CDR review

WP2 – CDR methods assessment

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1. Executive summary

In this deliverable report we provide an overview scenario and literature evidence related to carbon dioxide removal (CDR) and discuss how the representation of CDR in integrated assessment models (IAMs) could be improved further. First, we provide an overview of the concept of CDR, widely discussed CDR options, and the composition and development of the CDR research landscape. Second, we provide an overview of CDR options currently represented in climate change mitigation pathways produced by IAMs and related developments since the AR6 Assessment Cycle, as well as representation gaps of CDR in models. Third, we look into literature evidence that is currently underrepresented in IAMs but could contribute to a more comprehensive representation of CDR. Lastly, we provide a brief outlook of forthcoming evidence synthesis work relevant to UPTAKE task 2.

2. Introduction

This section provides a brief overview of the underlying concept of CDR, the CDR options that are currently widely discussed in scientific literature, and the key developments and dominant topics of the CDR-related research landscape.

2.1 What is CDR and what do we need it for?

CDR includes all 'anthropogenic activities removing CO_2 from the atmosphere and durably storing it (...) but excludes natural CO_2 uptake not directly caused by human activities.'[1] In other words, CO_2 removal has to be additional to natural fluxes, durable, and directly removed from the atmosphere to align with the definition above, used by the IPCC. In terms of CO_2 storage, various carbon storage pools exist, e.g., geological formations, vegetation and soils, oceans and minerals (see Figure 1 for details).

CDR serves three purposes in mitigation pathways that meet global climate objectives: (1) accelerate medium-term net-emission reductions by complementing fast and steep gross emission reductions, (2) to offset residual CO_2 or greenhouse gas (GHG) emissions in hard-to-abate sectors to achieve net-zero CO_2 or net-zero GHG emissions, and (3) to achieve net-negative CO_2 emissions thereafter leading to a long-term decline in warming[2–4]. The scale and composition of CDR options vary across climate change mitigation pathways which limit

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warming to 2 °C or less within this century (AR6 scenario categories C1-3)[5], as shown in Figure 4. A recent contribution to the literature argues for a fourth potential role for CDR, to hedge against a stronger-than-median climate response to cumulative emissions up to the point of net-zero CO_2[6]. However, such a preventive CDR capacity would imply that efforts to rapidly and deeply cut emissions have already been fully exhausted.

2.2 What are the current key CDR options under consideration?

Various concepts and methods exist today to deliberately remove and store CO_2 from the atmosphere. There are many different ways of grouping these methods - we adopt the categorisation from Smith et al. (2024) (ref. [7]) who divide methods into "conventional" options and "novel" options. Conventional CDR mostly comprises established options storing carbon in above-ground biomass or in soils, for example through afforestation and reforestation, or soil carbon sequestration in grasslands or croplands. These options are often characterized by high technological readiness levels and comparatively low costs per tonne of removed CO_2, and account for nearly all the CDR currently deployed[8]. Novel CDR comprises a group of more recently introduced concepts and methods to remove CO_2 from the atmosphere that go beyond conventional methods leveraging advancements in technology These include direct air carbon capture and storage (DACCS), bioenergy with carbon capture and storage (BECCS), ocean alkalinity enhancement (OAE), or enhanced rock weathering (EW) and the use of biochar. Novel CDR options are generally associated with higher costs per tonne of removed CO_2 compared to conventional methods and lower technological readiness levels (as many of these methods are still in early stages of development, which means they have not yet benefited from economies of scale or widespread deployment) - however, these options are deemed attractive when considering the postulated removal potentials and longer storage timescales compared to conventional CDR options[7]. Figure 1 provides an overview CDR options that are widely discussed in research and development, including their estimated mitigation potential, technological readiness level, and durability.

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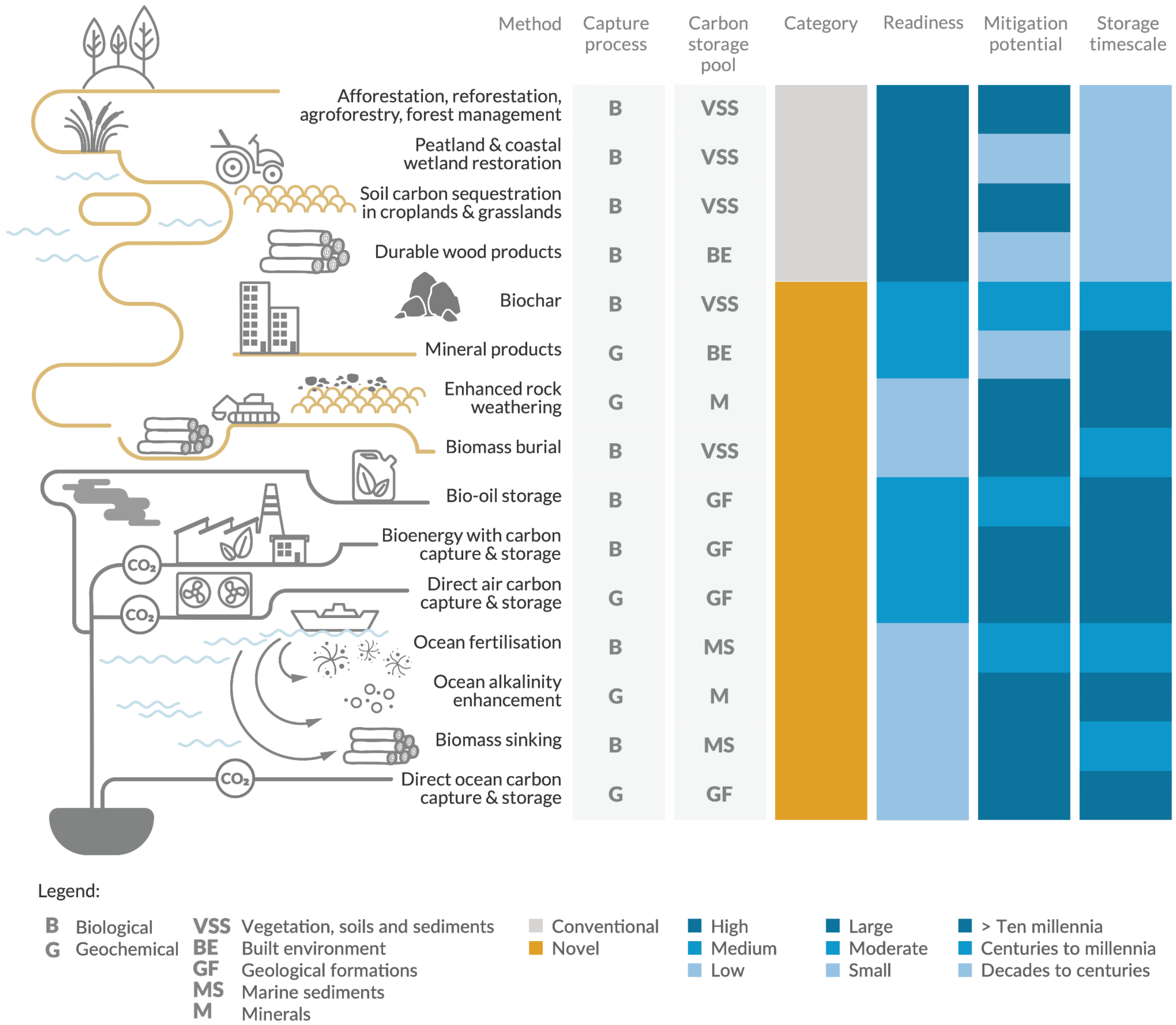

Figure 1. Overview of key CDR options under consideration in research and development (Source: State of CDR (2024)).

To date, global efforts to remove CO_2 from the atmosphere are around 2 billion tonnes per year, which makes up around 5% of current annual emissions[7]. More than 99% of the current removal is composed of conventional CDR options, mostly afforestation and reforestation. Projected removal levels in the national climate targets submitted by countries to meet their obligations under the Paris Agreement are far below the volumes deployed in mitigation pathways which limit warming to below 2°C[9] - such a gap in ambition in national climate targets can also be observed for gross emission reductions[10]. However, the idea of such a "CDR gap" raises substantial concerns since gigatonne-scale deployment of CDR may be

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associated with a number of negative externalities, and conflicts with broader sustainability objectives. The CDR options under consideration differ in terms of their side effect profiles - relevant constraining factors include high demand for water, land, energy, and fertilizer[11,12].

Given the need to scale CDR to gigatonne levels to meet climate goals on one hand, and potential sustainability risks associated with large-scale deployment of each CDR option on the other, a portfolio approach to CDR deployment will be necessary to balance these objectives[13–15]. Also, different CDR options may play distinct roles regarding the aforementioned purposes of CDR. In particular, some scholars advocate that continued fossil emissions should neither be equated with future removals to avoid shifting the burden to future generations and over-relying on unproven CDR. Nor should continued fossil emissions be equated with removals in the land-sector, among other reasons due to the high risk of reversibility and potential impacts on ecosystems[16]. Recent evidence suggests that CDR with storage timescales of at least 1000 years is required in the context of net-zero CO_2 targets to continuously balance emissions and removals to effectively halt warming[17]. Therefore, novel CDR options that offer the required storage durability are crucial to maintain a state of net-zero emissions over the long-term, ensuring that carbon removed from the atmosphere remains sequestered for centuries to come. Among these, BECCS and DACCS are at least at moderate technological readiness. On the other hand, conventional CDR options on land saturate in their potential and are less permanent, such as soil carbon sequestration or afforestation and reforestation. They can still play a critical role in mitigation by balancing non- CO_2 emissions of shorter atmospheric lifetimes and by lowering peak temperatures, offering more immediate climate benefits in the near-term[17,18].

2.3 What does the current evidence landscape on CDR look like?

Research on CDR has grown substantially over the last two decades, with the number of new research articles on CDR increasing exponentially (Figure 2a). The research field on CDR is growing faster than that of climate change research as a whole[19,20]. A recent study identified almost 29,000 research articles on CDR published between 1990-2022. This indicates that the body of literature on CDR is 2-4 times larger than previously estimated, even without considering grey literature[20] - the entire body of CDR literature is estimated to currently

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include up to 50,000 articles[7]. In terms of CDR options, there has been a strong focus on biochar as the most dominant topic in the last decade, which makes up more than 60% of CDR studies published in 2022[7]. Over the last two decades, biochar has become the CDR option that dominates the literature body and has replaced afforestation/reforestation and soil carbon sequestration, which previously held the largest share of the CDR-related research (Figure 2b)[7]. Generally, the majority of CDR research (86%) is currently focused on advancing removal technologies and approaches while only a small fraction of CDR research is aimed at understanding societal, environmental, and ultimately ethical implications of potential future large-scale CDR deployment[20].

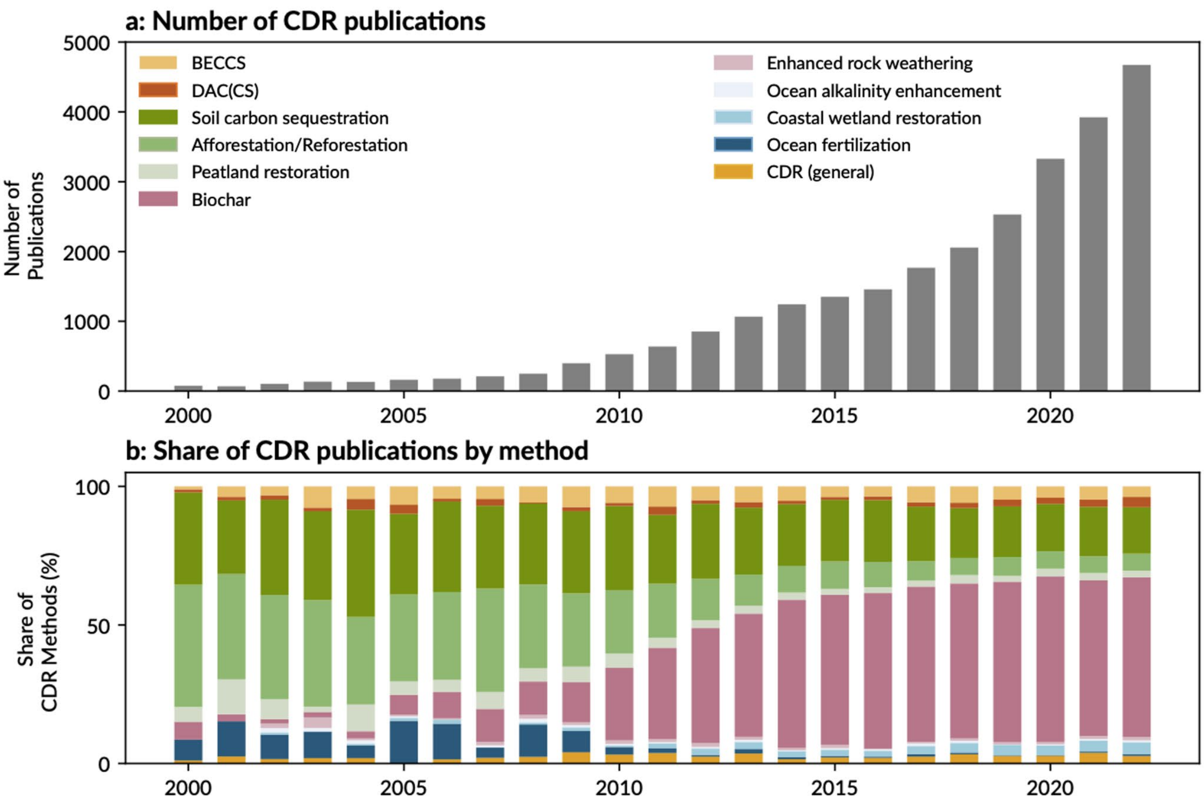

Figure 2. Overview of CDR-related research growth and composition (Source: Lück et al. (2024) and State of CDR (2024)).

Several evidence gaps in current CDR research can be observed. In terms of geographical coverage, a large part of existing studies with a regional scope focuses on China (accounting for 30% of all CDR studies) - so far, there is still limited research and development activity focused on Sub-Saharan Africa or Latin America, despite their critical role in land-intensive

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CDR options, such as afforestation or BECCS in many climate change mitigation pathways. However, over the last decade there has been substantial dynamic growth in CDR research focused on Africa (32% annual growth) and Latin America (26% annual growth); both of which have outpaced the overall annual growth rate of CDR research (18%)[7].

Novel CDR options are still least researched, including enhanced rock weathering, ocean alkalinity enhancement, or DACCS. This is especially true regarding place-specific evidence of DACCS, which is important given the high context specificity of performance and deployment implications[20]. However, the publication output for some of these novel options such as DACCS or enhanced rock weathering has been expanding rapidly in recent years[7].

The commercial landscape of CDR technologies is also evolving rapidly as industries, governments and climate innovators respond to the urgent global need to mitigate climate change. A recent study by researchers in the U.S. Department of Energy laboratories provided a graphical overview (Figure 3) of the CDR startup investment landscape highlighting key factors such as company age, funding stage, and total funding raised[21]. Agbo et al. (2024) (ref. [21]) explore opportunities for technological innovation to enhance the economic viability of CDR technologies with the overarching goal of stimulating innovation within the CDR field and directing R&D efforts toward areas with the greatest potential for cost reduction. These findings offer insights into the funding deals fuelling growth in technological CDR and highlights how the field is adapting to meet the challenges of global net-zero emissions targets. Such progress underscores the growing synergy between research advancements and commercial adoption, driving innovation and scaling efforts in CDR. More detail on the representation of CDR-related costs in IAMs is provided in the following section.

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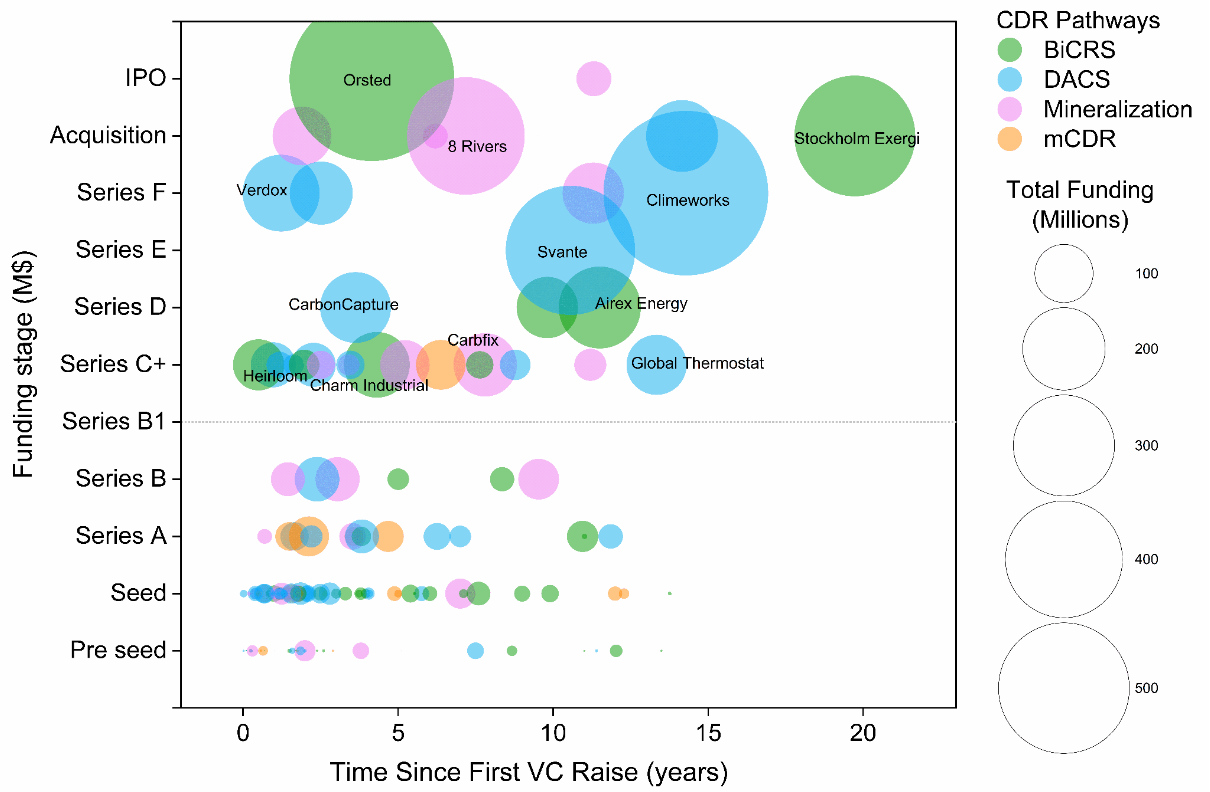

Figure 3. More than 175 companies from across the globe were categorized into one of four CDR pathway categories—direct air carbon capture and storage (DACS or DACCS), mineralization, bioenergy with carbon removal and storage (BiCRS), and marine carbon dioxide removal (mCDR)—using initial characterizations assigned by Sightline VC as a starting point. Each company was further classified into a startup stage based on its most recent venture capital raise. The Series C+ category served as a catch-all for companies that had surpassed the Series C funding round but had not yet reached the growth stage. For each company, the total funding was calculated by combining dilutive and non-dilutive deals. A few CDR companies, such as Ørsted and Climeworks, received funding exceeding $500 million; however, they are not shown in the graph at their true scale for simplicity. (Source: Agbo et al. 2024)

3. Overview of CDR in integrated assessment models

This section describes how CDR is represented in IAMs, which are used to produce climate change mitigation pathways. This includes an overview of the CDR options and deployment ranges across scenarios that were considered in the Sixth Assessment Report by the IPCC (AR6) and more recent efforts to expand the representation of CDR in IAMs. We also highlight aspects that are so far underrepresented in IAMs.

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Box 1: What can models tell us about CDR?

What types of models are used for informing deliberations of net-zero strategies?

The climate change mitigation analysis space is primarily shaped by integrated assessment models (IAMs) and energy system models[22]. These models are used to conduct a wide range of simulations to assess the impacts of different mitigation pathways and their associated costs, exploring the influence of critical assumptions on socio-economic growth, the costs, performance, and availability of technologies, as well as the timing, strength, and scale of mitigation policies[22–24].

How do different models operate?

Different **models used in climate change mitigation analysis operate by integrating key assumptions and representing complex relationships across sectors.** These models typically rely on *what-if* assumptions about future drivers of change –such as socioeconomic growth, technological advancements and policy measures– to generate a range of possible scenarios. within these scenarios, two primary objectives guide the model's operation: a) to identify cost-effective 'optimal' mitigation pathways within a framework that accounts for the linkages and trade-offs between energy, land use, climate, economy, and development (often referred to as "process-based IAMs")[25]; and b) maximising global welfare from a cost-benefit framework that integrates the cost of climate impacts[26]. Within the portfolio of measures available in IAMs to meet climate targets are different options for removing CO_2.

What do these modelling exercises tell us about CDR?

The output of mitigation pathways produced by IAMs provide information about various aspects of CDR. These models report on the types of CDR methods deployed within the set of represented options (see section below), highlighting the specific technologies or approaches used, such as BECCS, DACCS, or afforestation. Additionally, IAMs quantify the total amount of CO_2 removed through each option, offering a detailed assessment of their contribution to achieving climate targets. For regionally explicit models, they also reveal the geographic distribution of CDR deployment, providing important information about where each method could be implemented.

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3.1 Which CDR options dominate the scenarios in AR6?

Most mitigation scenarios assessed in the IPCC's 6th Assessment Report rely heavily on BECCS as the primary novel CDR option. When IAM frameworks consider additional novel CDR options, DACCS is the most frequently represented addition to the portfolio (Table 1)[1]. However, fewer modelling frameworks incorporate other novel CDR options such as EW or Biochar[27,28]. Assessing the role of conventional CDR such as afforestation and reforestation in these scenarios is complicated by inconsistent reporting and varying CDR system boundaries across IAM frameworks[5,29,30]. Gidden et al. (2024) (ref.[30]) proposed a method to consistently estimate conventional CDR based on reported land cover data using the earth system model OSCAR. This approach identified 407 1.5°C - 2°C scenarios (see Footnote 1 for definitions) that have sufficient reported data to assess the role of conventional CDR. Prütz et al. (2024) (ref. [11]) pursue a different approach and impute missing conventional CDR in incomplete pathways based on statistical relationships between net AFOLU CO_2 emissions and available conventional CDR data in AR6 pathways.

[1] We include the following categories of pathways assessed by the IPCC when we refer to “1.5°C - 2°C” pathways: C1 (limit warming to 1.5°C (>50%) with no or limited overshoot), C2 (return warming to 1.5°C (>50%) after a high overshoot) and C3 (limit warming below 2°C (>67%)). Not all of these pathways may be consistent with the climate objectives of the Paris Agreement (Schleussner et al., 2022).

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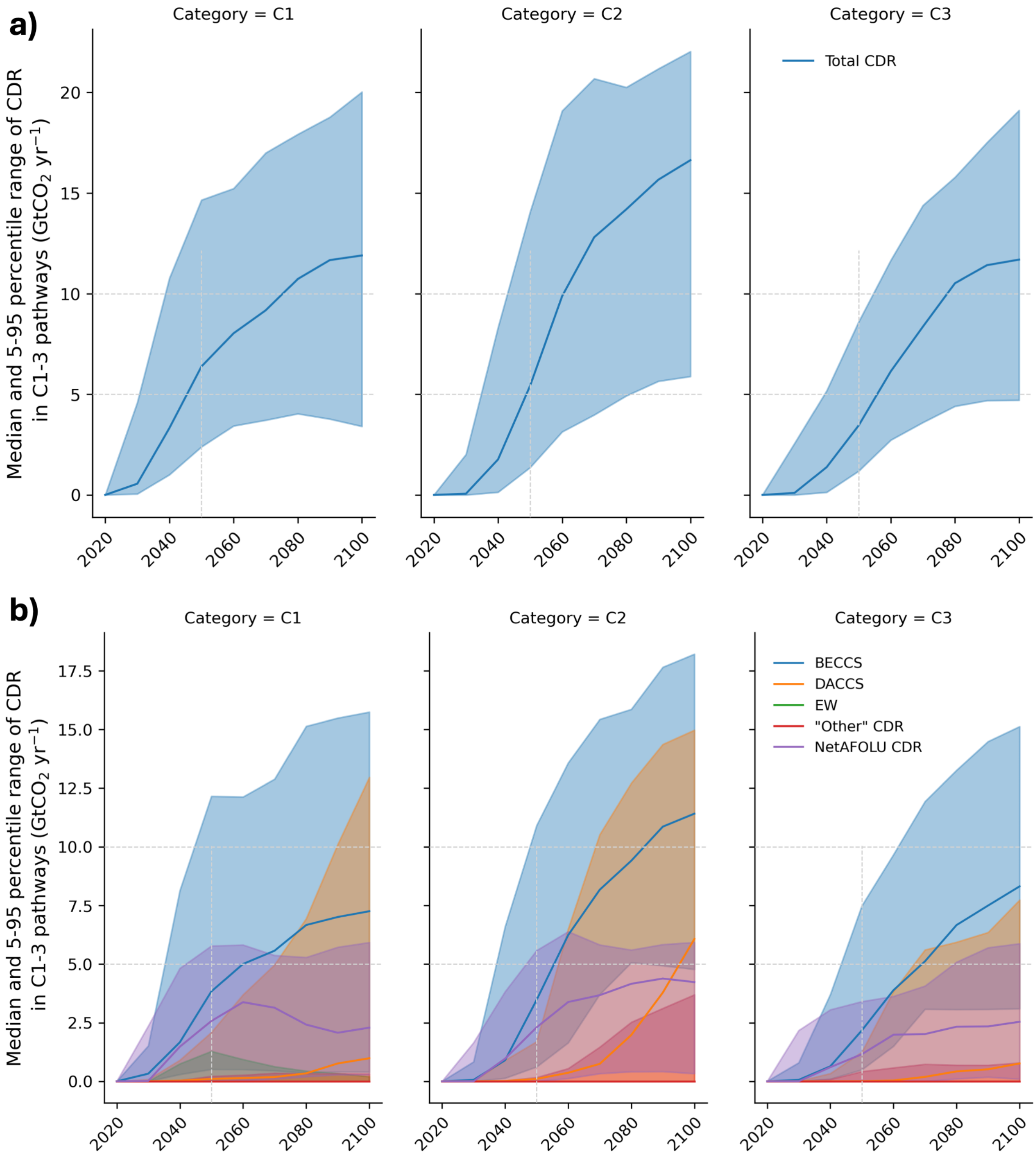

Figure 4. Carbon dioxide removal implied in AR6 climate change mitigation pathways limiting long-term warming to 1.5 °C with no or limited overshoot (C1), high overshoot (C2), or pathways which likely limit warming to 2°C (C3). Panel (a) shows total CDR deployment based on BECCS, DACCS, enhanced rock weathering (EW), net-removal from AFOLU, and 'other' CDR, as shown in Schleussner et al. (2024). Net-removal from AFOLU is used as conservative proxy for land use sequestration to account for reporting inconsistencies for this variable. Panel (b) shows removals for each of the CDR options described for panel (a). The underlying scenarios mostly rely on BECCS and enhancing land sinks and to a smaller extent also on DACCS - other CDR options such as EW are only represented in a small subset of scenarios: Across the C1 - C3 categories of pathways, the vast majority rely on

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BECCS as the only novel CDR option, with just over a quarter also including DACCS, and only four scenarios representing Enhanced Weathering as a novel CDR option (Table 1).

Figure 4 shows the CDR deployment across mitigation pathways that limit warming to below 2 °C (C1-3), based on the originally reported data in the AR6 Scenario Database. CDR is upscaled most rapidly in low or no overshoot pathways that limit warming to 1.5 °C by 2100 (C1). In the scenario ensemble shown in Figure 4, CDR deployment by the end of the century is generally higher in high overshoot pathways (C2) than in pathways with no or limited overshoot (C1). However, the 5–95 percentile range is similar across the two scenario categories. Pathways that likely limit warming to 2 °C but do not limit warming to 1.5 °C by 2100 (C3) are characterized by substantial CDR scale-up after mid-century, reaching deployment levels comparable to C1 pathways by 2080[5,6]. A recent analysis suggests that among all scenarios that limit end-of century warming to 1.5 °C (C1-2), substantial amounts of CDR are deployed to achieve net-zero CO_2 emissions[5]. The analysis, which focused on a subset of C1-2 pathways (n=83), found that the relative contribution of CDR to total mitigation at the time of net-zero CO_2 globally ranged between 8 - 45%, with a median of 21%. It is important to note that global and national scales are not easily comparable; regionally, especially in OECD countries, this relative contribution substantially exceeds what has been partly postulated as a sensible ratio of 9:1 between gross emission reductions and CDR deployment[5,31].

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Figure 5. Absolute and relative contribution of CDR deployment across a filtered subset of C1 and C2 pathways (n = 83) for achieving net-zero CO_2. Scenario filtering was necessary to account for reporting inconsistencies across scenarios and models for conventional CDR. Differences in total mitigation (upper panel) stem from differences in implied net CO_2 emission levels in 2020 across scenarios. The removal and emission reduction rates in the upper panel represent the difference in the respective annual rate at the timing of net-zero CO_2 compared to the rate in 2020 (Source: Prütz et al. (2023)).

3.2 What CDR options have been added to IAMs since AR6?

Building on the findings of the IPCC AR6, recent modelling efforts have expanded the portfolio of CDR options represented in IAM frameworks. While this report does not provide a comprehensive review of all post-AR6 scenarios, we take insights from the work of Smith et al. (2024), who compile and evaluate several such scenarios (Table 1). Notably, Smith et al. (2024) find that a larger proportion of post-AR6 scenarios now incorporate DACCS, and to a limited extent, EW. However, other novel CDR options remain underrepresented. A key limitation of the dataset compiled by Smith et al. (2024) is that it only covers scenarios assessed post-AR6 that are available in databases hosted by the International Institute for Applied Systems Analysis (IIASA) as of early 2024. This omits a few relevant single-model studies, including those from the GCAM modelling group who significantly expanded the portfolio of CDR options represented in their framework. GCAM now includes Biochar and

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Direct Ocean Carbon Capture and Storage (DOCCS)[14], as well as recent studies from the IMAGE and GCAM groups that investigate the role of ambitious emission reductions in so-called "hard to abate" sectors in reducing CDR reliance[32,33]. Scenarios available after early 2024 in IIASA scenario databases are also omitted, such as recent results from a "Sustainable Development Pathway" (SDP) model intercomparison project[34,35], which offers new insights into CDR strategies for sustainable development pathways.

Table 1. Carbon dioxide removal portfolios included in the scenario assessment (Source: Smith et al. (2024))

	Total number of 1.5°C - 2°C scenarios	Number of scenarios with conventional CDR	Number of scenarios with novel CDR			
			BECCS	DACCS	EW	Biochar
Scenarios in the AR6 database	540	407	516	146	4	1
New scenarios since AR6	90	48	85	71	11	0

3.3 What aspects around CDR are underrepresented in integrated assessment models?

In current process-based IAMs, CDR options are generally represented as processes with inputs (e.g., feedstocks) and usable outputs (e.g., captured CO_2 after potential system leakage, energy carriers etc.). The way a given CDR option is represented by the respective inputs and outputs can vary between different modelling frameworks. Inputs predominantly include (1) required energy (electricity, fuel, gas, heat or hydrogen), (2) material inputs such as different biomass feedstocks from energy crops or residues and waste materials, (3)

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respective removal costs per tonne of CO_2 removal, represented as total costs, or differentiated between investment costs, operational costs, and additional costs, such as CO_2 transportation, and (4) limiting factors such as regional annual geological CO_2 storage capacity, which may restrict the scale of CDR deployment in certain areas. Inputs can also pertain to temporal dynamics: this includes (among other aspects) the permanence of CO_2 storage or the impact of technological learning on cost and growth rates over time. Inputs and the representation of temporal dynamics do vary across IAMs due to assumptions made about technological advancements, storage durability, and the scalability of CDR options.

Outputs predominantly include (1) captured CO_2 - mostly for long term storage but partly also as a commodity for further industrial applications - as well as (2) energy output as electricity, fuel, gas or heat. Model outputs depend on the underlying assumptions about inputs as well as processes, for instance temporal dynamics as well as differences across regions as mentioned above. Differences across regions pertain to factors such as global or regional biomass availability, geological storage capacity or feasible annual injection rates. Assumptions about required inputs, temporal and regional process dynamics and differences as well as exogenous constraining factors may differ between IAMs. Efforts are being made (e.g., as part of the UPTAKE project) to continuously refine and update the above-mentioned aspects to improve the representation of CDR in IAMs.

However, the representation of some CDR options in the current generation of IAMs does not comprehensively consider material inputs and potential environmental implications of large-scale CDR deployment. Recent literature evidence highlights a number of environmental impacts of CDR deployment, notably water, land, and nutrient footprints (especially nitrogen, phosphorus, and potassium) (ref, ref). Many of these environmental implications can be quantified through environmental life cycle assessments[36]. These resource requirements are directly tied to other potential implications of large-scale CDR deployment such as impacts on food security or biodiversity loss[37]. While many IAMs represent overall scenario implications for water consumption and land use change, these implications are often not explicitly represented for, and hence attributable to, individual CDR options. A more comprehensive and granular representation of these footprints would allow for a more nuanced performance comparison across implemented CDR options. Figure 9 provides an

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overview of literature estimates for key parameters which can help improve the representation of CDR-related environmental implications in IAMs.

In addition to these techno-economic and environmental aspects of CDR, socio-political aspects play a crucial role for successfully scaling up CDR. However, socio-political aspects are so far largely underrepresented in IAMs[38], including dedicated assumptions about institutional capacity to roll out CDR as a global industry, assumptions about the efficacy of monitoring, reporting, and verification, and fairness considerations in the context of CDR burden sharing. Considering how the burden of climate change mitigation (and in this context the deployment of CDR) is shared among states is crucial to work towards just climate action[39,40].

Recent studies have started working towards an increased consideration of socio-political aspects and institutional constraints, e.g., ref.[41] and ref.[42]. Still, a more comprehensive consideration of socio-political aspects and especially constraints to annual CDR additions and maximum deployment in integrated modelling would allow to better evaluate the feasibility of climate change mitigation pathways beyond techno-economic and environmental constraints and to ensure policy-relevance and consideration of justice aspects of modelled pathways. In other words, what is considered feasible in the model may not be feasible in the 'real world' if socio-political barriers and limits are not accurately captured[38,43,44], as well as techno-economic, deployment rates and growth constraints.

4. Towards a more comprehensive picture of CDR in scenarios

Schleussner et al. (2024) (ref.[6]) highlight five key dimensions of potential overconfidence in large-scale CDR, namely (1) technological readiness, (2) permanence and resilience of CO_2 storage, (3) unintended system feedbacks to CDR deployment, (4) policy response to and governance of CDR, and (5) sustainability and societal acceptability (see Table 2). While the former three dimensions (1-3) primarily entail techno-economic and environmental aspects, the latter two dimensions (4-5) comprise more socio-political aspects. he following sections provide an overview of insights from literature evidence syntheses across dimensions 4-5, focusing on policy response and governance as well as on aspects around societal acceptability, perception, and sustainability - including potential side effects.

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Table 2. Overview of constraints of large-scale CDR (Source: Schleussner et al. (2024)).
Note: Endnotes in the table can be found in Schleussner et al. (2024).

	Description of constraints and potential for overconfidence
Readiness	Current removal capacities are far from what is required to be compatible with the Paris Agreement. In the coming years, removal scales need to go up while costs need to come down – both at highly ambitious levels. Implementation gaps already arise, potentially precluding reliance on CDR to steer back from overshoot[27].
Permanence & Resilience	Permanent and secure storage of removed carbon is key. Overconfidence may arise from neglected uncertainty of the geological storage potential[72] and overestimated storage durability of land and ocean sinks under progressing climate change. Carbon stored in soils and vegetation is especially susceptible to climate or non-climatic impacts, including fires or pest infestation, and may be constrained further if total sequestration potentials are lower than current best estimates[73-76]. Carbon sequestration in marine ecosystems is equally vulnerable to climate impacts[77].
System feedbacks	Mitigation effects of CDR may be offset by weakened and potentially reversed land and ocean carbon sinks, and other undesired system feedbacks[78], e.g., unfavourable albedo changes, or emissions due to direct or (unintended) indirect land use change. Carbon uptake potential of land-based CDR is highly uncertain, depending on bioenergy crop yields in the case of bioenergy and carbon capture and storage (BECCS) and soil carbon response to land-use change and the rate of forest regrowth in the case of afforestation[79,80].
Policy response & Governance	Betting on CDR effectiveness may lead to insufficient emission reductions if CDR underperforms, or physical climate feedbacks are stronger than expected. The outlook of potential future CDR availability could deter mitigation, meaning that required gross emission reductions may be delayed and/or weakened[25,81] - an effect that can also be observed in integrated assessment models[82,83]. Lacking monitoring and liability of removal additionality and permanence may pose an additional constraint[8].
Sustainability & Acceptability	The extensive land use footprint associated with large-scale CDR may threaten environmental integrity[9,84-86] and/or agricultural production[73]. However, some types of CDR (for example, via restoration of natural ecosystems and their associated carbon) would be more synergistic. CDR often requires public acceptance – an aspect not reflected in current scenarios. Consensus is critical, as CDR can lead to undesired distributional impacts (e.g., concerning land tenure or food prices if large areas are allocated for CDR). Further constraints arise when considering (transnational) equity criteria, as the burden of CDR may not be evenly distributed between polluters, regions, and generations[48,87]. Even with strong CDR deployment by high-income countries, equitable mitigation outcomes may not be achieved[88,89].

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4.1 What does the literature say about CDR policy response and governance?

In terms of policy response and governance, an array of relevant aspects has already been identified and documented in the literature. One of the most widely discussed aspects is the potential delay and lowered ambition in cutting emissions in the light of an expected future CDR capacity[45,46] - often referred to as moral hazard or mitigation deterrence, which is partly also suggested by IAM outputs[6,47,48]. However, there are more governance-related challenges that need to be considered when evaluating the feasibility of CDR-dependent mitigation pathways such as regulatory bottlenecks for rapidly scaling and monitoring CDR as well as conflicts between CDR deployment and other policy goals[37]. While research on CDR governance is rapidly growing[49], currently it is a niche topic within the body of CDR literature. As with CDR research in general, the evidence gap on CDR governance is especially large concerning location-specific studies focused on countries of the Global South[49]. Based on a recent mapping study by Lück et al. (2024), Figure 6 gives an overview of the growth and composition of CDR research focused on policy instruments and governance over the last three decades.

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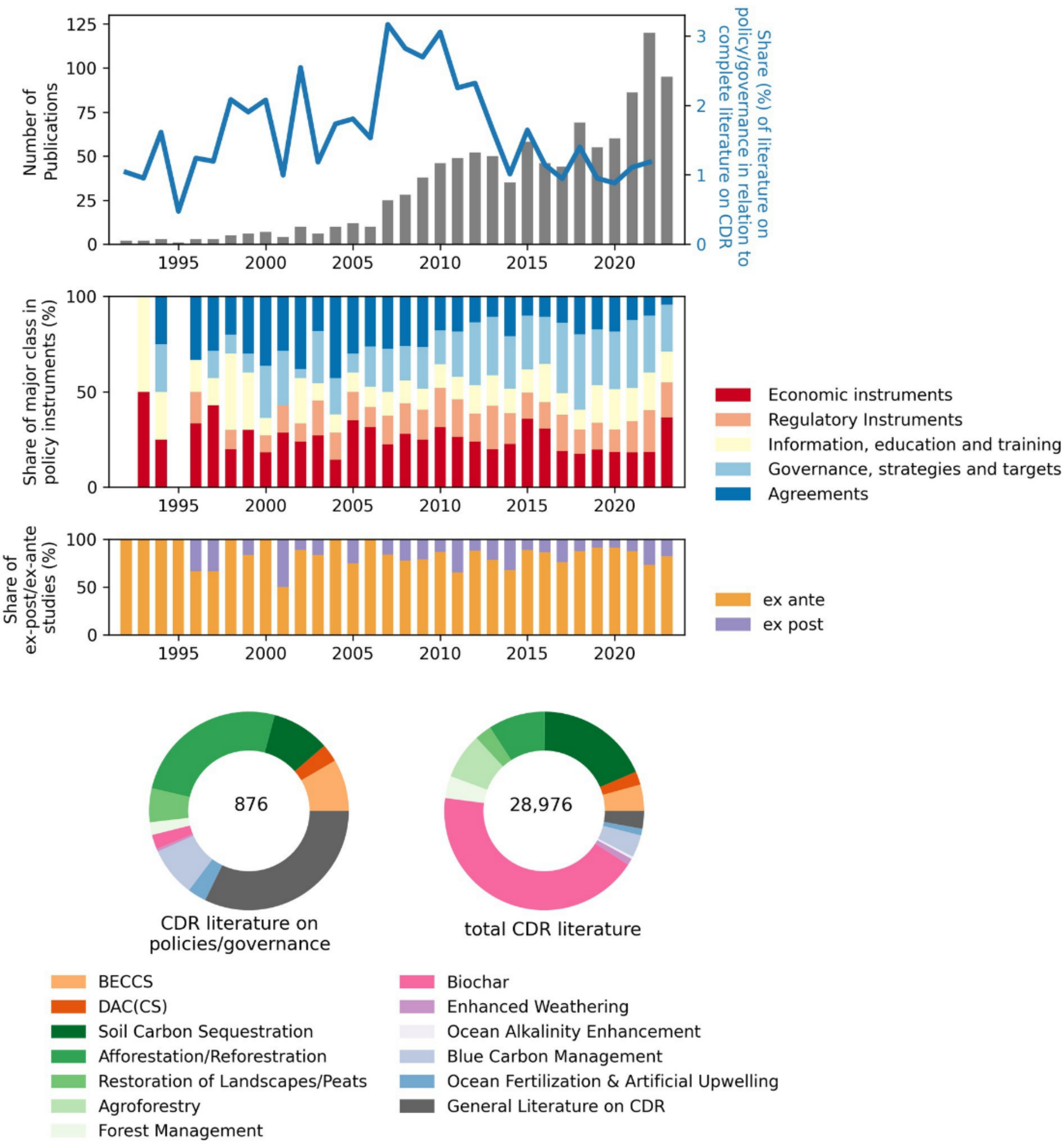

Figure 6. Overview of CDR research on policy and governance as documented in the English Language peer-reviewed scientific literature in terms of growth and composition over time. Multiple policy or governance instruments per underlying publication are possible (Source: Lück et al. (2024)).

The research on CDR policy and governance is still largely composed of ex-ante studies with few CDR policy evaluations - this may change as CDR is deployed and scaled. Unlike the

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broader body of CDR literature, the research subset on CDR policy and governance is not dominated by Biochar (see Figure 2 and 6). Instead, option unspecific CDR deliberations comprise the largest share[49]. So far, CDR policy and governance aspects are largely not represented in IAMs. Where possible and appropriate, information about political constraints such as regulatory bottlenecks should inform model-relevant processes such as the rate of increase in removal or storage capacity. When such information is not easy to translate into modelling frameworks, efforts should be made to highlight limitations of scenario-based insights. However, information about political constraints, for instance, regulatory bottlenecks affecting the feasible annual increase in removal or storage capacity, may be very relevant for modelers to refine assumptions about feasible scale-up.

4.2 What does the literature say about societal perception and acceptability of CDR?

The scientific literature on CDR has expanded significantly over the last two decades, and with it, research on attitudes and context factors influencing public perceptions of CDR has also grown (see Figure 7)[37,50,51]. Attention has shifted away from "geoengineering" as a general concept to more focused examination of specific CDR options, which find more positive sentiments for most CDR methods compared to controversial approaches like stratospheric aerosol injection[52]. Literature evidence suggests that the perception of 'naturalness' of a given CDR option plays a key role in shaping public preference. While people seem to be "cautiously supportive of CDR research and deployment"[51,52] public awareness of the need for CDR in the context of climate change mitigation and particularly concerning net zero targets remains low, despite growing media coverage[51]. Evidence suggests that careful communication about CDR is required to more closely engage with the wider public - this is especially important, as public trust in CDR-related political and regulatory processes and structures can heavily influence decision-making[51]. Careful communication about CDR is not to maximize acceptance of CDR deployment but to facilitate "informed participation in decision-making"[51].

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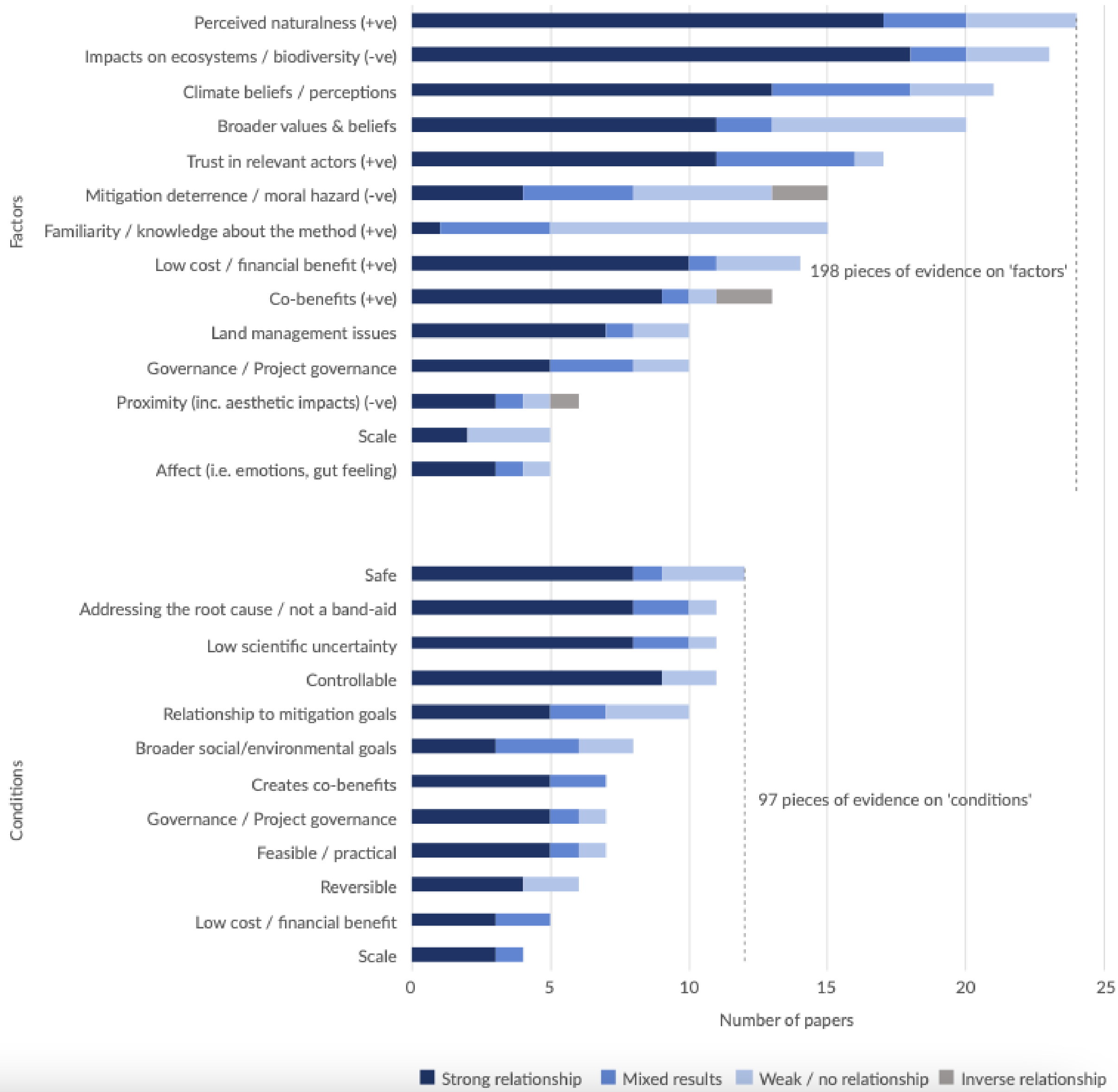

Figure 7. Literature evidence on key factors driving public attitudes towards CDR and conditions for CDR deployment. Where reasonably possible, the direction of the relationship is indicated as +ve (positive) or -ve (negative). Pieces of evidence refer to the total number of considered peer-reviewed articles discussing the respective factors or conditions (most articles cover several aspects) (Source: State of CDR (2024)).

Building on the available CDR perception literature, seven recommendations for responsible communication about CDR can be derived, namely (1) careful and reflective use of terminology, (2) contextualized communication about CDR, (3) two-way communication about CDR to disseminate information and receive thoughts and feelings about CDR, (4-5) transparency about potential negative implications as well as potential (co-)benefits, (6)

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emphasis of cutting gross emissions as priority, (7) no framing of CDR as "unnatural" or "natural" as this can divert focus away from the actual characteristics of CDR options[51].

While public perception and acceptability are challenging to quantify and model, they are important enablers or barriers for the socio-political feasibility of CDR research, deployment, and scale-up. Through IAMs focus on the technical and economic aspects of CDR, societal factors such as public opposition to deployment, especially in locations where infrastructure for CDR is being considered, could become significant barriers to scaling these technologies. Negative perceptions could constrain the speed at which CDR options are deployed, especially at large scale, and these social implications are often not sufficiently represented in current IAM frameworks.

4.3 What does the literature say about CDR sustainability and positive and negative side effects?

Recent literature evidence identifies 18 overarching categories of co-benefits, but also challenges and limits of CDR. Table 3 provides an overview of different categories that could bring co-benefits and/or challenges, while Figure 8 shows how the literature evidence is distributed across geographic regions.

Table 3. Overview of CDR-related side effect categories. Note: In many cases, side effects can be positive or negative, depending on the deployment context and mode of implementation (Source: Prütz et al. (2024))

Category	Description of CDR effect category irrespective of effect direction
Energy	The deployment of several CDR options has implications for the energy sector. This includes changes to energy supply and demand as well as impacts on energy independence and energy resource depletion[53–55].
Food & Yield	Implications for agricultural productivity are described for several CDR options – often driven by land use changes. Changes in yields impact competition over food, food prices, food security, and hunger. Impacts on agricultural exports and supply chains are also described in the literature[56–59].

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Land use	Several CDR options demand substantial amounts of land. This land demand can lead to land use conflicts and indirect land use change[60–62]. The land demand of several CDR options has implications for multiple other identified categories, such as food and yield or biodiversity.
Markets & Prices	The deployment or availability of CDR could influence GDP growth, electricity prices, marginal abatement costs, or carbon price development[63,64]. Livelihoods can be affected due to altered income opportunities and workforce competition, work conditions, and overall economic prosperity[65,66].
Air quality & condition	Some CDR options influence air quality and their condition, e.g., by changing particulate matter and photochemical ozone formation or carbon monoxide emissions with direct impacts on human health[55,67–69]. One study also described distortions of winds as well as changes to air pressure and planetary boundary layer depth as potential side effects[70].
Biodiversity	CDR impacts on biodiversity have been described for various indicators such as abundance and diversity, survival and growth rates of various animal and plant species or microorganisms, as well as habitat implications. Both aggregated and highly specific cases of biodiversity impacts of CDR were found[71–74].
Heavy metals	CDR deployment can impact the natural cycling of a variety of toxic and non-toxic heavy metals as well as their industrial demand for CDR implementation. Changes to heavy metal leaching and abundance in soils, plants, and foods are documented in the literature[12,53,75]. The implications for heavy metals thematically overlap with other identified categories, such as changes to soil conditions or the water cycle.
Nutrients & Minerals	Impacts on the flow and demand of nutrients and minerals such as nitrogen, phosphorus, potassium, and related compounds are widely discussed. Some CDR options influence nutrient and mineral stocks in plants and soils and alter their leaching into freshwater. Implications for marine, freshwater, and terrestrial eutrophication are also documented[12,76–78]. Impacts on nutrients and minerals thematically overlap with other effect categories in this analysis, such as changes to the soil conditions or the water cycle.
pH change	Some CDR options can alter marine, terrestrial, or freshwater pH and, therefore, potential acidification, e.g., in ocean surface water, soils, or drainage water[76,79,80]. The identified pH changes are closely related to the soil conditions and the water cycle.

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Raw materials	CDR-related changes to resource use and demand include a variety of materials such as different biomass types as feedstocks, sorbents, and silicates or different construction materials, including cement, steel, sand, and clay[53,81].
Soil condition	Some CDR options impact soils, e.g., compaction and composition, as well as their cation exchange capacity and electrical conductivity[82,83]. The formation of soil macroaggregates, gas exchange, soil temperature, and overall soil resilience can also be influenced by CDR[84,85]. This effect category thematically overlaps with other effect categories in this analysis, namely pH change, water cycle, heavy metals, as well as nutrients and minerals.
Toxicity & Radiation	Marine, freshwater, and terrestrial ecotoxicity, as well as human toxicity, are relevant considerations for CDR deployment, e.g., regarding ionizing radiation, stratospheric ozone depletion, or the leaching of polycyclic aromatic hydrocarbons[68,76,86]. Carcinogenic and non-carcinogenic human health impacts are relevant in this context[12,55,80].
Water cycle	Various water-related side effects of CDR are described in the literature, including changes to surface and groundwater quality and demand and, therefore, impacts on water scarcity. Some CDR options influence evapotranspiration, cloud formation, and precipitation patterns[87–89]. Structural changes in the environment can impact drainage and runoff with implications for flood protection[60,90]. This effect category thematically overlaps with other categories, namely pH change and soil condition, as well as nutrients and minerals.
Acceptance	Lacking support poses a potential implementation challenge for CDR. The literature describes insights into the general public perception of CDR but also the sentiments of direct stakeholders such as local communities, farmers, or landowners. The perception of CDR is influenced by a variety of factors, including perceived risks and benefits, legal aspects, as well as political and cultural beliefs[67,91–93].
Efficacy threats	An array of threats to successful CDR deployment were identified. Stored carbon may leak for various reasons, such as unintended natural sink disturbances, transportation, and geological storage leakages, non-climatic extreme events, climate shocks, sabotage, or human error. Removal rates can be reduced by sink saturation, climate-induced changes to biome productivity, indirect land use emissions, or a release of stored heat and CO_2 from the oceans when returning from an overshoot[94,95]. The unclear readiness and competitiveness of CDR options,

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	related accounting mechanisms, as well as removal markets and industries pose further threats[96–99]. Efficacy threats thematically overlap with other identified implications, such as changes to albedo in the category of thermal impacts.
Non-CO_2 GHGs	While removing CO_2 from the atmosphere, CDR can also impact non-CO_2 greenhouse gas emissions primarily from soils, such as methane and nitrous oxide emissions[79,100,101]. However, deliberate atmospheric removal of non-CO_2 greenhouse gases is beyond the scope of this study.
Policy response	The expected large-scale availability of CDR could lead to reduced or delayed emission reductions, obscured acknowledgment of policy failure, and carbon debt – often discussed as 'moral hazard'[102,103]. Ethical questions of mitigation burden sharing in the context of power imbalances and contrary geopolitical interests, as well as concerns of a CDR-induced commodification of nature and active climate design, pose challenges for policymakers[104,105]. CDR policies can further conflict with other policy goals, such as the SDGs, or provide co-benefits to ease the implementation of non-climate policy goals[106].
Thermal impact	Beyond CO_2-related global warming, some CDR options impact global and local air, surface, and ocean temperatures in various ways. This includes modifications to surface and cloud albedo, emissivity, changes to local heat-island effects, atmospheric circulation, aerodynamic resistance, and overall heat and energy fluxes[107,108]. The temperature impact of CDR may also influence thaw-freeze cycles and, therefore, permafrost or arctic summer ice[109]. Thermal impacts thematically overlap with the water cycle in terms of evapotranspiration and cloud formation.

Despite the crucial role of Africa and South America in future land-intensive CDR deployment - at least according to many IAM-based mitigation pathways - relatively few location-specific studies have been conducted to date, particularly those exploring potential side effects (positive and negative) of CDR deployment across these continents[37].

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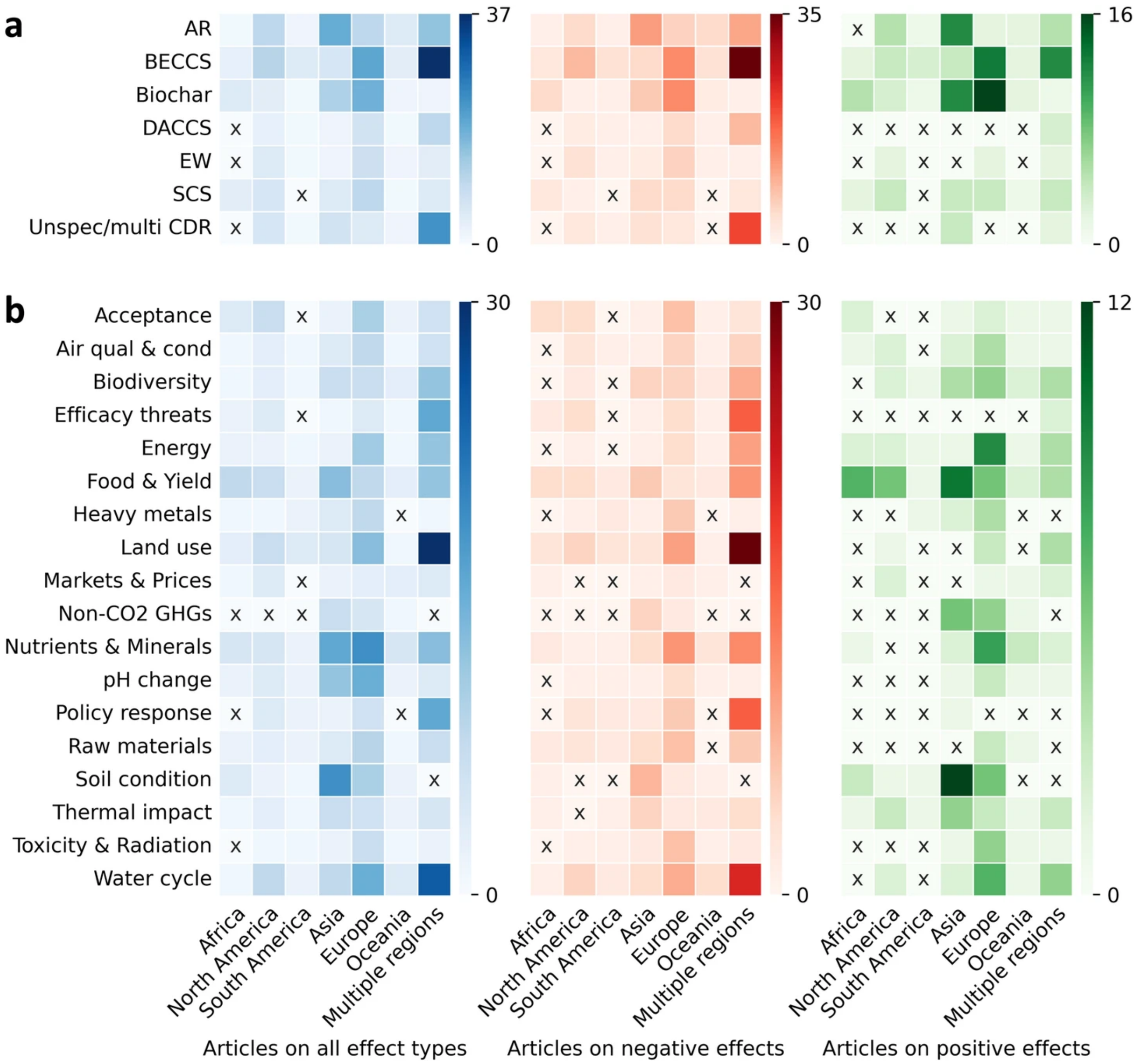

Figure 8. Geographic distribution of CDR side effect research across CDR options and 18 side effect categories. Panel (a) shows the number of articles per CDR option and world region across all effect categories. Panel (b) shows the number of articles per effect category and world region across all CDR options. "Multiple regions" refers to geographical study scopes covering more than one of the six listed continents. Studies without information on geographical scope were not considered in this figure. Double counting of articles is possible if articles mention multiple different effect desirabilities per region and effect category or CDR option. The blue column in (a, b) on all effect types also contains studies on effects with unclear or neutral desirability. Crossed cells indicate that no information is available in the evaluated evidence base (Source: Prütz et al. 2024).

So far, potential side effects of scaling CDR are largely not represented in IAMs. While the available literature estimates for key side effects such as land, water or fertilizer demand are subject to uncertainty and largely depend on the deployment context and CDR option setup,

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working towards endogenously representing such side effects in models would allow for more comprehensive assessments of scenario implications.

4.4 How can bottom-up research and scenario assessment inform the representation of CDR in models?

While many of the discussed aspects of policy response and governance, as well as sustainability and public acceptability in relation to CDR, are relevant to how CDR is represented in IAMs, comprehensively modelling all these aspects is challenging. This is partly due to the qualitative nature of some of these aspects, which makes it challenging to meaningfully parameterize and integrate such aspects into models. However, substantial uncertainties exist in the estimated effect sizes and their effect direction, which complicates the integration of available quantitative literature estimates into IAM frameworks.

In Figure 9, we present quantitative literature estimates for several CDR-related parameters, which are not yet widely represented in IAMs. Working towards integrating such parameters, despite the still large parameter uncertainty, would be an important step to allow for a more comprehensive evaluation of the role that CDR can play in deep mitigation pathways. In addition to expanding and improving the parameterization of CDR in models, scenario assessments and post-analyses of policy implications can help to complete the picture and facilitate the design of policy-appropriate mitigation pathways that align with real-world policy constraints, as further described below.

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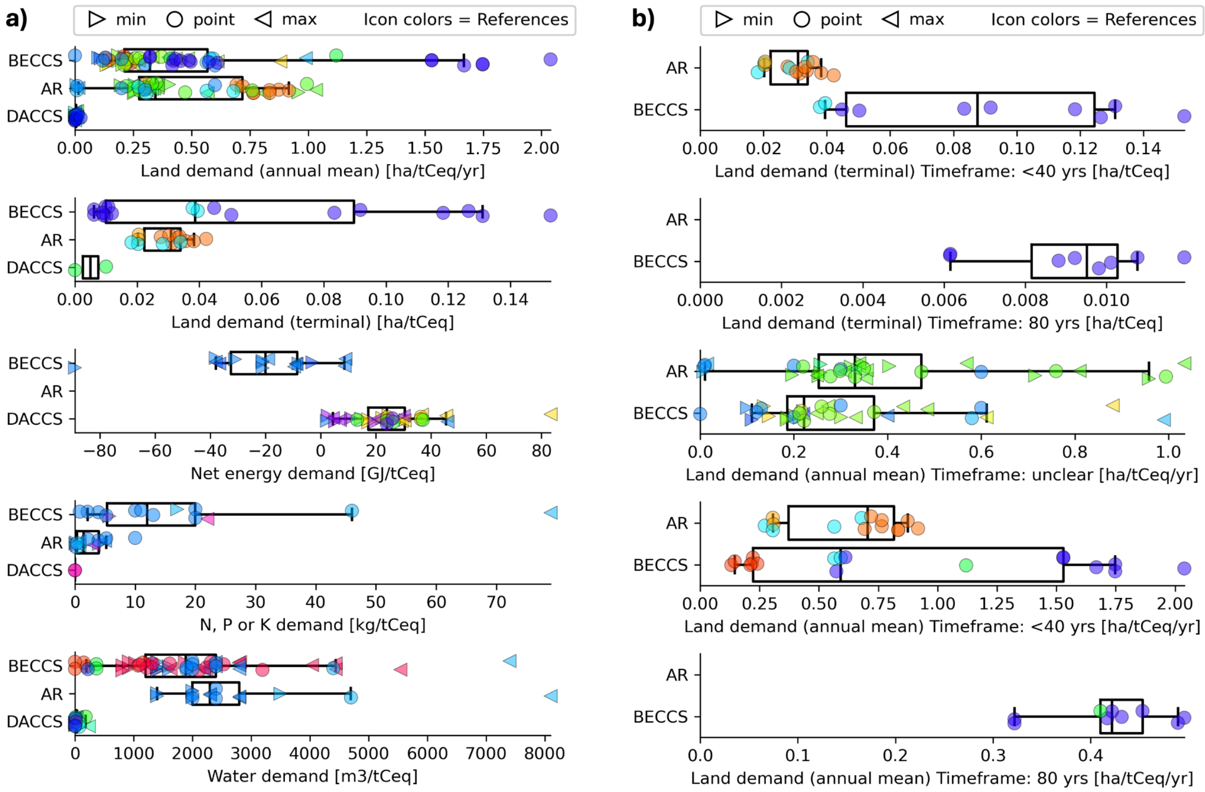

Figure 9. Overview of literature estimates for additional CDR parameters as potential input for IAMs to refine the representation of AR, BECCS, and DACCS. Markers show literature estimates as point, min or max estimates. Boxplots show the median, interquartile range with whiskers showing the 5-95 percentile range. Colour refers to the underlying studies, the estimates were compiled from. Estimates for nitrogen (N), phosphorus (P) or Potassium (K) are shown together. Net energy demand refers to the energy required to remove 1 tonne of carbon from the atmosphere. For BECCS, net energy demand is negative in most literature estimates as BECCS produces energy as a by-product to carbon removal. In a few outlier cases, net energy demand for BECCS is positive, which indicates that less bioenergy is produced through the BECCS setup than is required for the carbon capture and storage process. In terms of land demand to remove 1 tonne of carbon, different estimation approaches are documented in the literature with terminal land demand and annual mean land demand being prominent approaches. Terminal land demand is calculated by dividing the cumulative removal over a certain period by the total land use change over the same period. Annual mean land demand is calculated by dividing annual mean removal by annual mean land use change over a certain period. Literature estimates are not strictly comparable as the estimates refer to different spatial or temporal contexts as well as different technology setups or feedstock compositions, which have not been harmonized. Panel a) shows literature estimates across five key parameters. Panel b) provides more nuanced insights into terminal and annual mean land demand across different deployment timeframes. Rounded values of the literature estimates presented in this figure are provided in the supplementary data table.

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The overview of literature estimates in Figure 9 is restricted to, afforestation and reforestation, BECCS, and DACCS, as these options show comparatively good data availability across the considered parameters and are the CDR options that are most widely represented in IAMs. While being comprehensive, the selection of literature estimates from peer-reviewed articles and grey literature for this figure was not systematic. This figure is primarily intended to provide an overview of the large ranges in effect size estimates across studies. It needs to be noted that the presented literature estimates are not strictly comparable as the estimates may refer to different spatial or temporal contexts as well as different technology setups or feedstock compositions, which have not been harmonized. Figure 9b exemplifies the impact of different underlying deployment timeframes on effect size in terms of land demand for BECCS as well as afforestation and reforestation.

In terms of land demand for afforestation and reforestation or BECCS, two general approaches are observed in the literature. Terminal land demand describes the land that is required to achieve a cumulative removal at the end point of a time period, by dividing the cumulative removal over this period by the total land use change between the start and end point of the time period. The annual mean land demand instead, is calculated by dividing the mean removal over the time period by the mean land use change over the time period[110]. While it is not entirely clear whether the underlying studies consistently used this distinction between annual mean and terminal land use, the observed estimates for annual mean land use are substantially larger than the estimates for terminal land demand per tonne of removal. It is not surprising that the terminal land demand estimation approach generally yields lower effect size estimates, since the land intensity decreases over time as the removal accumulates - the annual mean land demand estimation approach is better suited to capture interannual variability in land demand per tonne of carbon removed. These two approaches can be seen as complementary rather than comparable as they highlight substantial temporal differences in impact-per-removal, which need to be considered when working towards representing CDR side effects in IAMs. However, this also points to an issue of the available literature estimates on impact-per-removal (in this case land demand), as corresponding temporal and spatial contexts as well as estimation approaches are often not sufficiently documented in the underlying studies.

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To complicate things further, lower land demand per tonne of carbon removed may not always be desirable. For example, afforestation or energy crop planting on marginal land may result in higher land demand per tonne of carbon removed than on fertile cropland. However, allocating marginal land rather than fertile cropland for CDR deployment may reduce land use pressure on food production[111].

In addition to improving the representation of CDR implications pertaining to sustainability goals (including some of the parameters presented in Figure 9) to fill scenario information gaps, dedicated scenario assessments are required to evaluate and select scenarios by considering policy-relevant factors beyond cost. A growing body of literature is focused on assessing the feasibility of deep mitigation scenarios by going beyond technical feasibility and considering other constraining factors[42,43,112–114]. Beyond feasibility, the desirability of mitigation pathways is another important consideration to identify the most policy relevant mitigation pathways. In the State of CDR Report (2024) (ref.[7]), a set of sustainability criteria is used to select a subset of 34 AR6 mitigation pathways and more recent scenarios, to identify scenarios consistent with not just the temperature target of the Paris Agreement but also its wider sustainability objectives linked to the Sustainable Development Goals. While the State of CDR assessment is an important contribution to the literature, it is constrained by lack of data on sustainability implications of CDR, which limits the sustainability criteria used for selecting scenarios. This underlines the importance of improving the representation of CDR externalities in climate models.

Ultimately, improving the endogenous model representation of CDR implications for sustainability as well as working towards further refined assessments of feasibility and desirability are two entry points for further research.

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Box 2: How can we represent uncertainty around CDR in models and scenarios?

The low technological readiness and system complexity of certain CDR pathways introduce significant uncertainties that challenge their inclusion and representation in modelling frameworks[115–117]. To address these challenges, different approaches have been suggested:

- Models should integrate factors such as biodiversity and toxicity to capture the environmental impacts associated with different CDR options[118,119].
- Representing different technological options within a CDR method to account for their unique characteristics, e.g., separately characterizing low-temperature and high-temperature direct air capture and storage (DACCS);
- Disaggregating deployed CDR to regionally-explicit levels[120].
- Evaluating multiple scenarios with varying assumptions about the value of key CDR parameters such as resource requirements, degree of storage permanence, or technological costs, even for values considered extreme or unlikely[121,122].
    - For those uncertain dimensions that are challenging to parametrise within IAMs, narratives about the geophysical, technological, economic, socio-cultural and institutional feasibility of CDR options could accompany scenarios[41,123–125]. Varying assumptions about feasibility could for instance constrain the available potential of a given CDR option[39,126].
    - Varying the underlying probability distributions of key parameters, in cases where such distributions can be known.
- Evaluating multiple scenarios with more than one model to elucidate the impact of structural model uncertainty on resultant mitigation pathways[127].
- Varying objective functions to account for disagreements in the desirability of pathways (e.g., fuzzy optimisation[128,129]).

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5. Outlook for CDR representation in scenarios

A substantial part of the literature evidence presented in the section "Towards a more comprehensive picture of CDR in scenarios" is based on systematic mapping studies, covering various cross-cutting issues of CDR research such as governance, side effects, or public perception. Such mapping studies are useful to provide condensed overviews of research topics, developments, and gaps. While the findings of such mapping studies can facilitate and inform the structured reflection of caveats of CDR representation in models, the rather broad outputs of systematic maps are often not directly parameterizable as input for modelling CDR. Other evidence synthesis approaches, namely systematic reviews and meta-analyses can contribute to harmonizing quantitative literature estimates and narrowing uncertainty ranges of important CDR aspects that are not yet parameterized in IAMs.

The Ecosystem of Reviews project is working towards a series of systematic reviews across several CDR options, guided by a shared review protocol to allow for a) in-depth analyses per considered CDR options, and b) comparability of outputs across reviews. This project is still ongoing with initial results from the systematic review on DACCS currently forthcoming. For UPTAKE, the outputs of the Ecosystem of Reviews may provide valuable data inputs to improve the representation of CDR in IAMs. Figure 10 gives a preliminary overview of anticipated outputs and assessed parameters from the Ecosystem of Reviews across data needs identified by the UPTAKE modellers in WP3 (for AR and biochar, information on the coding items is not yet made available). The figure shows that several identified data needs may be addressed by forthcoming results from the Ecosystem of Reviews throughout the project period of UPTAKE. Beyond this deliverable, we aim to foster and facilitate potential synergies across ongoing evidence synthesis projects and UPTAKE.

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	Information on...	AR	BECCS	Biochar	DACCS	EW	SCS	OAE	CCU
Costs	CAPEX	Pending	QN	Pending	QN	QN QL	XX	QN QL	QN
	CO2 transportation costs	Pending	XX	Pending	XX	XX	XX	XX	XX
	Cost reduction dynamics	Pending	QN	Pending	QN	QL	QN	XX	QN QL
	Economic attractiveness of retrofitting existing plants	Pending	QN	Pending	XX	XX	XX	XX	QN
	Labour costs	Pending	QN	Pending	QN	QN QL	QN	XX	QN
	Learning rates	Pending	QN	Pending	QN	QL	QN QL	XX	QN
	OPEX	Pending	QN	Pending	QN	QN QL	QN	QN QL	QN
	Regional biomass costs	Pending	QN	Pending	XX	XX	XX	XX	QN QL
Implications	Environmental impacts of residue removal	Pending	QN	Pending	XX	QN QL	QN	XX	XX
	Land demand	Pending	QN	Pending	QN	QN QL	XX	XX	QN QL
	Material use	Pending	XX	Pending	QN	QN QL	QN	QN QL	QN QL
	Energy penalty to capture CO2	Pending	QN	Pending	QN	QN QL	QN	QN QL	QN
	Nutrient demand	Pending	QN	Pending	XX	QN QL	QN	XX	QN QL
	Other environmental implications (other than water, land, or nutrients)	Pending	QN	Pending	QN	QN QL	QN QL	QN QL	QN QL
	Non-CO2 production emissions	Pending	QN	Pending	QN	QN QL	QN	XX	QN QL
	Quantified yield changes due to biochar application	Pending	XX	Pending	XX	QN QL	XX	XX	XX
	Water demand	Pending	QN	Pending	QN	QN QL	QN QL	XX	QN QL
MRV	How to account/credit the removals	Pending	QN	Pending	QL	QN QL	QN QL	QN QL	QN QL
	MRV reliability	Pending	QN	Pending	QL	QN QL	QN	QN QL	QN QL
Other	Agroforestry systems (sequestration rates, yield losses)	Pending	XX	Pending	XX	QL	QN	XX	XX
	Different implications between off/on-shore storage and reservoir types	Pending	XX	Pending	XX	XX	XX	XX	QN QL
	Most promising energy conversion routes	Pending	QN	Pending	XX	XX	XX	XX	XX
	Sequestration efficiencies	Pending	QN	Pending	XX	XX	QN	QN QL	QN QL
	Storage permanence or leakage rates	Pending	XX	Pending	XX	QN QL	QN QL	QN QL	QN QL
	The evolution of the European/global forest sinks	Pending	XX	Pending	XX	XX	QN	XX	XX
	The reasonability of feedstock matching	Pending	QN	Pending	XX	QL	XX	XX	QN QL
Potentials	Global energy crop potentials	Pending	XX	Pending	XX	XX	XX	XX	XX
	Global removal potentials	Pending	XX	Pending	QN	QN QL	QN	QN QL	QN
	Global residue potentials	Pending	XX	Pending	XX	QN QL	XX	XX	XX
	Regional energy crop potentials	Pending	XX	Pending	XX	XX	XX	XX	XX
	Regional transportation potentials using pipelines	Pending	XX	Pending	XX	XX	XX	XX	QN QL
	Regional transportation potentials using other means than pipelines	Pending	XX	Pending	XX	XX	XX	XX	QN QL
	Which CDR option setup has the largest potential	Pending	XX	Pending	XX	QL	QN	XX	QN QL
	Regional removal potentials	Pending	QN	Pending	XX	QL	QN	QN QL	QN QL
	Regional residue potentials	Pending	XX	Pending	XX	XX	XX	XX	XX
	Total geological storage potential per country	Pending	XX	Pending	XX	XX	XX	XX	XX
Scale up	Bottlenecks of the biomass value chain	Pending	QN	Pending	XX	XX	XX	XX	QN QL
	Feasible annual injection rates	Pending	XX	Pending	XX	XX	XX	XX	XX
	Whether removal is instantaneous	Pending	XX	Pending	QL	QN QL	XX	QN QL	QN QL
	Feasible carbon capture rates	Pending	XX	Pending	QN	QN QL	QN	QN QL	QN QL
	Realistic removal scales for 2030, 2040, 2050	Pending	XX	Pending	QN	QN	QN	XX	QN QL

Legend: QN: Quantitative **QL:** Qualitative **XX:** Not considered or not applicable

Figure 10. Anticipated outputs from the Ecosystem of Reviews per CDR option expert group across identified data needs for representing CDR in IAMs. AR: Afforestation and reforestation. BECCS: Bioenergy with carbon capture and storage. DACCS: Direct air capture with carbon capture and storage. EW: Enhanced weathering. SCS: Soil carbon sequestration. OAE: Ocean alkalinity enhancement. CCU: Carbon capture and utilization. CAPEX: Capital expenditures. OPEX: Operational expenditures. MRV: Monitoring Reporting and Verification. For the systematic reviews focused on AR and BECCS information on the coding items is not yet made available and therefore *pending*.

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Supplementary table

Rounded literature estimates linked to Figure 9

Option	Parameter	Estimate	Effect (rounded)	Unit	Period	Based/building on
BECCS	Land demand (annual mean)	point	0.2	ha/tCeq/yr	20 yrs	Ai et al. 2021
BECCS	Land demand (annual mean)	point	0.2	ha/tCeq/yr	20 yrs	Ai et al. 2021
BECCS	Land demand (annual mean)	point	0.1	ha/tCeq/yr	20 yrs	Ai et al. 2021
BECCS	Land demand (annual mean)	point	0.1	ha/tCeq/yr	20 yrs	Ai et al. 2021
BECCS	Land demand (annual mean)	point	0.2	ha/tCeq/yr	20 yrs	Ai et al. 2021
BECCS	Land demand (annual mean)	point	0.2	ha/tCeq/yr	20 yrs	Ai et al. 2021
AR	Land demand (annual mean)	point	0.7	ha/tCeq/yr	35 yrs	Austin et al. 2020
AR	Land demand (annual mean)	point	0.7	ha/tCeq/yr	35 yrs	Austin et al. 2020
AR	Land demand (annual mean)	point	0.9	ha/tCeq/yr	35 yrs	Austin et al. 2020
AR	Land demand (annual mean)	point	0.9	ha/tCeq/yr	35 yrs	Austin et al. 2020
AR	Land demand (annual mean)	point	0.8	ha/tCeq/yr	35 yrs	Austin et al. 2020
AR	Land demand (annual mean)	point	0.8	ha/tCeq/yr	35 yrs	Austin et al. 2020
AR	Land demand (annual mean)	point	0.8	ha/tCeq/yr	35 yrs	Austin et al. 2020
AR	Land demand (annual mean)	point	0.8	ha/tCeq/yr	35 yrs	Austin et al. 2020
AR	Land demand (annual mean)	point	0.3	ha/tCeq/yr	30 yrs	Busch et al. 2019
AR	Land demand (annual mean)	point	0.3	ha/tCeq/yr	30 yrs	Busch et al. 2019

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BECCS	Land demand (annual mean)	max	0.9	ha/tCeq/yr	unclear	Creutzig et al 2019
BECCS	Land demand (annual mean)	min	0.1	ha/tCeq/yr	unclear	Creutzig et al 2019
DACCS	Land demand (annual mean)	point	0.0	ha/tCeq/yr		Creutzig et al 2019
BECCS	Land demand (annual mean)	max	0.6	ha/tCeq/yr	unclear	Deprez et al. 2024
BECCS	Land demand (annual mean)	min	0.1	ha/tCeq/yr	unclear	Deprez et al. 2024
BECCS	Land demand (annual mean)	point	0.2	ha/tCeq/yr	unclear	Deprez et al. 2024
DACCS	Land demand (annual mean)	point	0.0	ha/tCeq/yr		Deutz and Bardow 2021
BECCS	Land demand (annual mean)	max	0.3	ha/tCeq/yr	unclear	Dooley et al. 2024
BECCS	Land demand (annual mean)	min	0.2	ha/tCeq/yr	unclear	Dooley et al. 2024
BECCS	Land demand (annual mean)	point	0.2	ha/tCeq/yr	unclear	Dooley et al. 2024
BECCS	Land demand (annual mean)	max	0.5	ha/tCeq/yr	unclear	Dooley et al. 2024
BECCS	Land demand (annual mean)	min	0.3	ha/tCeq/yr	unclear	Dooley et al. 2024
BECCS	Land demand (annual mean)	point	0.4	ha/tCeq/yr	unclear	Dooley et al. 2024
BECCS	Land demand (annual mean)	max	0.3	ha/tCeq/yr	unclear	Dooley et al. 2024
BECCS	Land demand (annual mean)	min	0.2	ha/tCeq/yr	unclear	Dooley et al. 2024
BECCS	Land demand (annual mean)	point	0.3	ha/tCeq/yr	unclear	Dooley et al. 2024
BECCS	Land demand (annual mean)	max	0.2	ha/tCeq/yr	unclear	Dooley et al. 2024
BECCS	Land demand (annual mean)	min	0.2	ha/tCeq/yr	unclear	Dooley et al. 2024
BECCS	Land demand (annual mean)	point	0.2	ha/tCeq/yr	unclear	Dooley et al. 2024

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BECCS	Land demand (annual mean)	max	0.4	ha/tCeq/yr	unclear	Dooley et al. 2024
BECCS	Land demand (annual mean)	min	0.2	ha/tCeq/yr	unclear	Dooley et al. 2024
BECCS	Land demand (annual mean)	point	0.3	ha/tCeq/yr	unclear	Dooley et al. 2024
AR	Land demand (annual mean)	max	0.4	ha/tCeq/yr	unclear	Harris et al. 2021
AR	Land demand (annual mean)	min	0.3	ha/tCeq/yr	unclear	Harris et al. 2021
AR	Land demand (annual mean)	point	0.3	ha/tCeq/yr	unclear	Harris et al. 2021
AR	Land demand (annual mean)	max	1.0	ha/tCeq/yr	unclear	Harris et al. 2021
AR	Land demand (annual mean)	min	1.0	ha/tCeq/yr	unclear	Harris et al. 2021
AR	Land demand (annual mean)	point	1.0	ha/tCeq/yr	unclear	Harris et al. 2021
AR	Land demand (annual mean)	max	0.3	ha/tCeq/yr	unclear	Harris et al. 2021
AR	Land demand (annual mean)	min	0.3	ha/tCeq/yr	unclear	Harris et al. 2021
AR	Land demand (annual mean)	point	0.3	ha/tCeq/yr	unclear	Harris et al. 2021
AR	Land demand (annual mean)	max	0.6	ha/tCeq/yr	unclear	Harris et al. 2021
AR	Land demand (annual mean)	min	0.4	ha/tCeq/yr	unclear	Harris et al. 2021
AR	Land demand (annual mean)	point	0.5	ha/tCeq/yr	unclear	Harris et al. 2021
AR	Land demand (annual mean)	max	0.3	ha/tCeq/yr	unclear	Harris et al. 2021
AR	Land demand (annual mean)	min	0.3	ha/tCeq/yr	unclear	Harris et al. 2021
AR	Land demand (annual mean)	point	0.3	ha/tCeq/yr	unclear	Harris et al. 2021
AR	Land demand (annual mean)	max	0.8	ha/tCeq/yr	unclear	Harris et al. 2021

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AR	Land demand (annual mean)	min	0.7	ha/tCeq/yr	unclear	Harris et al. 2021
AR	Land demand (annual mean)	point	0.8	ha/tCeq/yr	unclear	Harris et al. 2021
AR	Land demand (annual mean)	max	0.2	ha/tCeq/yr	unclear	Harris et al. 2021
AR	Land demand (annual mean)	min	0.2	ha/tCeq/yr	unclear	Harris et al. 2021
AR	Land demand (annual mean)	point	0.2	ha/tCeq/yr	unclear	Harris et al. 2021
AR	Land demand (annual mean)	max	0.4	ha/tCeq/yr	unclear	Harris et al. 2021
AR	Land demand (annual mean)	min	0.3	ha/tCeq/yr	unclear	Harris et al. 2021
AR	Land demand (annual mean)	point	0.3	ha/tCeq/yr	unclear	Harris et al. 2021
DACCS	Land demand (annual mean)	point	0.0	ha/tCeq/yr		IEA 2022
DACCS	Land demand (annual mean)	point	0.0	ha/tCeq/yr		IEA 2022
DACCS	Land demand (annual mean)	point	0.0	ha/tCeq/yr		IEA 2022
DACCS	Land demand (annual mean)	max	0.0	ha/tCeq/yr		IEA 2022
DACCS	Land demand (annual mean)	min	0.0	ha/tCeq/yr		IEA 2022
DACCS	Land demand (annual mean)	max	0.0	ha/tCeq/yr		IEA 2022
DACCS	Land demand (annual mean)	min	0.0	ha/tCeq/yr		IEA 2022
BECCS	Land demand (annual mean)	point	1.1	ha/tCeq/yr	30 yrs	Madhu et al. 2021
BECCS	Land demand (annual mean)	point	0.4	ha/tCeq/yr	80 yrs	Madhu et al. 2021
AR	Land demand (annual mean)	max	0.3	ha/tCeq/yr	unclear	Nolan et al. 2021
AR	Land demand (annual mean)	min	0.3	ha/tCeq/yr	unclear	Nolan et al. 2021

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DACCS	Land demand (annual mean)	max	0.0	ha/tCeq/yr		Own calculation, based on Terlouw et al. 2021
DACCS	Land demand (annual mean)	min	0.0	ha/tCeq/yr		Own calculation, based on Terlouw et al. 2021
DACCS	Land demand (annual mean)	max	0.0	ha/tCeq/yr		Realmonte et al. 2019
DACCS	Land demand (annual mean)	min	0.0	ha/tCeq/yr		Realmonte et al. 2019
DACCS	Land demand (annual mean)	point	0.0	ha/tCeq/yr		Realmonte et al. 2019
AR	Land demand (annual mean)	point	0.3	ha/tCeq/yr	30 yrs	Roe et al. 2021
AR	Land demand (annual mean)	point	0.7	ha/tCeq/yr	30 yrs	Roe et al. 2021
AR	Land demand (annual mean)	point	0.3	ha/tCeq/yr	30 yrs	Roe et al. 2021
AR	Land demand (annual mean)	point	0.6	ha/tCeq/yr	30 yrs	Roe et al. 2021
BECCS	Land demand (annual mean)	point	0.6	ha/tCeq/yr	30 yrs	Roe et al. 2021
BECCS	Land demand (annual mean)	point	0.6	ha/tCeq/yr	30 yrs	Roe et al. 2021
AR	Land demand (annual mean)	max	0.0	ha/tCeq/yr	unclear	Smith and Torn 2013
AR	Land demand (annual mean)	min	0.0	ha/tCeq/yr	unclear	Smith and Torn 2013
AR	Land demand (annual mean)	point	0.0	ha/tCeq/yr	unclear	Smith and Torn 2013
BECCS	Land demand (annual mean)	max	1.0	ha/tCeq/yr	unclear	Smith and Torn 2013
BECCS	Land demand (annual mean)	min	0.2	ha/tCeq/yr	unclear	Smith and Torn 2013
BECCS	Land demand (annual mean)	point	0.6	ha/tCeq/yr	unclear	Smith and Torn 2013

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AR	Land demand (annual mean)	point	0.0	ha/tCeq/yr	unclear	Smith et al. 2016a
AR	Land demand (annual mean)	point	0.2	ha/tCeq/yr	unclear	Smith et al. 2016a
AR	Land demand (annual mean)	point	0.3	ha/tCeq/yr	unclear	Smith et al. 2016a
AR	Land demand (annual mean)	point	0.6	ha/tCeq/yr	unclear	Smith et al. 2016a
BECCS	Land demand (annual mean)	point	0.0	ha/tCeq/yr	unclear	Smith et al. 2016a
BECCS	Land demand (annual mean)	point	0.2	ha/tCeq/yr	unclear	Smith et al. 2016a
BECCS	Land demand (annual mean)	point	0.1	ha/tCeq/yr	unclear	Smith et al. 2016a
BECCS	Land demand (annual mean)	point	0.1	ha/tCeq/yr	unclear	Smith et al. 2016a
BECCS	Land demand (annual mean)	max	0.4	ha/tCeq/yr	unclear	Smith et al. 2016a
BECCS	Land demand (annual mean)	min	0.1	ha/tCeq/yr	unclear	Smith et al. 2016a
BECCS	Land demand (annual mean)	point	0.3	ha/tCeq/yr	unclear	Smith et al. 2016a
BECCS	Land demand (annual mean)	point	0.6	ha/tCeq/yr	unclear	Smith et al. 2016a
DACCS	Land demand (annual mean)	max	0.0	ha/tCeq/yr		Smith et al. 2016a
BECCS	Land demand (annual mean)	max	0.2	ha/tCeq/yr	unclear	The Royal Society 2018
BECCS	Land demand (annual mean)	min	0.1	ha/tCeq/yr	unclear	The Royal Society 2018
DACCS	Land demand (annual mean)	point	0.0	ha/tCeq/yr		WRI 2021
DACCS	Land demand (annual mean)	point	0.0	ha/tCeq/yr		WRI 2021
DACCS	Land demand (annual mean)	point	0.0	ha/tCeq/yr		WRI 2021
DACCS	Land demand (annual mean)	point	0.0	ha/tCeq/yr		WRI 2021

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DACCS	Land demand (annual mean)	point	0.0	ha/tCeq/yr		WRI 2021
DACCS	Land demand (annual mean)	point	0.0	ha/tCeq/yr		WRI 2021
DACCS	Land demand (annual mean)	point	0.0	ha/tCeq/yr		WRI 2021
DACCS	Land demand (annual mean)	point	0.0	ha/tCeq/yr		WRI 2021
BECCS	Land demand (annual mean)	point	0.6	ha/tCeq/yr	30 yrs	Zhao et al. 2024
BECCS	Land demand (annual mean)	point	0.6	ha/tCeq/yr	30 yrs	Zhao et al. 2024
BECCS	Land demand (annual mean)	point	1.7	ha/tCeq/yr	30 yrs	Zhao et al. 2024
BECCS	Land demand (annual mean)	point	1.5	ha/tCeq/yr	30 yrs	Zhao et al. 2024
BECCS	Land demand (annual mean)	point	2.0	ha/tCeq/yr	30 yrs	Zhao et al. 2024
BECCS	Land demand (annual mean)	point	1.7	ha/tCeq/yr	30 yrs	Zhao et al. 2024
BECCS	Land demand (annual mean)	point	1.7	ha/tCeq/yr	30 yrs	Zhao et al. 2024
BECCS	Land demand (annual mean)	point	1.5	ha/tCeq/yr	30 yrs	Zhao et al. 2024
BECCS	Land demand (annual mean)	point	0.3	ha/tCeq/yr	80 yrs	Zhao et al. 2024
BECCS	Land demand (annual mean)	point	0.3	ha/tCeq/yr	80 yrs	Zhao et al. 2024
BECCS	Land demand (annual mean)	point	0.4	ha/tCeq/yr	80 yrs	Zhao et al. 2024
BECCS	Land demand (annual mean)	point	0.4	ha/tCeq/yr	80 yrs	Zhao et al. 2024
BECCS	Land demand (annual mean)	point	0.5	ha/tCeq/yr	80 yrs	Zhao et al. 2024
BECCS	Land demand (annual mean)	point	0.4	ha/tCeq/yr	80 yrs	Zhao et al. 2024
BECCS	Land demand (annual mean)	point	0.5	ha/tCeq/yr	80 yrs	Zhao et al. 2024

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BECCS	Land demand (annual mean)	point	0.5	ha/tCeq/yr	80 yrs	Zhao et al. 2024
AR	Land demand (terminal)	point	0.0	ha/tCeq	35 yrs	Austin et al. 2020
AR	Land demand (terminal)	point	0.0	ha/tCeq	35 yrs	Austin et al. 2020
AR	Land demand (terminal)	point	0.0	ha/tCeq	35 yrs	Austin et al. 2020
AR	Land demand (terminal)	point	0.0	ha/tCeq	35 yrs	Austin et al. 2020
AR	Land demand (terminal)	point	0.0	ha/tCeq	35 yrs	Austin et al. 2020
AR	Land demand (terminal)	point	0.0	ha/tCeq	35 yrs	Austin et al. 2020
AR	Land demand (terminal)	point	0.0	ha/tCeq	35 yrs	Austin et al. 2020
AR	Land demand (terminal)	point	0.0	ha/tCeq	35 yrs	Austin et al. 2020
AR	Land demand (terminal)	point	0.0	ha/tCeq	30 yrs	Busch et al. 2019
AR	Land demand (terminal)	point	0.0	ha/tCeq	30 yrs	Busch et al. 2019
DACCS	Land demand (terminal)	point	0.0	ha/tCeq		Madhu et al. 2021
DACCS	Land demand (terminal)	point	0.0	ha/tCeq		Madhu et al. 2021
AR	Land demand (terminal)	point	0.0	ha/tCeq	30 yrs	Roe et al. 2021
AR	Land demand (terminal)	point	0.0	ha/tCeq	30 yrs	Roe et al. 2021
AR	Land demand (terminal)	point	0.0	ha/tCeq	30 yrs	Roe et al. 2021
AR	Land demand (terminal)	point	0.0	ha/tCeq	30 yrs	Roe et al. 2021
BECCS	Land demand (terminal)	point	0.0	ha/tCeq	30 yrs	Roe et al. 2021
BECCS	Land demand (terminal)	point	0.0	ha/tCeq	30 yrs	Roe et al. 2021
BECCS	Land demand (terminal)	point	0.1	ha/tCeq	30 yrs	Zhao et al. 2024
BECCS	Land demand (terminal)	point	0.0	ha/tCeq	30 yrs	Zhao et al. 2024
BECCS	Land demand (terminal)	point	0.1	ha/tCeq	30 yrs	Zhao et al. 2024
BECCS	Land demand (terminal)	point	0.1	ha/tCeq	30 yrs	Zhao et al. 2024
BECCS	Land demand (terminal)	point	0.2	ha/tCeq	30 yrs	Zhao et al. 2024

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BECCS	Land demand (terminal)	point	0.1	ha/tCeq	30 yrs	Zhao et al. 2024
BECCS	Land demand (terminal)	point	0.1	ha/tCeq	30 yrs	Zhao et al. 2024
BECCS	Land demand (terminal)	point	0.1	ha/tCeq	30 yrs	Zhao et al. 2024
BECCS	Land demand (terminal)	point	0.0	ha/tCeq	80 yrs	Zhao et al. 2024
BECCS	Land demand (terminal)	point	0.0	ha/tCeq	80 yrs	Zhao et al. 2024
BECCS	Land demand (terminal)	point	0.0	ha/tCeq	80 yrs	Zhao et al. 2024
BECCS	Land demand (terminal)	point	0.0	ha/tCeq	80 yrs	Zhao et al. 2024
BECCS	Land demand (terminal)	point	0.0	ha/tCeq	80 yrs	Zhao et al. 2024
BECCS	Land demand (terminal)	point	0.0	ha/tCeq	80 yrs	Zhao et al. 2024
BECCS	Land demand (terminal)	point	0.0	ha/tCeq	80 yrs	Zhao et al. 2024
BECCS	Land demand (terminal)	point	0.0	ha/tCeq	80 yrs	Zhao et al. 2024
DACCS	Net energy demand	max	21.7	GJ/tCeq		Creutzig et al 2019
DACCS	Net energy demand	max	29.4	GJ/tCeq		Creutzig et al 2019
DACCS	Net energy demand	max	45.5	GJ/tCeq		Creutzig et al 2019
DACCS	Net energy demand	max	83.3	GJ/tCeq		Creutzig et al 2019
DACCS	Net energy demand	min	14.7	GJ/tCeq		Creutzig et al 2019
DACCS	Net energy demand	min	24.6	GJ/tCeq		Creutzig et al 2019
DACCS	Net energy demand	min	27.5	GJ/tCeq		Creutzig et al 2019
DACCS	Net energy demand	min	30.8	GJ/tCeq		Creutzig et al 2019
DACCS	Net energy demand	point	24.2	GJ/tCeq		Creutzig et al 2019
DACCS	Net energy demand	point	36.3	GJ/tCeq		Creutzig et al 2019
DACCS	Net energy demand	point	36.3	GJ/tCeq		Creutzig et al 2019
DACCS	Net energy demand	max	22.0	GJ/tCeq		Creutzig et al 2019

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DACCS	Net energy demand	max	30.5	GJ/tCeq		Creutzig et al 2019
DACCS	Net energy demand	max	36.7	GJ/tCeq		Creutzig et al 2019
DACCS	Net energy demand	min	17.2	GJ/tCeq		Creutzig et al 2019
DACCS	Net energy demand	min	17.2	GJ/tCeq		Creutzig et al 2019
DACCS	Net energy demand	min	22.4	GJ/tCeq		Creutzig et al 2019
DACCS	Net energy demand	point	24.0	GJ/tCeq		IEA 2022
DACCS	Net energy demand	point	37.0	GJ/tCeq		IEA 2022
DACCS	Net energy demand	point	26.4	GJ/tCeq		Madhu et al. 2021
DACCS	Net energy demand	point	13.2	GJ/tCeq		Madhu et al. 2021
DACCS	Net energy demand	point	24.0	GJ/tCeq		McQueen et al. 2021
DACCS	Net energy demand	point	26.0	GJ/tCeq		McQueen et al. 2021
DACCS	Net energy demand	max	7.0	GJ/tCeq		Ozkan et al. 2024
DACCS	Net energy demand	min	5.2	GJ/tCeq		Ozkan et al. 2024
DACCS	Net energy demand	max	30.1	GJ/tCeq		Ozkan et al. 2024
DACCS	Net energy demand	min	19.7	GJ/tCeq		Ozkan et al. 2024
DACCS	Net energy demand	max	4.4	GJ/tCeq		Ozkan et al. 2024
DACCS	Net energy demand	min	2.6	GJ/tCeq		Ozkan et al. 2024
DACCS	Net energy demand	max	20.6	GJ/tCeq		Ozkan et al. 2024
DACCS	Net energy demand	min	11.0	GJ/tCeq		Ozkan et al. 2024
BECCS	Net energy demand	max	-9.0	GJ/tCeq		Smith et al. 2016a
BECCS	Net energy demand	min	-21.0	GJ/tCeq		Smith et al. 2016a
BECCS	Net energy demand	max	-19.0	GJ/tCeq		Smith et al. 2016a
BECCS	Net energy demand	min	-31.0	GJ/tCeq		Smith et al. 2016a

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BECCS	Net energy demand	max	-38.0	GJ/tCeq		Smith et al. 2016a
BECCS	Net energy demand	min	-89.0	GJ/tCeq		Smith et al. 2016a
BECCS	Net energy demand	max	9.0	GJ/tCeq		Smith et al. 2016a
BECCS	Net energy demand	min	-38.0	GJ/tCeq		Smith et al. 2016a
BECCS	Net energy demand	max	8.7	GJ/tCeq		Smith et al. 2016a
BECCS	Net energy demand	min	-8.0	GJ/tCeq		Smith et al. 2016a
BECCS	Net energy demand	max	-8.7	GJ/tCeq		Smith et al. 2016a
BECCS	Net energy demand	min	-21.0	GJ/tCeq		Smith et al. 2016a
BECCS	Net energy demand	max	-9.6	GJ/tCeq		Smith et al. 2016a
BECCS	Net energy demand	min	-21.0	GJ/tCeq		Smith et al. 2016a
DACCS	Net energy demand	max	46.0	GJ/tCeq		Smith et al. 2016a
DACCS	Net energy demand	min	2.3	GJ/tCeq		Smith et al. 2016a
BECCS	Net energy demand	max	-36.7	GJ/tCeq		The Royal Society 2018
BECCS	Net energy demand	min	-2.9	GJ/tCeq		The Royal Society 2018
AR	Nitrogen demand	max	0.7	kgN/tCeq		Smith and Torn 2013
AR	Nitrogen demand	min	0.1	kgN/tCeq		Smith and Torn 2013
AR	Nitrogen demand	point	0.3	kgN/tCeq		Smith and Torn 2013
BECCS	Nitrogen demand	max	79.0	kgN/tCeq		Smith and Torn 2013
BECCS	Nitrogen demand	min	17.0	kgN/tCeq		Smith and Torn 2013

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BECCS	Nitrogen demand	point	46.0	kgN/tCeq		Smith and Torn 2013
AR	Nitrogen demand	point	3.9	kgN/tCeq		Smith et al. 2016a
AR	Nitrogen demand	point	10.0	kgN/tCeq		Smith et al. 2016a
AR	Nitrogen demand	point	2.1	kgN/tCeq		Smith et al. 2016a
AR	Nitrogen demand	point	5.2	kgN/tCeq		Smith et al. 2016a
BECCS	Nitrogen demand	point	3.9	kgN/tCeq		Smith et al. 2016a
BECCS	Nitrogen demand	point	10.0	kgN/tCeq		Smith et al. 2016a
BECCS	Nitrogen demand	point	13.0	kgN/tCeq		Smith et al. 2016a
BECCS	Nitrogen demand	point	11.0	kgN/tCeq		Smith et al. 2016a
BECCS	Nitrogen demand	point	20.0	kgN/tCeq		Smith et al. 2016a
BECCS	Nitrogen demand	point	2.1	kgN/tCeq		Smith et al. 2016a
BECCS	Nitrogen demand	point	5.2	kgN/tCeq		Smith et al. 2016a
DACCS	Phosphorus demand	point	0.0	kgP/tCeq		Reforth 2012
AR	Phosphorus demand	max	0.8	kgP/tCeq		Smith and Torn 2013
AR	Phosphorus demand	min	0.2	kgP/tCeq		Smith and Torn 2013
AR	Phosphorus demand	point	0.3	kgP/tCeq		Smith and Torn 2013
AR	Phosphorus demand	max	5.0	kgP/tCeq		Smith et al. 2016a
AR	Phosphorus demand	min	4.0	kgP/tCeq		Smith et al. 2016a
BECCS	Phosphorus demand	point	20.0	kgP/tCeq		Smith et al. 2016a

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BECCS	Phosphorus demand	point	0.8	kgP/tCeq		Smith et al. 2016a
AR	Potassium demand	max	3.1	kgK/tCeq		Ovington and Madgwick 1959
AR	Potassium demand	min	0.4	kgK/tCeq		Ovington and Madgwick 1959
BECCS	Potassium demand	max	22.0	kgK/tCeq		Roncucci et al. 2015
BECCS	Potassium demand	min	5.7	kgK/tCeq		Roncucci et al. 2015
DACCS	Potassium demand	point	0.0	kgK/tCeq		Smith et al. 2016b
BECCS	Water demand	point	195.4	m3/tCeq	20 yrs	Ai et al. 2021
BECCS	Water demand	point	149.0	m3/tCeq	20 yrs	Ai et al. 2021
BECCS	Water demand	point	1077.7	m3/tCeq	20 yrs	Ai et al. 2021
BECCS	Water demand	point	1157.4	m3/tCeq	20 yrs	Ai et al. 2021
BECCS	Water demand	point	0.0	m3/tCeq	20 yrs	Ai et al. 2021
BECCS	Water demand	point	0.0	m3/tCeq	20 yrs	Ai et al. 2021
DACCS	Water demand	point	184.0	m3/tCeq		IEA 2022
DACCS	Water demand	max	7.0	m3/tCeq		IEA 2022
DACCS	Water demand	min	3.0	m3/tCeq		IEA 2022
BECCS	Water demand	point	365.0	m3/tCeq		Madhu et al. 2021
BECCS	Water demand	point	365.0	m3/tCeq		Madhu et al. 2021
DACCS	Water demand	point	18.0	m3/tCeq		Madhu et al. 2021
DACCS	Water demand	point	11.0	m3/tCeq		Madhu et al. 2021
DACCS	Water demand	max	239.0	m3/tCeq		Own calculation, based on Terlouw et al. 2021
DACCS	Water demand	min	5.0	m3/tCeq		Own calculation, based on

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						Terlouw et al. 2021
DACCS	Water demand	point	73.0	m3/tCeq		Realmonte et al. 2019
DACCS	Water demand	point	73.0	m3/tCeq		Realmonte et al. 2019
BECCS	Water demand	max	1629.0	m3/tCeq		Rosa et al. 2021
BECCS	Water demand	min	811.0	m3/tCeq		Rosa et al. 2021
BECCS	Water demand	point	1222.0	m3/tCeq		Rosa et al. 2021
BECCS	Water demand	max	2811.0	m3/tCeq		Rosa et al. 2021
BECCS	Water demand	min	1402.0	m3/tCeq		Rosa et al. 2021
BECCS	Water demand	point	2110.0	m3/tCeq		Rosa et al. 2021
BECCS	Water demand	max	4441.0	m3/tCeq		Rosa et al. 2021
BECCS	Water demand	min	918.0	m3/tCeq		Rosa et al. 2021
BECCS	Water demand	point	2239.0	m3/tCeq		Rosa et al. 2021
BECCS	Water demand	max	5542.0	m3/tCeq		Rosa et al. 2021
BECCS	Water demand	min	1872.0	m3/tCeq		Rosa et al. 2021
BECCS	Water demand	point	3193.0	m3/tCeq		Rosa et al. 2021
BECCS	Water demand	max	2239.0	m3/tCeq		Rosa et al. 2021
BECCS	Water demand	min	918.0	m3/tCeq		Rosa et al. 2021
BECCS	Water demand	point	1321.0	m3/tCeq		Rosa et al. 2021
BECCS	Water demand	max	2789.0	m3/tCeq		Rosa et al. 2021
BECCS	Water demand	min	1285.0	m3/tCeq		Rosa et al. 2021
BECCS	Water demand	point	1615.0	m3/tCeq		Rosa et al. 2021
BECCS	Water demand	max	4441.0	m3/tCeq		Rosa et al. 2021
BECCS	Water demand	min	1285.0	m3/tCeq		Rosa et al. 2021
BECCS	Water demand	point	2312.0	m3/tCeq		Rosa et al. 2021
BECCS	Water demand	max	4037.0	m3/tCeq		Rosa et al. 2021
BECCS	Water demand	min	1028.0	m3/tCeq		Rosa et al. 2021
BECCS	Water demand	point	2532.0	m3/tCeq		Rosa et al. 2021
BECCS	Water demand	max	1285.0	m3/tCeq		Rosa et al. 2021
BECCS	Water demand	min	807.0	m3/tCeq		Rosa et al. 2021

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BECCS	Water demand	point	1101.0	m3/tCeq		Rosa et al. 2021
DACCS	Water demand	max	25.0	m3/tCeq		Rosa et al. 2021
DACCS	Water demand	min	7.0	m3/tCeq		Rosa et al. 2021
DACCS	Water demand	point	15.0	m3/tCeq		Rosa et al. 2021
AR	Water demand	max	8100.0	m3/tCeq		Smith and Torn 2013
AR	Water demand	min	3500.0	m3/tCeq		Smith and Torn 2013
AR	Water demand	point	4700.0	m3/tCeq		Smith and Torn 2013
BECCS	Water demand	max	7400.0	m3/tCeq		Smith and Torn 2013
BECCS	Water demand	min	1600.0	m3/tCeq		Smith and Torn 2013
BECCS	Water demand	point	4400.0	m3/tCeq		Smith and Torn 2013
AR	Water demand	max	2800.0	m3/tCeq		Smith et al. 2016a
AR	Water demand	min	2000.0	m3/tCeq		Smith et al. 2016a
AR	Water demand	point	2400.0	m3/tCeq		Smith et al. 2016a
AR	Water demand	max	2300.0	m3/tCeq		Smith et al. 2016a
AR	Water demand	min	1400.0	m3/tCeq		Smith et al. 2016a
AR	Water demand	point	2000.0	m3/tCeq		Smith et al. 2016a
AR	Water demand	max	2800.0	m3/tCeq		Smith et al. 2016a
AR	Water demand	min	2000.0	m3/tCeq		Smith et al. 2016a
AR	Water demand	point	2400.0	m3/tCeq		Smith et al. 2016a
AR	Water demand	max	2300.0	m3/tCeq		Smith et al. 2016a

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AR	Water demand	min	1400.0	m3/tCeq		Smith et al. 2016a
AR	Water demand	point	2000.0	m3/tCeq		Smith et al. 2016a
BECCS	Water demand	max	2800.0	m3/tCeq		Smith et al. 2016a
BECCS	Water demand	min	2000.0	m3/tCeq		Smith et al. 2016a
BECCS	Water demand	point	2400.0	m3/tCeq		Smith et al. 2016a
BECCS	Water demand	max	2300.0	m3/tCeq		Smith et al. 2016a
BECCS	Water demand	min	1400.0	m3/tCeq		Smith et al. 2016a
BECCS	Water demand	point	2000.0	m3/tCeq		Smith et al. 2016a
BECCS	Water demand	max	2400.0	m3/tCeq		Smith et al. 2016a
BECCS	Water demand	min	1400.0	m3/tCeq		Smith et al. 2016a
BECCS	Water demand	point	1900.0	m3/tCeq		Smith et al. 2016a
BECCS	Water demand	max	2400.0	m3/tCeq		Smith et al. 2016a
BECCS	Water demand	min	1400.0	m3/tCeq		Smith et al. 2016a
BECCS	Water demand	point	2000.0	m3/tCeq		Smith et al. 2016a
BECCS	Water demand	max	2200.0	m3/tCeq		Smith et al. 2016a
BECCS	Water demand	min	1600.0	m3/tCeq		Smith et al. 2016a
BECCS	Water demand	point	1900.0	m3/tCeq		Smith et al. 2016a
BECCS	Water demand	max	2800.0	m3/tCeq		Smith et al. 2016a
BECCS	Water demand	min	2000.0	m3/tCeq		Smith et al. 2016a

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BECCS	Water demand	point	2400.0	m3/tCeq		Smith et al. 2016a
BECCS	Water demand	max	2300.0	m3/tCeq		Smith et al. 2016a
BECCS	Water demand	min	1400.0	m3/tCeq		Smith et al. 2016a
BECCS	Water demand	point	2000.0	m3/tCeq		Smith et al. 2016a
DACCS	Water demand	point	1.5	m3/tCeq		Smith et al. 2016a
BECCS	Water demand	point	220.0	m3/tCeq		The Royal Society 2018
DACCS	Water demand	max	33.0	m3/tCeq		WRI 2021
DACCS	Water demand	min	0.0	m3/tCeq		WRI 2021
DACCS	Water demand	point	7.3	m3/tCeq		WRI 2021
DACCS	Water demand	point	5.9	m3/tCeq		WRI 2021

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