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A Review of Life Cycle Assessment Methods to Inform the Scale-Up of Carbon Dioxide Removal Interventions

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ABSTRACT

Life Cycle Assessment (LCA) methods are increasingly used for policy decision-making in the context of identifying and scaling up sustainable carbon dioxide removal (CDR) interventions. This article critically reviews CDR LCA case-studies through three key lenses relevant to policy decision-making on sustainable CDR scale-up, namely comparability across CDR assessments, assessment of the climatic merit of a CDR intervention, and consideration of wider CDR co-benefits and impacts. Our results show that while providing valuable life cycle understanding, current practices utilize diverse methods, usually attributional in nature, which are CDR and time-specific. As a result, they do not allow comprehensive cross-comparison between CDRs, nor reveal the potential consequences of scaling up CDRs in the future. We suggest CDR LCA design requires clearer definitions of the study scope and goal, the use of more consistent functional units, greater comprehensiveness in system boundaries, and explicit baseline definitions. This would allow for robust assessments, facilitating comparison with other CDR methods, and better evidencing net climate benefits. The inventory should collect time-dependent data on the full CDR life cycle and baseline, and report background assumptions. The impact assessment phase should evidence the climatic merits, co-benefits, and trade-offs potentially caused by the expanding CDR. Finally, to ensure a sustainable scale-up of CDR, consequential analyses should be performed, and interpretation involves the comparison of all selected metrics and the permanence of carbon storage against a baseline scenario.

Abbreviations: aLCA, attributional Life Cycle Assessment; CCS, carbon capture and storage; CDR, carbon dioxide removal; cLCA, consequential Life Cycle Assessment; DAC, direct air capture; FU, functional unit in a Life Cycle Assessment study; GCP, Global Cooling Potential; GHG, Greenhouse Gases; GTP100, 100-year Global Temperature change Potential; GWP, Global Warming Potential; GWP100, 100-year Global Warming Potential; IPCC, Intergovernmental Panel on Climate Change; LCA, Life Cycle Assessment; MRV, monitoring reporting and verification (or measurement reporting and verification, in some UNFCCC literature and derived sources); NET, Negative Emission Technology; UNFCCC, United Nations Framework Convention on Climate Change

1 | Introduction

The goal of The Paris Agreement to limit the global average temperature increase to well below 2°C requires global carbon dioxide (CO_2) emissions to be net zero by 2050 or soon thereafter (IPCC 2018, 2022). "Net zero CO_2" emissions imply that, in addition to anthropogenic emission reductions, any residual CO_2 emissions would need to be compensated by "negative" CO_2 emissions: that is, carbon dioxide removal (CDR). For net-zero across all Greenhouse Gases (GHGs) additional CDR may be needed to compensate for the residual emissions of non-CO_2 gases. The Intergovernmental Panel on Climate Change (IPCC) 2018 Special Report on 1.5, considered two negative emission technologies (NETs), or CDR, as key: afforestation and reforestation (AR) and bioenergy with carbon capture and storage (BECCS) (IPCC 2018). The IPCC 6th Assessment Report in 2022 (IPCC 2022) further considered potentially significant CDR to include: biochar, direct air carbon capture and storage (DACCS), enhanced weathering (EW), peatland restoration, ocean methods (fertilization, artificial upwelling, alkalinization, blue carbon), and soil carbon sequestration (SCS) (see Figure 1). The role of CDR in meeting the Paris Agreement's overarching goal also evolved from balancing hard to abate GHG emissions, to additionally providing net negative CO_2 emissions after 2050 to limit peak warming and, it has been argued, eventually contribute to declining temperatures (Rogelj et al. 2021), minimizing the size of any global temperature overshoot.

Life Cycle Assessment (LCA) has historically been used to investigate potential environmental impacts related to products and services, considering their full life cycle, that is, from cradle-to-grave (production to end of use and disposal), to ensure that improvements in one point of the life cycle do not cause or exacerbate impacts elsewhere. Given the increased visibility of CDR in the global policy arena, research on different CDR approaches has increased exponentially (Carton et al. 2020; Minx et al. 2018, and see Box 1 for UK examples), including CDR-related LCA research.

The plethora of new CDR demonstration projects globally presents opportunities for research to answer key questions for policy- and decision-makers and other stakeholders: can these projects deliver high-quality net CDR across their full life cycles? Given the diversity of removal options, how can we compare different approaches to CDR? To what extent could different CDR options be scaled up? By when? How? What are the potential co-benefits and trade-offs of this CDR scale-up?

Some of these questions are partially answered by existing LCA studies, for example, the quantification of the removal potential (e.g., García-Freites, Gough, and Röder 2021), and some insight into the assessment of the direct environmental consequences of deploying CDR (Terlouw, Treyer, et al. 2021; Vetter et al. 2022). However, the diversity of CDR approaches and the variety of LCA methods with which they have been assessed have led previous LCA practitioners and experts to conclude that these results should be interpreted with caution (Goglio et al. 2020; Terlouw, Bauer, et al. 2021). Key methodological issues suggested for further development include: (1) a clearer definition of the goal and scope of the study, including defining clear system boundaries, consistent functional units, stating the type of LCA undertaken, and higher transparency of accounting methods (Brander et al. 2021; Goglio et al. 2020); (2) consideration of the temporal distribution of emissions and removals (Brander et al. 2021; Terlouw, Bauer, et al. 2021); (3) establishment of a baseline against which the removal potential and climatic additionality can be assessed (Brander et al. 2021); (4) multifunctionality and consideration of other impact categories beyond climate change, for example, environmental and socio-economic effects (Terlouw, Bauer, et al. 2021). Furthermore, a lack of consistency and transparency limits the comparability

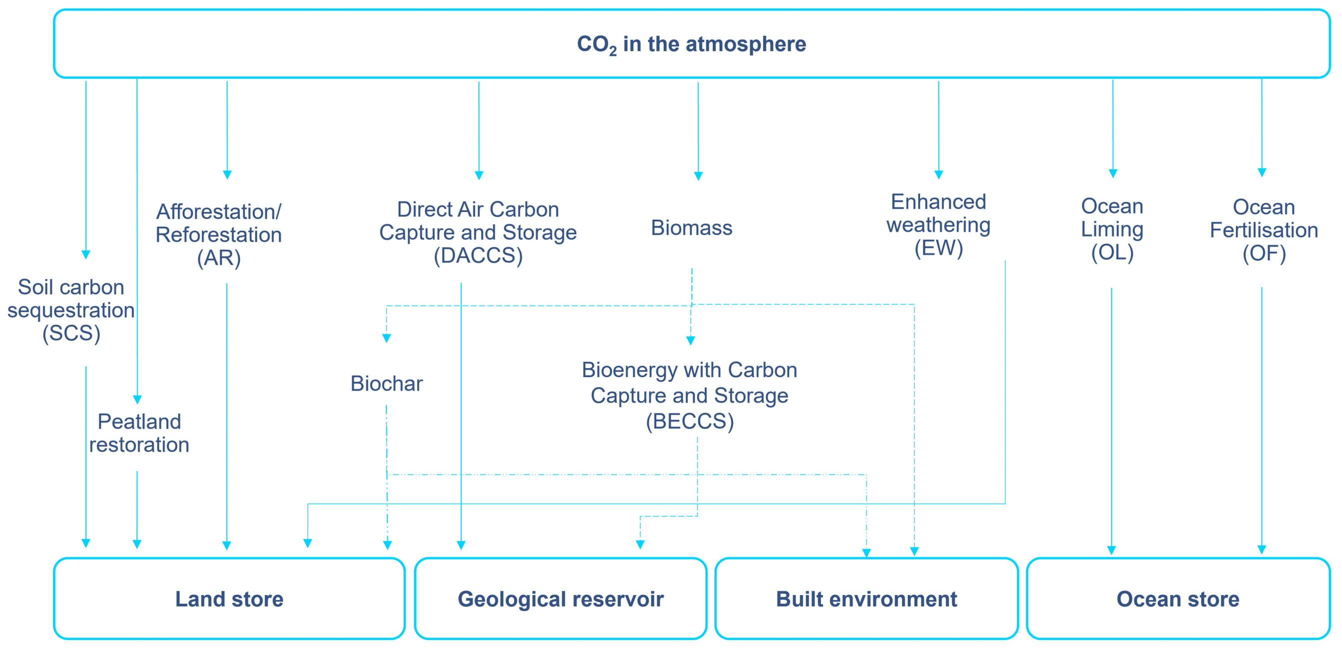

FIGURE 1 | Examples of CDR methods, illustrating the two key stages involved in any CO_2 removal: (1) sequestration or capture of CO_2 from the atmosphere, and (2) storage of CO_2 away from the atmosphere, that is, on land, in oceans, geological storage, in the built environment.

BOX 1 | Recent CDR research initiatives (including LCA) in the United Kingdom (UK).

In the UK, research funding through the Greenhouse Gas Removal from the Atmosphere Programme (https://www.ggrprogramme.org.uk/) supported CDR LCA research on biochar (Lefebvre, Williams, Kirk, Meersmans, et al. 2021), BECCS (García-Freites, Gough, and Röder 2021; Röder et al. 2019), enhanced soil carbon sequestration (Sykes et al. 2020; Vetter et al. 2022), enhanced rock weathering (Lefebvre et al. 2019), reforestation (Lefebvre, Williams, Kirk, Paul, et al. 2021), and specific LCA review papers (Brander et al. 2021; Goglio et al. 2020). In 2021, the UK GGR-Demonstrator 4-year program funded research on GHG removal at scale, with a research hub, CO_2RE (https://co2re.org/), and five demonstrators, investigating peatland restoration, tree planting, biochar, enhanced rock weathering, and energy crops for BECCS. In parallel, the direct air capture (DAC) and other Greenhouse Gas Removal Technologies program run by the UK Department for Business, Energy & Industrial Strategy funded 23 demonstrator projects in Phase 1 (2021–2022) and 15 projects in Phase 2 (2022–2025).

of different CDR approaches, making it hard to directly use the information provided by these LCA studies in decision-making.

This study focuses on which features of LCA are of particular importance to inform the scaling up of CDR approaches, exploring potential gaps, and identifying best practices in using LCA methods to inform policy- and decision-making on CDR scale-up. We conducted a focused literature review of CDR LCA case-studies at the start of 2023 through the lenses of three key aspects relevant to policy decision-making on CDR scale-up: (1) comparability of results across CDR LCA assessments, (2) assessment of the climatic merit of a CDR intervention across its full life cycle, and (3) consideration of wider co-benefits and trade-offs associated with CDR interventions. In this article, first, we compile current practice in defining goal and scope, functional units, and system boundaries; and suggest best practices that would ensure the comparability of future studies. Second, noting that most previous studies appraise the potential for removals by demonstrating net-negativity over the full CDR life cycle, we discuss the usefulness of additionally comparing this removal potential against a baseline. This would enable assessment of what would have happened in the absence of the CDR intervention, to ensure that CDR implementation is additional in terms of removals, and does not displace other options which could prove even more climatically beneficial. In this context, we also discuss the definition of temporal boundaries and potential challenges posed to decision-making by results from static LCA studies, that is, studies that assess CDR interventions at a fixed point in time and with a fixed supply chain configuration, not necessarily assessing consequences of expansion of these supply chains. Third, we highlight how LCA methodological development can help assess wider issues affecting the sustainable scale-up of CDR, with a focus on environmental co-benefits and trade-offs and other consequential considerations. Finally, key recommendations to improve CDR LCA and assist in decision-making are given.

2 | Methods

We conducted a focused LCA CDR literature review at the start of 2023 by performing a Google scholar search using combinations of the keywords "life cycle assessment," "LCA," "Carbon dioxide removal," "Greenhouse gas removal," "negative emission technology," and "review." The Google scholar searches returned 226 results using the keywords "life cycle assessment" and "Carbon dioxide removal" and "review," and another 98 results when using "life cycle assessment," "negative emission technology," and "review."

These search results were screened to eliminate double entries, publications that mentioned LCA but were not LCA studies, and LCA publications that analyzed only parts of CDR life cycle, for example, only the direct carbon capture stage ignoring upstream inputs, or only plantation of energy crops. At the end of this screening, the remaining 26 publications (see Table 1) were investigated in depth considering three key aspects relevant to policy decision-making on CDR scale-up: (1) comparison across CDR assessments, which requires clarity and standardization of goal and scope definition; (2) assessment of the climatic merit of a CDR intervention, which requires a definition of a baseline and robust and coherent temporal boundaries; and (3) consideration of wider co-benefits or impacts associated with CDR interventions.

Note that seven of the 26 publications selected for review in Table 1, were themselves predominantly framed as critical assessments of CDR LCA practices, undertaking and/or reviewing LCAs to make broader methodological points.

3 | Results

This section summarizes the findings of the in-depth review. First, we focus on goal and scope definition (Section 3.1), covering type of LCA approach, functional unit selection, and system boundaries definition. Second, we compare different approaches to evaluating the climatic merits of CDR (Section 3.2) covering temporal boundaries, baseline/counterfactual, permanence of carbon storage, and climate change characterization factors. We close with a less frequently included topic, but nevertheless critical to any decision-making on CDR scale-up, namely wider impact assessment, or co-benefits and trade-offs of CDR application and scale-up (Section 3.3). Here we review the coverage across different impact categories beyond climate change and approaches for CDR co-products assessment.

3.1 | Goal and Scope Definition

The first step in undertaking an LCA is to define its goal and scope, see Figure 2, reflected in the choice of the type of LCA to employ (attributional or consequential), and the choice of the functional unit and system boundaries. Attributional LCA (aLCA) focuses on describing environmentally relevant flows from and to the life cycle and its phases. Considering an example of an enhanced rock weathering project, an aLCA would

TABLE 1 | Summary of the selected 26 LCA publications for in-depth review.

CDR type	References	Type of LCA	Functional unit (FU)
Various CDR approaches	Terlouw, Bauer, et al. (2021)	Review paper	Wide range of functional units: typically per area or per mass of CO_2 removed, or per type of agricultural output (e.g., specific crops or meat/dairy production)
Various CDR approaches	Goglio et al. (2020)	Review paper	Mass (e.g., kg, t, Gt) of CO_2 removed, the economic value of carbon removed, amount of co-product (e.g., mass of cement, carbon fiber, food)
Various CDR approaches	Jeswani, Saharudin, and Azapagic (2022)	Review paper	1 t of CO_2 removed
BECCS	Almena-Ruiz et al. (2021)	Review paper	N/a
Forest bioenergy	Cowie et al. (2021)	Review paper	N/a
Biochar	Tisserant and Cherubini (2019)	Review paper	Typically per kg feedstock or per kg biochar; few papers per kg food produced; per unit area managed for biochar feedstock production
Biochar	Gahane, Biswal, and Mandavgane (2022)	Review paper	1 MJ or 1 MWh or 1 kW
Anaerobic digestion with CCS	Styles et al. (2022)	aLCA	1 mg fresh matter AD feedstock (ton fresh matter digested)
BECCS algae	Melara, Singh, and Colosi (2020)	aLCA	The annual power demand within 300-mile radius around potential geological storage sites within the three regional clusters
BECCS electric	Negri et al. (2021)	aLCA	BECCS supply chains in 1 year in the European Union
BECCS electric	Briones-Hidrovo et al. (2022)	aLCA	2 FUs: 1 t Carbon stored and 1 MWh_e output
BECCS H_2	Rosa and Mazzotti (2022)	aLCA	Not specified
BECCS from olive pruning	Galán-Martín et al. (2022)	aLCA	$kgCO_2$ removed
Biochar	Azzi, Karltun, and Sundberg (2022)	aLCA	1 unit of product dependent on product-system: (i) one tree planted, (ii) 1 m^2 year of green roof, (iii) 1 m^3 landscaping soil, (iv) 1 concrete tile, (v) 1 m^3 water treated, and (vi) 1 kg pig iron
Biochar	Azzi, Karltun, and Sundberg (2021a)	aLCA	Dependent on the application of biochar: (i) agriculture, (ii) industrial, (iii) forestry, urban
Biochar	Azzi, Karltun, and Sundberg (2021b)	aLCA	Heating provision for 1 year
Biochar	Tisserant et al. (2022)	aLCA	Management of 1 ha of land producing barley over 1 year with addition of biochar
Biochar	Brassard et al. (2018)	aLCA	Production of 1 mg of biochar
Biochar	Brassard, Godbout, and Hamelin (2021)	cLCA	The management of 1000 kg of dry biomass

(Continues)

TABLE 1 | (Continued)

CDR type	References	Type of LCA	Functional unit (FU)
Biochar	Yang et al. (2021)	aLCA	1 MJ energy produced for a demonstration biomass intermediate pyrolysis poly-generation system
CO_2 mineralization	Nazir et al. (2021)	aLCA	Removal per 1 kg of recycled concrete aggregate carbonated
DACCS	Deutz and Bardow (2021)	aLCA	"1 kg CO_2 captured" around ambient conditions with a purity above 99% v/v
DACCS	Terlouw, Treyer, et al. 2021	aLCA	Gross removal of 1 t CO_2 from the atmosphere via a DAC plant combined with geological storage
Enhanced weathering	Eufrasio et al. (2022)	aLCA	Gt CO_2 year^{-1} for CDR impacts of ERW per unit area (ha) of cropland; other units and impact points for all other categories
Enhanced weathering	Lefebvre et al. (2019)	aLCA	2 FUs: (i) per ha of agricultural land amended by < 5 mm basalt particles, and (ii) per ton of CO_2 removed
Ocean liming	Foteinis et al. (2022)	aLCA	Removal of 1 t of atmospheric CO_2 by ocean liming

Note: For further description of these publications see Table A1 in the Supporting Information.
Abbreviations: aLCA, attributional LCA; cLCA, consequential LCA methods.

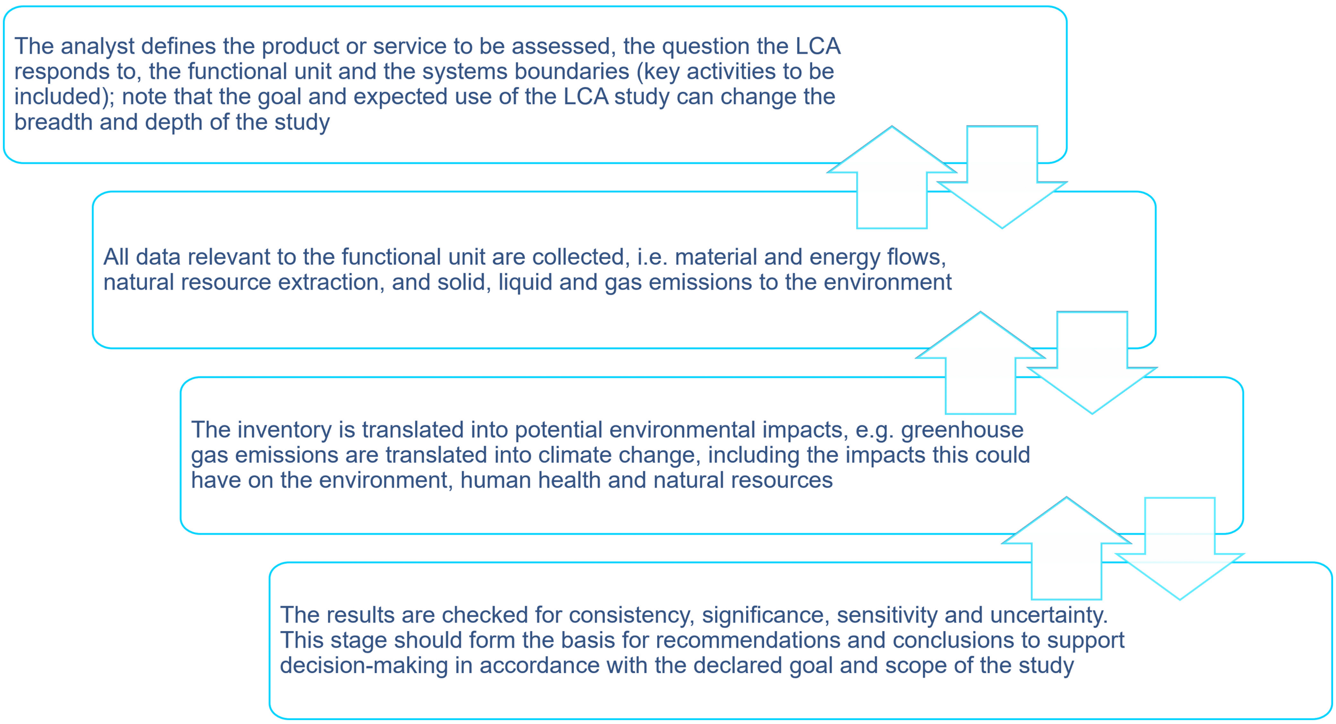

FIGURE 2 | Stages of Life Cycle Assessment: (1) scope and goal definition, (2) inventory, (3) impact assessment, and (4) interpretation.

focus on describing environmental impacts potentially caused by using a ground rock for CO_2 sequestration by spreading rock dust on cropland. This assessment should include the full life cycle, that is, from mining and grinding the rock, transporting rock dust, and spreading it on land. In comparison, consequential LCA (cLCA) focuses on how flows to and from the environment to the life cycle studied change as a result of interventions or decisions. Continuing with the example of enhanced rock weathering, a cLCA would consider how the environmental impacts (including greenhouse gas fluxes) change when rock dust is applied to cropland. In this case, a baseline to compare against is needed, for example, crop cultivation without rock dust application. The cLCA will also consider all the indirect effects caused by the change, including market effects and land use changes (see below for further details).

The LCA results of different CDR approaches can be compared if studies use the same functional unit and have the same level of comprehensiveness in system boundary definition, or at least provide enough details and transparency in methods and results so that they can be converted and standardized.

3.1.1 | Purpose of LCA: Attributional vs. Consequential LCA

Eighteen out of 19 studies reviewed here (not including the 7 review papers) employed an aLCA, which covers the supply chains formed by direct material and energy links related to CDR deployment. This methodological choice is understandable given that the majority of CDR interventions currently operate as demonstration projects, or at very small commercial scale, with little or no information on the scope of their (potential) scale-up. aLCA is the right approach if the study wants to identify key hotspots along the supply chain. However, if the question we are trying to answer is "What are the environmental impacts caused by the deployment of a scaled-up version of a CDR?" then a more appropriate choice would be the cLCA. The cLCA quantifies the system-wide change in environmental impacts or benefits from implementing a change in the system, such as CDR interventions, which is currently not widely deployed. The implementation of the change, that is, the scaling up of a CDR intervention, could result in product(s) and service(s) displacement, change in the price and/or production of different commodities in relevant markets (for example energy, biomass). Hence, a cLCA approach would cover not only direct and indirect energy and material flows associated with CDR deployment, but also the displacement of current products, services, and/or supply chains, changes in market composition for these products or services, and other background system changes (which are typically assumed static in aLCA).

While some studies we reviewed explored the evolution of impacts over time (Azzi, Karltun, and Sundberg 2021b; Brassard, Godbout, and Hamelin 2021), only Brassard, Godbout, and Hamelin (2021) adopted a cLCA. This implies that the majority of LCA CDR results reviewed here are less useful for deciding on which CDR intervention to scale up, as they do not address and discuss potential leakage of impacts from the scaled-up CDR supply chain, nor potential market displacement, nor potential change in the background system itself to accommodate the growing CDR. Nevertheless, aLCA results are critical for understanding where impacts may sit along the supply chain of a CDR, and may be useful for the monitoring reporting and verification (MRV) of CDR supply chains over time (see Box 2), including feeding into national GHG emission reporting.

The choice of LCA methods, aLCA or cLCA, will have different consequences on the uncertainty of the LCA assessment. As the aLCA usually looks at existing life cycle stages, the uncertainty around the estimated environmental impacts and trade-offs, including the removal potential, is reduced. As we explore potential future evolutions of the CDR supply-chains and the supporting background system, the uncertainty of evaluation increases. However, a transparent definition of this uncertainty space may be the most important factor for decision-making, helping stakeholders to identify potentially damaging scaling-up options and assisting in designing a more environmentally sustainable scale-up of CDR approaches.

BOX 2 | Opportunities and importance of linking LCA and Monitoring, Reporting, and Verification (MRV).

Monitoring, reporting, and verification are required at different levels, from large-scale National GHG Inventory (NGHGI) level MRV to individual project level MRV. The two types of MRV require different methods, both informed by LCA. For instance, NGHGI MRV could use high-precision data on national GHG fluxes but is not concerned with trans-national flows, for example, indirect land use change (iLUC). In contrast, project MRV considers the full life cycle of the product or service under assessment regardless of where it happens, for example, an iLUC estimation is also included when estimating carbon trading across national borders. However, individual project MRV methods are specific to the given project, and they are not meant to monitor and report the wider system changes, which are essential to consider when making decisions on scaling-up CDR.
Note that if MRV data collected though either type of MRV is to be used for LCA, the data collected in a given year may not be representative technologically (if the technology continues to be developed over time), geographically (if the CDR expands outside to the current location), temporally (1 year data is never representative, especially in the case of land-use activities), or complete (if data is collected from one site when the CDR employs several sites in the same location). These uncertainties should be adequately represented in the life cycle inventory and reflected upon correctly at the impact assessment and result interpretation stages.

3.1.2 | Functional Unit

Expressing all quantities per net amount (typically metric ton) of CO_2 removed over full life cycle—that is, using tons of CO_2 removal as the functional unit—would provide the most direct comparison of alternative CDR interventions. This functional unit could be made even more specific and further, ensure inter-comparability by incorporating the time duration over which carbon is removed. We discuss considerations over permanence (including potential definitions) further in Section 3.2 below, and ultimately recommend that providing all details of removal timings and expected storage duration (or risks to it) is the most comprehensive approach. We recommend that an evaluation of final carbon storage durability based on these temporal expectations is included as key additional information reported alongside the functional unit.

In the LCA studies reviewed herein, the quantity of CO_2 removed was not the universal functional unit, except for when the CO_2 removal was the sole "output" of the CDR intervention. For instance, some DACCS, BECCS, EW, and ocean liming (OL) studies used a functional unit of tons CO_2 removed from the atmosphere, either as recorded at the point at which CO_2 is physically captured or stored; or net, potentially diffuse, removals aggregating across a larger life cycle (see Table 2). However, most studies chose a functional unit related to the "co-product" which accompanies CO_2 removal. The co-product or service used as functional unit depends on the type of CDR, for example, electricity, heat, hydrogen from BECCS (Melara, Singh, and Colosi 2020; Briones-Hidrovo et al. 2022; Rosa and Mazzotti 2022), energy, improved production efficiency of an agricultural commodity, construction material additive from biochar (Azzi, Karltun, and Sundberg 2021a, 2022; Tisserant and Cherubini 2019; Tisserant et al. 2022; Brassard et al. 2018; Brassard, Godbout, and Hamelin 2021), waste management services, and biogas production (Styles et al. 2022).

These results, highlighting a variety of functional unit choices, are in line with previous CDR LCA reviews, for example, (Goglio et al. 2020; Jeswani, Saharudin, and Azapagic 2022; Terlouw, Bauer, et al. 2021; Tisserant and Cherubini 2019). This practice makes comparison between different CDR LCA studies challenging, if not impossible. While in some cases a reader would be able to convert impacts expressed per unit of co-product or energy to per ton CO_2 removed, this requires a significant amount of extra work and may need further data, not typically included within the original study. However, a number of studies reviewed here show that using net CO_2 removed from the atmosphere over the full life cycle as the functional unit is possible, and already being done, across diverse types of CDR, that is, DACCS (Terlouw, Treyer, et al. 2021), BECCS (Negri et al. 2021), EW (Eufrasio et al. 2022; Lefebvre et al. 2019), and OL (Foteinis et al. 2022). We argue that a fully comprehensive functional unit definition should also include the permanence of removal, that is, net CO_2 durably removed from the atmosphere over the full life cycle, see more in Sections 3.2 and 3.3. Applying this functional unit choice would help in CDR comparisons, and for MRV which should accompany any CDR deployment, to ensure that it is fit and stays fit for purpose, that is, keeps delivering net durable removal from the atmosphere.

3.1.3 | System Boundary Definition

The boundary selection for CDR LCA studies should include all processes and material flows relevant to climate change and any other impacts, with comprehensive coverage of direct activities. The boundary should include at least (1) the capture of CO_2 from the atmosphere, for example, by growing biomass, (2) all the processes between capture and final storage, for example, the harvest and processing of this biomass, transport, and (3) final storage of carbon, for example, application on soil, or transfer into geological storage. Indirect impacts associated with energy generation and impacts embedded in other goods and services utilized along the full life cycle should be included. cLCA should expand the boundaries further still, to cover displaced products, services, and corresponding supply chains.

As shown in Table 3, the systems covered in the current literature vary significantly, as different types of CDR have their own specific inputs and production processes. We found that LCA studies usually cover the full life cycle of the CDR under study, that is, from the sourcing of feedstocks and material

TABLE 2 | Choice of functional unit (FU) in the selected LCA case-studies reviewed in this work.

FU: ton co-product of the system	FU: ton CO_2 removed (at point of capture/storage)	FU: net ton CO_2 removed over full life cycle
Heating provision for 1 year, 1 m^3 landscaping soil using biochar (Azzi, Karltun, and Sundberg 2021a, 2022)	Ton CO_2 captured (Deutz and Bardow 2021)	Ton CO_2 removed by DACCS (Terlouw, Treyer, et al. 2021)
Kilograms biochar produced, or per kilogram feedstock used for biochar production (Brassard et al. 2018; Brassard, Godbout, and Hamelin 2021; Tisserant and Cherubini 2019)	Ton CO_2 stored and per MWh electricity from BECCS (Briones-Hidrovo et al. 2022)	Ton CO_2 removed by BECCS (Galán-Martín et al. 2022; Negri et al. 2021)
Hectare land barley managed with and without biochar addition (Tisserant et al. 2022)		Ton CO_2 removed by EW (Eufrasio et al. 2022; Lefebvre et al. 2019)
1 MJ, 1 MWh, 1 kW end-use energy generated from biochar production (Gahane, Biswal, and Mandavgane 2022; Yang et al. 2021)		Ton CO_2 removed by OL (Foteinis et al. 2022)
kWh electricity from BECCS (Melara, Singh, and Colosi 2020)		
Hydrogen potential from BECCS in Europe (Rosa and Mazzotti 2022)		
Kilogram recycled concrete aggregate carbonated (Nazir et al. 2021)		
Ton fresh matter digested (Styles et al. 2022)		

TABLE 3 | Choice of physical system boundaries in the selected LCA case-studies reviewed in this work, organized by type of CDR approach.

Biochar	DACCS	BECCS	Enhanced weathering	Ocean liming
Biomass production, pyrolysis, valorization of pyrolysis co-products, production and supply of other materials, transport, manufacture of the biochar product, biochar use and disposal (Azzi, Karltun, and Sundberg 2021a, 2022; Gahane, Biswal, and Mandavgane 2022), and additional wastewater treatment (Yang et al. 2021).	DAC plant, auxiliaries production, including solar PV and storage (Terlouw, Treyer, et al. 2021), other energy supply, adsorbent, recycling and disposal of all used materials after useful lifetime, CO_2 transport, and injection in geological storage (Deutz and Bardow 2021).	Energy crop production, harvesting, processing, transport to processing, pelletizing, transport to energy plant, carbon capture, CO_2 transport to geological site (Almena-Ruiz et al. 2021; Negri et al. 2021).	Basalt mining, comminution, transportation, and spreading (Eufrasio et al. 2022; Lefebvre et al. 2019).	Limestone mining, comminution, calcination, carbon capture, hydration, transportation, ocean spreading, and atmospheric CO_2 uptake (Foteinis et al. 2022).
Forestry activities, forest residue extraction, sawmill operations, biochar production, soil application, heat generation from co-products, and related transport (Brassard, Godbout, and Hamelin 2021; Tisserant et al. 2022).		Aquaculture (including nursery, cultivation, harvest), biomass transport, pre-treatment, digestion to bio-methane, digestate residue management, electricity generation, CO_2 capture and compression, CO_2 transport, and CO_2 injection for enhanced oil recovery (Melara, Singh, and Colosi 2020).		
Cultivation of switchgrass on marginal lands, harvesting, transport, conditioning, pyrolysis, amendment of biochar in soil, and valorization of bio-oil and syngas (Brassard et al. 2018).		Waste collection, anaerobic digestion, energy generation (electricity, transport fuel, heat), digestate use, carbon capture, and geological storage (Styles et al. 2022).		
		Anaerobic digestion, biogas upgrading, steam methane reforming, hydrogen purification and use, carbon capture, and geological storage (Rosa and Mazzotti 2022).		
		Forest management, residue harvesting, processing, transport, electricity generation carbon capture, and geological storage (Briones-Hidrovo et al. 2022).		

and energy inputs to the use of resulting products and co-products, and sometimes the end of life of these products and co-products. There were some differences in terms of how far studies tracked the use of products, and especially CO_2, with some studies covering CO_2 transportation and geologic storage, while others stop at the point of CO_2 capture. The latter difference in system boundaries selection reflects the choice of functional unit as "carbon removed" or "carbon stored," as discussed in the previous section. We highlight the absence of displaced supply chains, explained by the choice of attributional approaches, as opposed to consequential ones. Note that accounting for displaced activities, or leakage, is usually a requirement in the incipient market of carbon offset certification. The *GHG Protocol Land Sector and Removals Guidance* (WRI and WBCSD 2022) calls for all displacements to be accounted for, both when the displacement is direct, for example, firewood collection displaced to adjacent woods, or market-mediated, for example, when the current demand for displaced agricultural commodities is met though deforestation elsewhere.

It is interesting to note that despite using attributional approaches, which are arguably fewer data intensive as compared with cLCA due to considering only direct effects, the majority of the reviewed studies use a combination of experimental and modeled data, with some using exclusively modeled and secondary data, for example, Negri et al. (2021). While this is a perfectly acceptable approach in aLCA, it does raise questions around the uncertainty of the results obtained and how it would affect decision-making based on these results. More importantly, the type of data collected experimentally usually does not cover life cycle stages which are paramount for evidencing genuine removal and co-benefits from deploying it, for example, real biomass growth rates, real carbon loss from biochar applied in different conditions, CO_2 losses from CO_2 transport to geological storage.

3.2 | Climatic Merit of CDR

The effectiveness, or climatic merit, of a CDR intervention is determined by the size of net atmospheric CO_2 removal over the full life cycle including the impacts of any other greenhouse gas emissions/removals, the timing of removal, and the stability of CO_2 storage (Fridahl, Hansson, and Haikola 2020). All these aspects will influence the physical climate effects associated with the CDR deployment. To enable a comprehensive, transparent assessment of the climatic merit of the CDR approaches, LCA studies should report on each of these aspects.

3.2.1 | Net Atmospheric Removal: Importance of Baseline Definition

The climatic merit is ideally defined not only by the overall net removal over the full life cycle, but also in comparison to a baseline, to ensure policies are not promoting CDR interventions which would lead to lower removals than would be expected without the intervention occurring. A baseline definition is also useful in practice, to demonstrate the climate additionality of any climate benefits when claiming carbon credits. Several current carbon offsetting programs request defining a baseline, for example, Woodland Carbon Code (Scottish Forest Research 2022), although there is no agreement on how such baselines should be defined.

In terms of LCA methodologies, aLCA does not require a counterfactual baseline in the sense of "the most likely scenario in the absence of the intervention, but will require a 'non-anthropogenic baseline' in order separate out anthropogenic from non-anthropogenic (sometimes described as 'natural')" emissions and/or removals. This separation of anthropogenic/non-anthropogenic processes is particularly important in appraising GHG fluxes associated with land-use, although there are different views on how these baselines should be determined: see for instance the interchange between Soimakallio et al. (2015, 2016) and Brander (2015, 2016). Despite this, and the fact that many of our reviewed CDR studies rely on land-use to some degree, no study provided a clear statement of whether or how their emissions/removals were defined compared with "natural" fluxes.

Several of the reviewed studies here (6 of 19, see Table 4) did provide a comparison point, or "default" conditions, described as a "reference" against which to compare the environmental performance of their CDR. In these studies, all defined as aLCAs, the default was often implicit and could mean either "without biochar, and doing as usual" (Tisserant et al. 2022) (status quo reference) or "without biochar, but with an alternative product or process" (alternative reference) (Azzi, Karltun, and Sundberg 2021b, 2022). As aLCA is an inventory of emissions and removals from the processes used in the life cycle of the product/technology, it should not have a "baseline" in the sense of "the anthropogenic scenario that would exist in the absence of the product/technology." If the intention is to explore change relative to an alternative anthropogenic baseline, then a cLCA approach should be utilized.

Only one study, Brassard, Godbout, and Hamelin (2021), employed a cLCA approach and defined a baseline which they called "reference scenario" or counterfactual. The baseline was defined as leaving the residues in the forest to decay (alternative forest management), instead of using them for biochar production.

The GHG Protocol Land Sector and Removals Guidance (Policy and Action Standard: GHG Protocol, 2014) suggests two approaches to handle baseline definition in consequential analyses: (i) project-specific, that is, the scenario most probable in the absence of CDR deployment (with least barriers to implementation), or (ii) performance standard, which incorporates all baseline candidates. In the latter case, it advises choosing a stringent baseline, which is defined as ranging from higher than the weighted average of all net removals to the most stringent (most removal). This suggests that the baseline scenario should not be a historical reference point (i.e., 1 year) but instead, it should include time-specific assumptions about what there would be in the absence of the CDR deployment (Policy and Action Standard: GHG Protocol, 2014). For forestry removals, The *GHG Protocol Land Sector and Removals Guidance* (WRI and WBCSD 2022) recommends

TABLE 4 | Reporting of a baseline or counterfactual in the selected LCA case-studies reviewed in this work, organized by type of CDR.

No baseline definition—12 studies	
Biochar	Brassard et al. (2018)
DACCS	Deutz and Bardow (2021) and Terlouw, Bauer, et al. (2021) analyze potential DACCS scale up scenarios, all considering DACCS deployed; baseline (no DACCS) not mentioned.
BECCS	Almena-Ruiz et al. (2021), Briones-Hidrovo et al. (2022), Galán-Martín et al. (2022), Melara, Singh, and Colosi (2020), Negri et al. (2021), and Rosa and Mazzotti (2022) do not include baseline or counterfactual definition.
Enhanced weathering	Eufrasio et al. (2022) estimates removal from scaling up EW in a business-as-usual vs. a clean energy mix scenario to 2050, but no scenario without EW. Lefebvre et al. (2019) considered three basalt application rates: 5, 50, and 20 t/ha, but no case with no addition of basalt. Foteinis et al. (2022) do not include baseline or counterfactual definition.
Ocean liming	Foteinis et al. (2022) do not include baseline or counterfactual definition.
No baseline, but reference state definition (1 year)—6 studies	
Biochar	Azzi, Karltun, and Sundberg (2022) considered reference biomass feedstock to willow chips (urban garden waste; wood pellets from residues of the wood processing industry; and logging residues), reference biochar uses to improve soil (tree growing, extensive green roof, landscaping soil, biofilm carrier, pig iron production, and construction materials). Azzi, Karltun, and Sundberg (2021a) considered reference biomass use (waste incinerated as opposed to biochar production), reference co-product heat production (wood chip combustion in combined heat and power), and reference biochar use (tree planting with conventional soil substrates and stormwater treated as opposed to biochar application in urban tree planting). Tisserant et al. (2022) include farming activities (plowing, fertilization, pesticide application) and inputs (fertilizers, machineries, lime) required for the management of 1 ha of land producing barley over the period of 1 year without addition of biochar to soil. Gahane, Biswal, and Mandavgane (2022) used current plant and supply chains configurations with current grid-based electricity as baseline. Yang et al. (2021) used as reference the current biochar supply chains configuration and the current percentage of agricultural residues used for energy in China. The reference is estimated over the same period as the rest of the biochar deployment and BECCS scenarios, 2020–2050.
BECCS	Styles et al. (2022) compare anaerobic digestion coupled with BECCS performance in 2050 against different counterfactual marginal energy sources, marginal (substituted) animal feed, marginal food and feed production, substituted fertilizer, manure management, and counterfactual food waste management (composting).
Baseline definition—1 study	
Biochar	Brassard, Godbout, and Hamelin (2021) consider a baseline scenario which they called “reference” scenario when the primary forest residues are left in the forest, as opposed to using them for biochar production.

adopting a dynamic baseline, to capture forest disturbances and growth over time.

3.2.2 | Timing of Removal/Temporal Boundaries

To establish removals and emissions over time and ascertain the benefits and impacts of removing or releasing a given GHG over this period, temporal emission and removal accounting is required in both the CDR intervention case and the baseline. This would need recording/estimating time series of emissions and sinks over the full supply chain for the period of CDR deployment and well into the future. The temporal aspect of emissions and removals is acknowledged to be important in all LCA reviews we have included in this study, for example, see Goglio et al. (2020) and Terlouw, Bauer, et al. (2021). However, in the papers we reviewed here, the inventories were usually defined for one average year (Figure 3). This is typical for studies with an

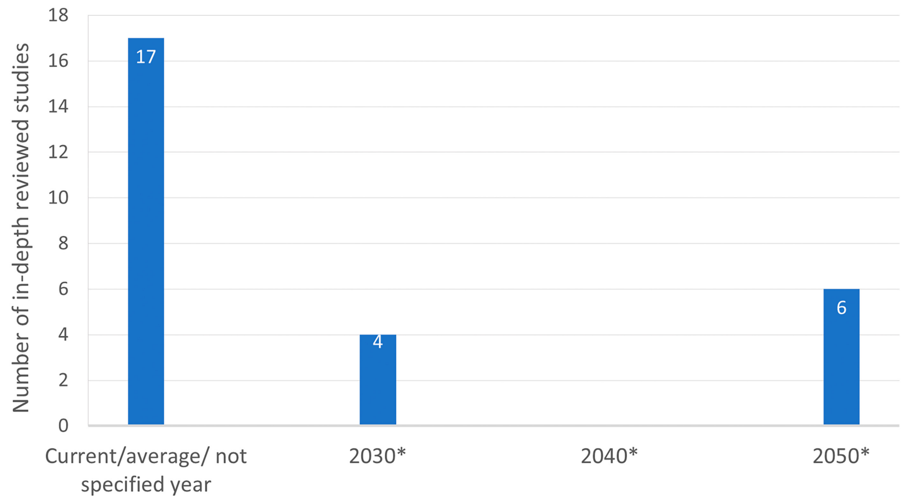

FIGURE 3 | Choice of temporal system boundaries in the 19 selected LCA case-studies reviewed in this work. All studies report the current year or an average undefined year when the functioning of the CDR is assessed. Two studies (Deutz and Bardow 2021; Terlouw, Bauer, et al. 2021) assess the same CDR scaled up in 2030, and 4 studies report a 2050 picture (Deutz and Bardow 2021; Styles et al. 2022; Eufrasio et al. 2022, and Nazir et al. 2021). Two studies (Azzi, Karltun, and Sundberg 2021b; Brassard, Godbout, and Hamelin 2021) report modeling results over periods, 2020–2048 and 30 years, respectively, hence included with an asterisk in the years 2030–2050 in the figure.

attributional approach to LCA, which covers the supply chains formed by direct material and energy links related to the CDR deployment in a given current or generic year. Less than half (8 out of 19) of the studies investigated here considered how emissions may change over time. For instance, Azzi, Karltun, and Sundberg (2021b) reported changes in heat demand under different climate change scenarios over the period 2020–2048, Deutz and Bardow (2021) and Terlouw, Bauer, et al. (2021) assessed potential changes in the energy system fueling DACCS over time.

If the question we are trying to answer is how a given CDR would perform at a larger scale, not at the current small scale that is currently being demonstrated in most CDR projects around the world, one could expect to see changes in the location of the bigger CDR intervention, in supply sources and markets for inputs, markets for co-products, changes in regulation concerning CDRs, and so on. For robust decision-making concerning which CDR to be scaled up, where, when, and how, the LCA should consider all potential changes over time in scenario analyses. Guidelines on how to set up such an analysis are already available, for example, see the GHG Protocol Policy and Action (Policy and Action Standard: GHG Protocol, 2014).

The timing of emissions and removals is critical for understanding the climatic merit of each CDR intervention. The faster global emissions reach net zero, the lesser is the probability of overshooting 1.5°C–2°C, as described by IPCC's Sixth Assessment Report (IPCC 2022). Although offering uncertain carbon storage (affected by reversibility, see also section on permanence of removal below), land-based CDRs may have a critical role in getting us to net zero on the path of least emissions. Robust CDR policies should reward land-based CDR for this critical function. A good practice would imply quantifying sinks and emissions over time, evidencing immediate contribution to removals. Meanwhile, we can work on developing CDR interventions [hopefully] offering permanent carbon storage, again evidenced by quantifying removals and emissions as a time series. This time series reporting enables evidencing the point in time when some interventions may turn from net emitters to net removals, and how removals are maintained over time or lost, turning the intended CDR into a permanent emitter and not a net removal. An example of an accounting method suitable for representing the temporal distributions of emissions/removals over time is the GHG Protocol Policy and Action Standard (WRI 2014).

Special attention needs to be paid to how background conditions are represented and communicated, for example, greenhouse gas emissions intensity associated with energy use. This is essential to address questions of sustainable scaling up as if the background/reference conditions change, so too could net climatic merit and/or other sustainability criteria.

CDR interventions should, by definition, offer a net removal of CO_2, but may be associated with increased emissions of other GHGs. The standard LCA approach is to use 100-year Global Warming Potentials (GWP100) relative to CO_2 as a common metric to weight the climatic impacts of different GHG emissions and use aggregated GWPs as the characterization factor for total climate impact assessment. We argue that emissions should be reported as individual GHGs, and not reported solely as aggregated totals using GWPs, for a number of reasons. First, GWPs are updated with each IPCC report, which induces differences between reported net climatic benefits depending on the point in time that the study was undertaken (not reflecting temporal dependence in emissions or their impacts, as above, but simply the numerical conversion factors in the most recent IPCC report). Second, the United Nations Environment Programme and Society of Environmental Toxicology and Chemistry (UNEP-SETAC) Life Cycle Initiative guidance (Jolliet et al. 2018) also recommends reporting aggregated climate impacts with both GWP100 and GTP100 (the 100-year Global Temperature change Potential, an alternative characterization factor suggested as indicating longer-term climate impacts) to provide further temporal insight. If individual GHG emissions are provided then users can explore sensitivity to any climate characterization factor, or directly employ climate modeling-based methods with the data provided. Thirdly, the GWP100, which is the most used climate impact assessment indicator across all the LCA CDR studies we reviewed, may not be an appropriate practice when, following IPCC AR6 model pathways, net negative emissions are expected from mid-century onwards. If we are to reach a state of continuous negative global GHG emissions, after 2050 or when net negative emissions are reached, then it has been argued it may be more appropriate to use a Global Cooling Potential (GCP) (Fridahl, Hansson, and Haikola 2020), an impact assessment method not yet defined in LCA.

3.2.3 | Permanence or Durability

A key requirement for a successful removal is that the carbon removed needs to be durably sequestered, preventing it from returning to the atmosphere (Brander et al. 2021; Fridahl, Hansson, and Haikola 2020). Currently there is no universally agreed definition of what durable sequestration or carbon store means. In line with the recommendation from the *GHG Protocol Land Sector and Removals Guidance* (WRI and WBCSD 2022), we suggest that for a removal intervention to provide a reduction in global cumulative CO_2 emissions—the basis for net-zero CO_2 and thus contributing to long-term temperature outcomes as required under the Paris Agreement (Allen et al. 2022)—the final store of carbon needs to be maintained over a millennial scale, with all carbon leakages reported when they occur. Although currently many prominent institutions and voluntary carbon market certifications suggest using a timeframe of 100 years and a discount rate for shorter time storage, see for example, UNFCCC Article 6.4 Supervisory Body, we argue against discounting of temporary storage, as it could lead to false temperature alignment and net zero claims, see for example, Brander and Broekhoff (2023). There can still be climatic merit in temporary carbon storage (Matthews et al. 2023), but given the geophysical perspective above highlighting that genuine compensation of fossil emissions requires removals to last for millennia or longer, we emphasize very long-term durability, and suggest that, at minimum, potentially temporary removals must be reported with a risk of reversal timeline, rather than reported as a single CO_2 removal quantity at the point of capture. Storing carbon through mineralization and in geological formations is generally considered permanent, as reported in several of the reviewed studies here, see for example, Lefebvre et al. (2019) for enhanced weathering, Foteinis et al. (2022) for ocean liming, Terlouw, Bauer, et al. (2021) for DACCS, and Briones-Hidrovo et al. (2022) for BECCS. While there is the possibility of minimal leakage of stored carbon in geological formations (Alcalde et al. 2018), this is not mentioned in the reviewed studies, for example, Briones-Hidrovo et al. (2022) include leakage of CO_2 from compression and pipeline transport, but not from geological storage.

In contrast, land-based CDR interventions are generally considered as offering a more temporary storage for carbon, due to exposure to disturbance from disease, fires, and/or human intervention. This temporary removal can range from a few decades to hundreds of years. The impermanence of carbon stores in biochar is acknowledged in all biochar LCAs reviewed here, which usually assume a degradable fraction of carbon between 15% and 30% and integrate the carbon loss over 100 years (Tisserant and Cherubini 2019). To ensure permanence in the land store, temporary removals need to be replaced with further temporary removals in perpetuity (Brander et al. 2021). The *GHG Protocol Land Sector and Removals Guidance* (WRI and WBCSD 2022) advises on covering three key aspects to ensure permanence: (i) risk-assessment of non-permanence both in current and future conditions, (ii) implement actions to reduce the risk of reversals, and (iii) address residual risks through financial (e.g., insurances), legal contracts (e.g., commitment to restore), or CDR buffers or portfolios of CDRs (equivalent to collective insurance). All these raise the question on whether these actions should also be included within the boundaries of any CDR LCA, in particular the actions taken to reduce the risk of reversal. We argue that ensuring the durability of removals is a key feature of any CDR intervention, hence all activities undertaken to reduce the risk of reversal and restore the carbon store should be included within the boundaries of a CDR LCA, with all carbon leakage reported. This would not only complete the GHG accounting, as any potential additional GHG emission caused by these activities is accounted for, but would also increase the credibility of removals by increasing transparency around their management.

3.3 | CDR Co-Benefits and Trade-Offs: Other Environmental Impact Categories

The focus of CDR LCA studies is usually on removals and GHG emissions only (carbon balances), with other environmental co-benefits and trade-offs as secondary to the performed analysis. From a practical point of view this is understandable, given the large amount of information to convey when reporting GHGs and the large range of other impact categories (18 midpoint indicators if using the IMPACT World + LCA framework, for example). However, the "other" impact categories are not of marginal importance to CDR scale-up, as they can make or break CDR supply chains. For example, current and future water availability will significantly affect many CDR methods, such as by impacting on the biomass or soil CO_2 sequestration rate, or by changing the availability of water supply for meeting cooling requirements of industrial CDR interventions.

Of the studies we reviewed here, while five exclusively reported climate impacts and/or net carbon balance, the majority (13 papers; 72%) also explore additional impact categories (see Figure 4 and Table A1 in the Supporting Information for further detail). A number of papers (6 studies; 33%) reported the full range of midpoint impacts recommended by LCA frameworks, with the most comprehensive, Eufrasio et al. (2022) and Foteinis et al. (2022), covering the 18 midpoint impacts suggested by the ReCiPe 2016 life cycle impact assessment method (Huijbregts et al. 2017).

Previous LCA reviews have similarly highlighted that there is incomplete coverage across different impact categories, and

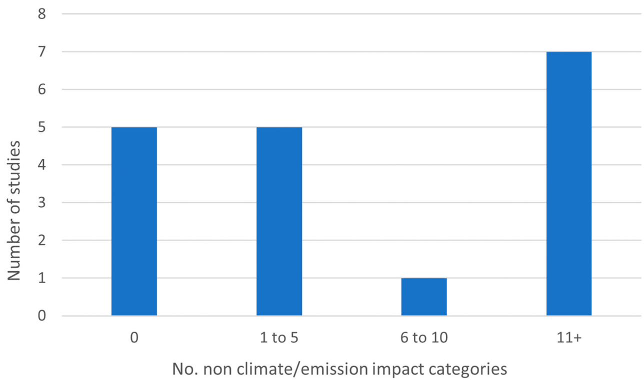

FIGURE 4 | Histogram showing the numbers of non-climatic impact categories reported across CDR LCA papers assessed (excluding papers that were predominantly reviews of other studies).

often only climate change impacts are considered (Terlouw, Treyer, et al. 2021). This is not unique to CDR LCA practice: for example, McClelland et al. (2018) highlighted that more than a quarter of livestock LCA papers between 2000 and 2016 only explored a single impact category, and more than half had less than 4.

Furthermore, co-products associated with CDR are rarely reported and inconsistently handled. As noted in Section 3.1, where CDR does provide additional outputs, LCA studies typically report these as the primary functional unit, with CO_2 removal as the co-product. While this reflects the focus of these studies, it presents a challenge when trying to compare CDR methods. As also highlighted in Section 3.1, there is not always sufficient data to convert to a standardized functional unit of tons CO_2 removed. Similar conversions, with the same underlying needs for sufficient data availability and transparency, could be used to scale the "co-products," enabling standardized approaches to explore the relative quantity or value of co-benefits associated with a ton of CO_2 removed.

We propose that LCA of CDR should primarily adopt the mass of carbon or CO_2 removed and permanently stored as a functional unit, such as per ton of CO_2, since this is their main function, while possible co-products and co-benefits should be examined using a system expansion rather than allocation, in a cLCA approach. Although the system expansion would result in more uncertainty to be handled by decision-makers, it is precisely this uncertainty space that allows the decision-maker to explore different ways to scale-up CDRs, and base the final decision on which CDR to scale up where on more than GHG balances solely.

Whether or not a study can capture broader environmental benefits may depend on how comprehensive the study is, which relates to the goal and scope of the LCA study. As highlighted above, there is incomplete coverage of impact categories beyond climate change, so these are unknown even if wider impacts might be positive. Establishing positive wider effects will typically amount to whether impacts are lessened with respect to a baseline scenario, if this exists and has been defined in the study: thus further emphasizing the importance of developing transparent and comprehensive baselines against which the impacts are calculated and reported in a cLCA approach.

4 | Learnings, Gaps, and Opportunities for Future Research

Despite the anticipated rapid and extensive scale-up of CDR to meet national and international climate policy targets, the LCA literature assessing the scaling-up of different CDR approaches is sparse and arguably underdeveloped, with some aspects in very early development, for example, co-benefits modeling. As highlighted in this review, there are relatively few LCA studies on CDR scale-up, centered around different functional units, and providing limited analysis on the changes CDR approaches will go through as they scale up and the changes this scale-up may induce in the wider system. Each CDR approach could scale-up through a number of different pathways, depending on the local conditions, for example, feedstock availability, climatic conditions, and wider conditions, for example, regulatory, market conditions, and wider system integration. How the future will look is highly uncertain, but this uncertainty should be reflected in LCA scenarios of CDR scale-up, as it would inform decision-makers on the range of possible outcomes and what conditions underpin these.

Robust scalability assessments require consequential, scenario-based analyses exploring interacting, system-level interventions over time, thus requiring a broad range of detailed information. The aLCA, as used in almost all the studies reviewed here, can provide relevant data for these consequential analyses, but the omissions noted above raise concerns over the expectation of large-scale CDR in most climate-economic integrated assessment models (IAMs). As CDR technological readiness advances, the amount of carbon they can capture and their potential wider impacts may all change, so it is important to be clear on what assumptions (in the CDR intervention itself or wider system conditions) give rise to current life cycle impact assessment estimates, and how these may change upon scaling-up. We, therefore, urge caution over making broad statements of potential CDR deployment based on direct scaling up of aLCA data (e.g., total feasible deployment area multiplied by removals per unit area) unless used simply for highlighting maximum physical potential, and emphasize the need for cLCA to address systemic impacts.

Our review also showed that not all studies considered wider impacts beyond climate, and except for the biochar studies, we found limited inclusion and discussion of co-benefits related to CDR deployment and scale-up. Furthermore, even for consistently included impact assessment categories, specifically climate change, not all studies provide the same detail, for example, the temporal evolution of emissions and removals, and composition of different GHGs. It is thus challenging to make detailed assessments of what different CDR approaches can ultimately achieve and how they might compare, and to anticipate or mitigate against any potential negative secondary effects of large-scale CDR deployment. Even from a more positive perspective, the lack of a wider impact assessment to date may obscure the potential for sustainable CDR deployment and estimation of the potential co-benefits that may result.

Considerations beyond GHG fluxes and climate impacts may require further data collection and will induce further uncertainty around the feasibility of sustainable scale-up of CDR approaches. While the extra data collection may incur further complications, for example, data availability, and extra costs, such as those associated with data quality assurance, it is very important that efforts to define, collect, and verify these additional data are made even from small scale CDR deployment to ensure a holistic assessment of CDR scale-up. And while we recognize these challenges, adding additional components does not necessarily dramatically increase the scope of a study: wider impact assessment categories will largely require the same underlying data to estimate climate impacts, so extending an extant study can provide added value, without requiring a whole new design. Existing life cycle impact assessment (LCIA) methods (e.g., ReCiPe 2016) can already help ensure comprehensiveness.

For LCA studies of any complexity, expanded reporting and clearer transparency are paramount. Conversions or further elaborations may be key for subsequent analysis, such as assessing scalability, but are only possible when all details and assumptions are clearly stated. Similarly, full reporting covering, as far as is possible, all energy and material flows, emissions, mid- and end-point impacts would facilitate standardization and enable users to explore sensitivity to different assessment methods (e.g., alternative impact measures and/or under different baseline assumptions). This could also enhance the usefulness of aLCA studies, enabling follow-up studies to extend analysis into further aspects beyond the scope of the initial work. Through projects such as the GGR-D demonstrator program, the demonstrator projects from the DAC and other Greenhouse Gas Removal Technologies UK government program, and the CO_2RE GHG removal hub, as noted above, work is also ongoing to suggest further standardization and best practice approaches for sustainable assessment of CDR.

As CDR moves from concept to reality, researchers have an important role in defining key environmental dimensions that would need to be included and how, that is, which parameters should be monitored, reported, and verified. Regulators would need to consider these dimensions and include them in any new CDR subsidy or planning application. Investors should also consider them in their decision-making as many of these environmental parameters will be related to the resilience of the new industry being created. Given the potentially large amounts of data being created, there is a role for independent scientific bodies to develop shared databases with harmonized methods for data collection, update, and utilization. These independent bodies could provide starting data, for instance on baseline selection as suggested by the WRI (Policy and Action Standard: GHG Protocol, 2014), which then would be updated based on scientific evidence as we are learning from the growing CDR space.

Considering these concerns, we suggest a number of ways to improve LCA of CDR and subsequent decision-making, summarized in Figures 1 and 5 in more detail. For CDR LCA researchers, we encourage more comprehensive and transparent approaches to LCA, which provide sufficient detail in all the areas outlined above, from clearly defined system boundaries and background conditions, consideration of multiple impact categories (both aLCA and cLCA), to adopting features like time series inventories and clear baseline definitions—see Figures 1 and 5 for an overview of key requirements in each LCA stage. Given the increased complexity of performing a cLCA and the increased need for data, there is lots of work to do in defining CDR-specific standards and providing tools and datasets that are readily available and assist the cLCA user. Databases such as PREMISE, collating IAM scenario data in a harmonized way, are a useful starting point, enabling more straightforward and transparent parametrization of future

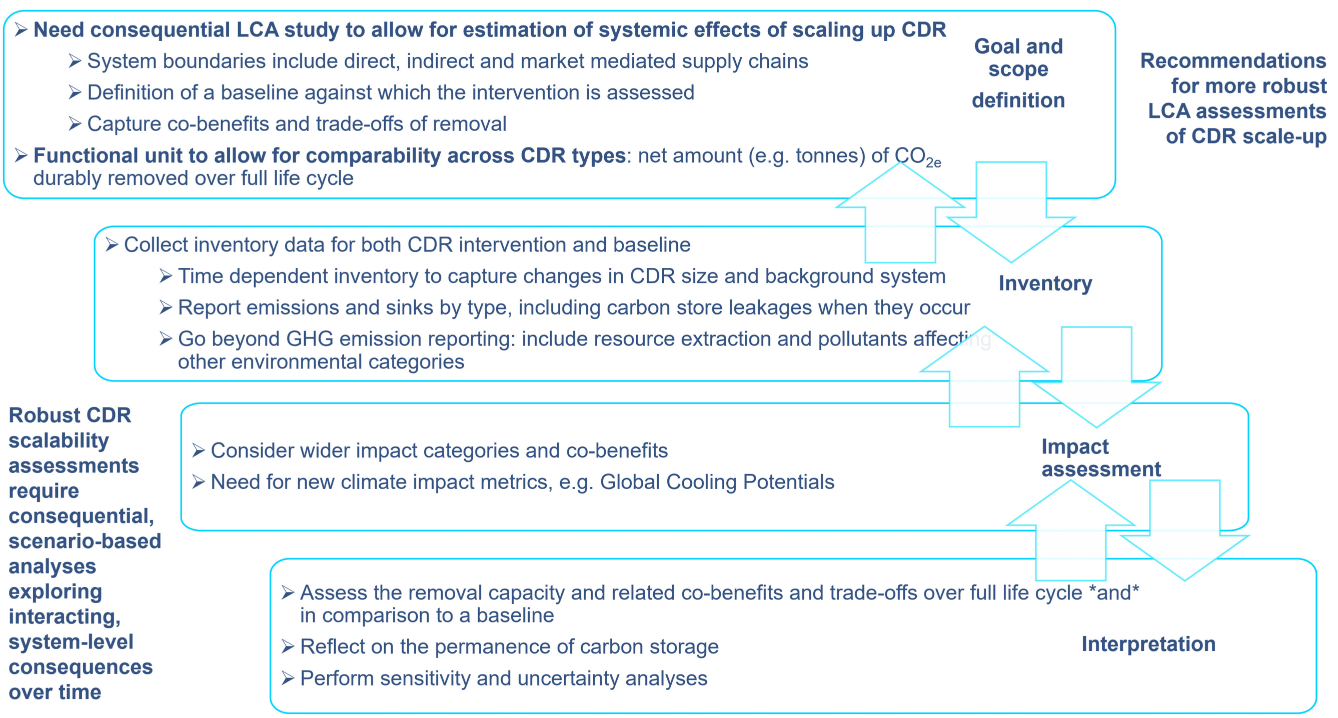

FIGURE 5 | Key recommendations for CDR LCA practitioners, split by LCA stage for clarity.

scenarios. However, more work is needed to improve the projection of non-GHG pollutant emissions in future scenarios, and better estimate their fate and toxicity (Sacchi et al. 2022). Ecoinvent already includes marginal data for cLCA, and some good guidance for cLCA exists, for example, Weidema (2003) and Weidema, Ekvall, and Heijungs (2009). More work is needed to create harmonized, spatially explicit, and open-source CDR datasets, which would form the base of cLCA. Creation of open-source cLCA software would bring data and methods together in a coherent way, while creating a shared platform for further scrutiny and development as we learn from scaling up the CDR industry.

For those at the science–policy interface, particularly those making decisions based on aLCA studies, we call for greater recognition and acknowledgment of the limitations inherent to aLCA. Despite a significant amount of work and many useful studies, the LCA literature on CDR remains at an early stage, comprising mostly attributional LCAs with significant constraints to their decision-making utility. Expanded sensitivity analyses are required to deploy this information for policy-design and avoid committing to weaker, undesirable, or even impossible pathways for CDR deployment; with particular attention to key assumptions in original LCA studies and whether they are likely to hold. Furthermore, the need for comprehensive sustainability criteria is already recognized by policymakers. The proposed EU Carbon Removal Certification Framework requires confirmation that "[a] carbon removal activity shall have a neutral impact on or generate co-benefits for" a range of other sustainability objectives, including sustainable use and protection of water and marine resources, pollution prevention and control, and protection and restoration of biodiversity and ecosystems. The proposal is vague on how these wider sustainability components will be quantified (Štrubelj et al. 2023), but it is likely that LCA methods will play at least some part, so it is imperative that a broader range of CDR impact assessment categories are addressed. It is important that this is done at an early stage so that methodologies can keep pace with policy needs and developments in CDR, and to ensure that plans are not made on the basis of limited partial LCA data, which prove unviable when further impacts are considered.

We acknowledge that this paper presents a potentially narrow slice of the wider CDR sustainability literature. By focusing exclusively on research that describes itself as life cycle assessment, we may have overlooked other papers that grapple with, and perhaps suggest other ways to address, the points we raise. In particular, we would expect that expanding the scope to IAMs would have highlighted many different approaches capturing consequential aspects and/or addressing more scale-related questions. However, we believe that LCA studies should also be mindful of these issues, and deploy tools to help address them (particularly as LCA-specific approaches to address many of these concerns do exist), and it is important to progress in the field of CDR LCA, given the legitimacy leant through the use of LCA and particular concerns that the common use of LCA as a simple comparison of climatic merit misleads policy makers (Plevin, Delucchi, and Creutzig 2014). Overcoming the challenges highlighted in this review would provide a clearer pathway to the level of CDR required, and help to achieve this in as efficient and sustainable manner as possible.

Author Contributions

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Conflicts of Interest

Mirjam Röder is Associate Editor for Bioenergy at WIREs Energy and Environment. The rest of the authors declare no conflicts of interest.

Data Availability Statement

Data sharing is not applicable to this article as all data and analyses are fully reported in results section and Supporting Information.

Related Wires Articles

An overview of palm oil biomass for power generation sector decarbonization in Malaysia: Progress, challenges, and prospects

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.