Definition of parameters Our analysis was limited to the ranges of parameters set in the study. Other approaches and parameter definitions would lead to differences in impact distributions, rankings, and decision tree classification rules. With a broader parameter range, other potential scenarios could be considered, but might not be very relevant or realistic. Based on this trade-off, two different rationales for defining parameters can be distinguished. In Rationale 1, each parameter is given its maximum theoretical range; e.g. for biochar stability, the parameter range defined would be 0–100%, meaning that all possible scenarios are considered, even unreasonable scenarios. However, when defining parameters which do not have a clear maximum or minimum, such as transport distances, there is still a need to set a subjective, reasonable limit. In Rationale 2, each parameter is given a likely range in a given context; e.g. for biochar with fairly good stability, the stability range could be constrained to, e.g. 60–90%. The range can be defined by e.g. consulting the literature and adding a margin of uncertainty.

Fig. 3 Pair-wise comparisons of systems and scenarios, showing the share of computations for which each system (bioenergy with carbon capture and storage (BECCS), Biochar, combined heat and power (CHP)) had a lower climate impact than the other for each functional unit (heat, electricity, biomass, carbon sequestration)



Applying Rationale 1 would probably result in many calculated results being deemed unrealistic, but would allow identification of extreme cases and lead to more general conclusions. Rationale 2 might result in a distribution that omits some possible results, but is more context-specific. Rationale 2 was chosen in this study, with the implication that cases of relevance in the individual assessments may have fallen outside the parameter ranges defined, and are thus outside the analysis.

Other impact categories In LCA in this study, we only calculated the climate impacts, though there are many other impact categories of interest when assessing the environmental performance of a system. For bioenergy-based systems, impact categories such as land use, natural resource use, eutrophication, and acidification are of particular interest (Caffrey and Veal 2013). Including additional impact categories or even decision-making tools could also clarify which system is preferable in general, although this would entail assessment of several criteria instead of just one. We focused on the climate impact since it is a crucial impact category for energy systems and CDR technologies, and analysing several impact categories would add another layer to LCA exploration of these complex systems. It could be possible to use fully parameterised models for this purpose, while using decision trees for interpretation. An interesting area for further study is then how to adapt use of decision trees for analysis of several impact categories. Lastly, we only modelled climate impacts using GWP₁₀₀ as metric, although other metrics or time scales could yield different results. We also do not take into account the timing of emissions in using this metric.

5 Conclusions

From a climate change mitigation perspective, the two CDR systems studied were preferable to the reference CHP system in most scenarios analysed. However, the better CDR system of the two depended on the choice of FU. Biochar was preferable with heat and carbon sequestration as FU, while BECCS was preferable with electricity and biomass use as FU. Thus, when conducting comparative LCA for multi-functional systems, the FU affects the conclusions and must be chosen to suit the purpose of the LCA. In the case of bioenergy with CDR, the choice of FU could reflect views on the use of limited biomass resources, the role of bioenergy in energy systems, and the role of CDR in climate change mitigation. We reached no general conclusion as to which FU is most relevant in decision-making, but we showed that in most circumstances, regardless of FU, both CDR systems led to climate change mitigation in bioenergy-based systems. Specific choices between BECCS and Biochar will depend on

additional contextual factors such as actual project parameters, other sustainability aspects, scale, and economics.

The substitution method was used to account for, and give credit for, all products delivered by the multi-functional systems studied. The parameters contributing most to the variance in results, both for individual systems and in pair-wise comparisons of scenarios, were related to heat and electricity reference activities because of a large difference in climate impact between the alternative background energy supplies considered. Therefore, the background energy system should be chosen with care, depending on the location and purpose of the LCA. We must stress that the conclusions from one context-specific LCA do not necessarily apply in another energy context. We also recommend systematic sensitivity analysis on background energy systems when working with CDR.

We used decision tree analysis to identify parameter values most affecting the climate performance of the studied systems. This was particularly helpful because of the extensive parameterisation of the model, which also allowed for more general analysis than conventional LCA practice. However, choice of parameter ranges should be clearly justified, and potential interdependencies should be addressed. In addition, presenting climate impact results with contributions (e.g. carbon storage, supply-chain emissions, substitutions), rather than just a net score, is important for understanding the composition of climate change mitigation potential of multi-functional CDR systems.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s11367-023-02144-2>.

Funding Open access funding provided by Swedish University of Agricultural Sciences. VINNOVA, 2016–03392, Elias S. Azzi, Sveriges Lantbruksuniversitet.

Data availability Additional data are available upon request. The code is available online at <https://github.com/SLU-biochar/Bioenergy-CDR-LCA>.

Declarations

Conflict of interest The author Elias Azzi is currently working as an independent consultant for Puro.earth Oy.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Ahlgren S, Björklund A, Ekman A, Karlsson H, Berlin J, Börjesson P, Ekvall T, Finnveden G, Janssen M, Strid I (2015) Review of methodological choices in LCA of biorefinery systems - key issues and recommendations. *Biofuels Bioprod Biorefin* 9:606–619. <https://doi.org/10.1002/bbb.1563>
- Azzi ES, Karlton E, Sundberg C (2019) Prospective life cycle assessment of large-scale biochar production and use for negative emissions in Stockholm. *Environ Sci Technol* 53(14):8466–8476. <https://doi.org/10.1021/acs.est.9b01615>
- Azzi ES, Karlton E, Sundberg C (2022) Life cycle assessment of urban uses of biochar and case study in Uppsala, Sweden. *Biochar* 4(18). <https://doi.org/10.1007/s42773-022-00144-3>
- Berndes G, Abt B, Asikainen A, Cowie A, Dale V, Egnell G, Lindner M, Marelli L, Paré D, Pingoud K, Yeh S (2016) Forest biomass, carbon neutrality and climate change mitigation. *Sci Policy* 3. European Forest Institute. <https://doi.org/10.36333/fs03>
- Brander M, Ascui F, Scott V, Tett S (2021) Carbon accounting for negative emissions technologies. *Clim Policy* 21(5):699–717. <https://doi.org/10.1080/14693062.2021.1878009>
- Caffrey KR, Veal MW (2013) Conducting an agricultural life cycle assessment: challenges and perspectives. *Sci World J* 472431(1–472431):13. <https://doi.org/10.1155/2013/472431>
- Cherubini F, Strømman AH (2011) Life cycle assessment of bioenergy systems: state of the art and future challenges. *Bioresour Technol* 102(2):437–451. <https://doi.org/10.1016/j.biortech.2010.08.010>
- Chiquier S, Patrizio P, Bui M, Sunny N, Mac Dowell N (2022) A comparative analysis of the efficiency, timing, and permanence of CO₂ removal pathways. *Energy Environ Sci* 15:4389–4403. <https://doi.org/10.1039/D2EE01021F>
- Erlandsson J, Tannoury F (2020) *Climate footprint of transportation and storage of carbon dioxide (CO₂)*. BSc thesis, KTH Royal Institute of Technology, Stockholm, Sweden. <http://urn.kb.se/resolve?urn=urn:nbn:se:kth:diva-281757>
- Friedlingstein P, O'Sullivan M, Jones MW, Andrew RM, Hauck J, Olsen A, Peters GP, Peters W, Pongratz J, Sitch S, Le Quére C, Canadell JG, Ciais P, Jackson RB, Alin S, Aragão LEOC, Arneeth A, Arora V, Bates NR, Becker M, Benoit-Cattin A, Bittig HC, Bopp L, Bultan S, Chandra N, Chevallier F, Chini LP, Evans W, Florentie L, Forster PM, Gasser T, Gehlen M, Gilfillan D, Gkritzalis T, Gregor L, Gruber N, Harris I, Hartung K, Haverd V, Houghton RA, Ilyina T, Jain AK, Joetzer E, Kadono K, Kato E, Kitidis V, Korsbakken JI, Landschützer P, Lefèvre N, Lenton A, Lienert S, Liu Z, Lombardozzi D, Marland G, Metzl N, Munro DR, Nabel JEMS, Nakaoka SI, Niwa Y, O'Brien K, Ono T, Palmer PI, Pierrot D, Poulter B, Resplandy L, Robertson E, Rödenbeck C, Schwinger J, Séférian R, Skjelvan I, Smith AJP, Sutton AJ, Tanhua T, Tans PP, Tian H, Tilbrook B, Van De Werf G, Vuichard N, Walker AP, Wanninkhof R, Watson AJ, Willis D, Wiltshire AJ, Yuan W, Yue X, Zaehle S (2020) Global carbon budget 2020. *Earth Syst Sci Data* 12(4):3269–3340. <https://doi.org/10.5194/essd-12-3269-2020>
- Fuss S, Lamb WF, Callaghan MW, Hilaire J, Creutzig F, Amann T, Beringer T, De Oliveira Garcia W, Hartmann J, Khanna T, Luderer G, Nemet GF, Rogelj J, Smith P, Vicente JV, Wilcox J, Del Mar Zamora Dominguez M, Minx JC (2018) Negative emissions - Part 2: costs, potentials and side effects *Environ Res Lett* 13(6). <https://doi.org/10.1088/1748-9326/aabf9f>
- Gustafsson K, Sadegh-Vaziri R, Grönkvist S, Levihn F, Sundberg C (2021) BECCS with combined heat and power: assessing the energy penalty. *Int J Greenh Gas Control* 110: 103434. <https://doi.org/10.1016/j.ijggc.2021.103434>
- Hammar T, Stendahl J, Sundberg C, Holmström H, Hansson PA (2019) Climate impact and energy efficiency of woody bioenergy systems from a landscape perspective. *Biomass Bioenergy* 120:189–199. <https://doi.org/10.1016/j.biombioe.2018.11.026>
- Heijungs R, Allacker K, Benetto E, Brandão M, Guinée J, Schaubroeck S, Schaubroeck T, Zamagni A (2021) System expansion and substitution in LCA: a lost opportunity of ISO 14044 amendment 2. *Front Sustain* 2:692055. <https://doi.org/10.3389/frsus.2021.692055>
- IPCC (2021) *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press. In Press
- Jolivet R, Clavreul J, Brière R, Besseau R, Prieur Vernat A, Sauze M, Blanc I, Douziech M, Pérez-López P (2021) lca_algebraic: a library bringing symbolic calculus to LCA for comprehensive sensitivity analysis. *Int J Life Cycle Assess* 26:2457–2471. <https://doi.org/10.1007/s11367-021-01993-z>
- Kemper J (2015) Biomass and carbon dioxide capture and storage: a review. *Int J Greenh Gas Control* 40:401–430. <https://doi.org/10.1016/j.ijggc.2015.06.012>
- Koponen K, Soimakallio S, Kline KL, Cowie A, Brandão M (2018) Quantifying the climate effects of bioenergy – choice of reference system. *Renew Sustain Energy Rev* 81(2):2271–2280. <https://doi.org/10.1016/j.rser.2017.05.292>
- Lehmann J, Cowie A, Masiello CA, Kammann C, Woolf D, Amonette JE, Cayuela ML, Camps-Arbestain M, Whitman T (2021) Biochar in climate change mitigation. *Nat Geosci* 14:883–892. <https://doi.org/10.1038/s41561-021-00852-8>
- Levihn F, Linde L, Gustafsson K, Dahlen E (2019) Introducing BECCS through HPC to the research agenda: the case of combined heat and power in Stockholm. *Energy Rep* 5:1381–1389. <https://doi.org/10.1016/j.egy.2019.09.018>
- Luderer G, Madeddu S, Merfort L, Ueckerdt F, Pehl M, Pietzcker R, Rottoli M, Schreyer F, Bauer N, Baumstark L, Bertram C, Dirnauichner A, Humpenöder F, Levesque A, Popp A, Rodrigues R, Streffer J, Kriegler E (2022) Impact of declining renewable energy costs on electrification in low-emission scenarios. *Nat Energy* 7:32–42. <https://doi.org/10.1038/s41560-021-00937-z>
- Matušík J, Hnátková T, Kočí V (2020) Life cycle assessment of biochar-to-soil systems: a review. *J Clean Prod* 259:120998. <https://doi.org/10.1016/j.jclepro.2020.120998>
- Minx JC, Lamb WF, Callaghan MW, Fuss S, Hilaire J, Creutzig F, Amann T, Beringer T, De Oliveira Garcia W, Hartmann J, Khanna T, Lenzi D, Luderer G, Nemet GF, Rogelj J, Smith P, Vicente Vicente JL, Wilcox J, Del Mar Zamora Dominguez M (2018) Negative emissions - Part 1: research landscape and synthesis. *Environ Res Lett* 13(6). <https://doi.org/10.1088/1748-9326/aabf9b>
- Mutel C (2017) Brightway: an open source framework for life cycle assessment. *J Open Source Softw* 2(12):236. <https://doi.org/10.21105/joss.00236>
- Nossent J, Elsen P, Bauwens W (2011) Sobol' sensitivity analysis of a complex environmental model. *Environ Model Softw* 26(12):1515–1525. <https://doi.org/10.1016/j.envsoft.2011.08.010>
- Oni BA, Oziegbe O, Olawole OO (2019) Significance of biochar application to the environment and economy. *Ann Agric Sci* 64:222–236. <https://doi.org/10.1016/j.aos.2019.12.006>
- Pedregosa F, Varoquaux G, Gramfort A, Michel Y, Thirion B, Grisel O, Blondel M, Prettenhofer P, Weiss R, Dubourg V, Vanderplas J, Passos A, Cournapeau D, Brucher M, Perrot M, Duchesnay É (2011) Scikit-learn: machine learning in Python. *J Mach Learn Res* 12:2825–2830

- Quinlan JR (1993) C4.5: Programs for Machine Learning, Morgan Kaufmann, San Mateo, CA
- Rockström J, Steffen W, Noone K, Persson Å, Chapin FS III, Lambin EF, Lenton TM, Scheffer M, Folke C, Schellnhuber HJ, Nykvist B, de Wit CA, Hughes T, van der Leeuw S, Rodhe H, Sörlin S, Snyder PK, Costanza R, Svedin U, Falkenmark M, Karlberg L, Corell RW, Fabry VJ, Hansen J, Walker B, Liverman D, Richardson K, Crutzen P, Foley JA (2009) A safe operating space for humanity. *Nature* 461:472–475. <https://doi.org/10.1038/461472a>
- Sakhiya AK, Anand A, Kaushal P (2020) Production, activation, and applications of biochar in recent times. *Biochar* 2:253–285. <https://doi.org/10.1007/s42773-020-00047-1>
- Sobol IM (2001) Global sensitivity indices for nonlinear mathematical models and their Monte Carlo estimates. *Math Comput Simul* 55(1–3):271–280. [https://doi.org/10.1016/S0378-4754\(00\)00270-6](https://doi.org/10.1016/S0378-4754(00)00270-6)
- Spokas KA (2010) Review of the stability of biochar in soils: predictability of O: C molar ratios. *Carbon Manag* 1(2):289–303. <https://doi.org/10.4155/cmt.10.32>
- Steubing B, de Koning D, Haas A, Mutel CL (2020) The activity browser — an open source LCA software building on top of the brightway framework. *Softw Impacts* 3:100112. <https://doi.org/10.1016/j.simpa.2019.100012>
- Tanzer SE, Ramírez A (2019) When are negative emissions negative emissions? *Energy Environ Sci* 12:1210–1218. <https://doi.org/10.1039/C8EE03338B>
- Terlouw T, Bauer C, Rosa L, Mazzotti M (2021) Life cycle assessment of carbon dioxide removal technologies: a critical review. *Energy Environ Sci* 1701–1721. <https://doi.org/10.1039/d0ee03757e>
- Wernet G, Bauer C, Steubing B, Reinhard J, Moreno-Ruiz E, Weidema B (2016) The ecoinvent database version 3 (part I): overview and methodology. *Int J Life Cycle Assess* 21(9):1218–1230. <https://doi.org/10.1007/s11367-016-1087-8>
- Woolf D, Amonette J, Street-Perrott F, Lehmann J, Joseph S (2010) Sustainable biochar to mitigate global climate change. *Nat Commun* 1:56. <https://doi.org/10.1038/ncomms1053>
- Woolf D, Lehmann J, Ogle S, Kishimoto-Mo AW, McConkey B, Baldock J (2021) Greenhouse gas inventory model for biochar additions to soil. *Environ Sci Technol* 55:14795–14805. <https://doi.org/10.1021/acs.est.1c02425>

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.