How carbon dioxide removal lost its way: tracing the origin and transformation of the 10-Gt durable CDR target

Rebecca B. Neumann, Civil & Environmental Engineering, University of Washington, Seattle, WA

ABSTRACT

Durably removing ~10 Gt CO_2 yr^{-1} by 2050 is widely treated as necessary to meet Paris temperature goals. Tracing CDR magnitude claims across ~50 sources spanning five sectors, I found this benchmark derives from IPCC scenario ensembles in which CDR magnitude correlated with near-term mitigation ambition rather than temperature targets. When targets relaxed, scenarios continued emitting rather than reducing CDR. While both IPCC ensembles and independent studies included scenarios with substantially less CDR, these pathways received little downstream attention. Instead, a single number above the IPCC ensemble median was extracted and, as it propagated into NGO and industry contexts, stripped of its conditionality. Framing became prescriptive, risk discussion diminished, and CDR type narrowed to exclude approaches the scenarios themselves relied upon. The result is a CDR discourse stripped of the context needed for informed decision-making — context connecting removal to mitigation, characterizing costs, risks, and feasibility, and encompassing all available approaches.

INTRODUCTION

Carbon dioxide removal (CDR) is currently considered a cornerstone for addressing climate change and meeting the temperature goals of the Paris Agreement[1]. Across climate policy, industry, and public discourse, it is widely repeated and largely unquestioned that ~10 Gt CO_2 yr^{-1} of *durable* CDR—removal that keeps carbon out of the atmosphere for centuries to millennia—is required by 2050 to limit warming to 1.5–2 °C[2–19]. The emergence of the 10-Gt durable removal target has coincided with growing financial and regulatory commitment to CDR: over the past three years, private companies have invested ~$10 billion into durable carbon-removal credits[2], the U.S. and E.U. governments have committed billions to durable CDR technology and infrastructure[20,21], and the E.U. adopted the world's first government-backed standard for certifying carbon removals[22]. Given that this target is widely accepted in the spaces where climate investments and policies are made[2–7,11,13–15,18,19], understanding where it originated and how it became a fixed benchmark is critical for assessing whether it should be the organizing target for these efforts.

Achieving ~10 Gt durable CDR by 2050 would require scaling existing durable capacity by more than three orders of magnitude in ~20 years, making the accuracy of this target consequential. Ten Gt of CO_2 removal rivals the average annual uptake of the Earth's oceans (10.6 Gt CO_2 yr^{-1}) and land surface (11.7 Gt CO_2 yr^{-1})[23]. Current global CDR is ~2 Gt CO_2 yr^{-1}, achieved primarily by nature-based methods like afforestation and soil carbon sequestration, which store carbon for decades to centuries[24]— timescales not considered as durable. Less than 0.01 Gt CO2 yr^{-1} is removed via technological methods like bioenergy with carbon capture and storage (BECCS), direct air capture (DAC), and enhanced rock weathering (ERW), which sequester carbon for centuries to millennia[24].

Relying on ~10 Gt yr^{-1} of CDR poses well-documented risks, including high costs, resource constraints, limited societal acceptance, and the possibility of lower-than-anticipated effectiveness[25–32]. CDR dependence also raises the ethical problem of delaying present-day mitigation in lieu of future removals, with the burden of failure borne by future generations[33]. Further, due to asymmetry in the climate-carbon cycle, emitting CO_2 now and removing it later is not equivalent to avoiding the emission[34,35], and intervening warming increases the probability of triggering irreversible tipping points[36,37].

The 10 Gt CO_2 yr^{-1} target is not self-evident. The IPCC describes three roles for CDR — reducing net emissions in the near term, counterbalancing residual emissions at net-zero, and achieving net-negative emissions — but the scale required for each depends on assumptions about mitigation pace, residual emission scope, and desired net-negative drawdown, respectively. Bottom-up estimates of residual emissions alone, when stringently scoped, are 3 to 7 times smaller than 10 Gt[39]. Yet the 10-Gt durable target continues to organize investment and policy[2–7,11,13–15,18,19].

In this study, I traced CDR magnitude claims between 2017 and 2025 and tracked how their framing evolved as they moved through ~50 documents spanning five sectors. In addition, I identified what correlates with CDR magnitude within the IPCC scenarios that anchor a majority of the claims. I found two patterns. First, within the IPCC modeling ensemble, CDR magnitude does not scale with temperature targets. Instead, it correlates with near-term mitigation ambition, and in the median scenarios, when temperature targets relaxed, the additional carbon-budget space absorbed continued emissions rather than reducing CDR. Second, as CDR magnitude claims propagated from IPCC modeling scenarios into policy, corporate, and media contexts, a single number larger than the ensemble median (10 Gt) was extracted and repeated, framing became more prescriptive, risk discussion diminished, CDR type narrowed towards durable approaches, and scenarios minimizing CDR received limited attention. Together, these findings reveal a citation cascade in which CDR claims were not only amplified but transformed — producing a discourse organized around a benchmark that is biased high, disconnected from the mitigation choices that shape CDR magnitude, and narrowed to exclude approaches that the scenarios themselves relied upon.

RESULTS

10-Gt benchmark traces to IPCC, exceeds the median, and obscures low-CDR pathways

The citation analysis showed that IPCC synthesis reports are the dominant pathway through which CDR magnitude estimates reach policy, corporate, and media discourse. Twenty of the 51 compiled sources presented CDR magnitudes based on original analyses[1,15,39–56] and the remaining 31 presented CDR magnitudes based on cited estimates or without clear attribution[2–14,16–19,57–70]. Of the 31 citation-dependent sources, 29 (i.e., 94%) directly or implicitly cited IPCC synthesis products (AR5, SR1.5, AR6), reports that reanalyzed IPCC scenarios (State of CDR), or government reports that cited these products (National Academy, UNEP). Of the 20 sources presenting original analyses, only five outside of the IPCC products were cited by downstream sources (van Vuuren et al., Grubler et al., Holz et al., CDR Primer, and IEA; see SI Table 1).

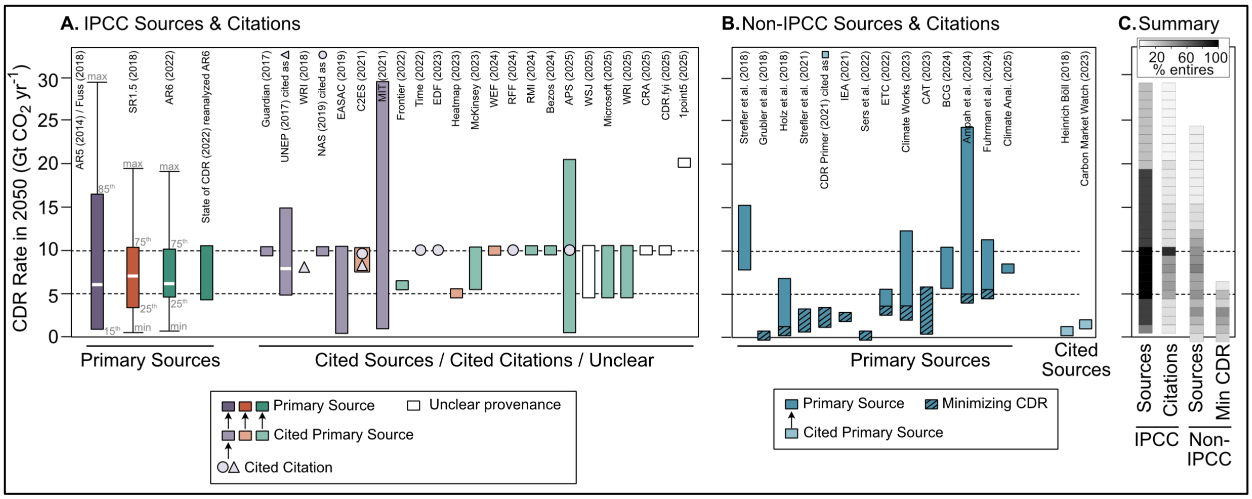

Figure 1 | 2050 CDR magnitude claims across sources for meeting Paris Agreement goals. (**A**) Left side: IPCC primary sources, which includes IPCC synthesis reports (AR5, SR1.5, AR6) and the State of CDR, which re-analyzed AR6. The first bar plots Fuss et al. (2018) quantification of CDR implied by AR5 scenarios, as AR5 itself did not report explicit CDR magnitudes. Right side: Documents that directly or indirectly cite the IPCC products. Colors connect citations to the corresponding primary source. Documents that cited a citation are marked with a triangle (cited UNEP) and circle (cited NAS). (**B**) Left side: Non-IPCC primary sources. Cross-hatching marks ranges from scenarios or analyses that explicitly minimized CDR use. Right side: Two reports that cite non-IPCC primary sources. (**C**) Summary of magnitudes from IPCC primary sources, documents citing IPCC sources, non-IPCC primary sources, and efforts to minimize CDR. Back-and-white scale is proportional to percent of entries in each group. **In all panels**: Bars represent ranges; percentiles are labeled if available. Point symbols indicate single values. Dashed lines at 5 and 10 Gt CO_2 yr^{-1} mark key reference thresholds. Not all sources from SI Table 1 are included, only those reporting 2050 CDR rates.

Figure 1 shows 2050 CDR rates presented in the compiled documents. As IPCC estimates were cited, the range of magnitudes reported by the primary sources narrowed and converged on 10 Gt CO_2 yr^{-1} (Figure 1A, 1C). The original IPCC sources reported a 2050 CDR rate that extended from close to zero up to 20 Gt CO_2 yr^{-1} or larger, with median rates between ~5 and ~7 Gt CO_2 yr^{-1}. Of the 23 citation-dependent sources in the IPCC chain that reported a 2050 rate, 14 reported a single annual rate rather than a range, and of those, 10 reported 10 Gt CO_2 yr^{-1} (Figure 1A).

The 10-Gt number did not emerge from a direct reading of the IPCC outputs but from informal estimates that were subsequently treated as authoritative. The earliest appearance of 10 Gt CO_2 yr^{-1} in the dataset was a 2017 Guardian article (Figure 1A) where a scientist was quoted as saying “The models are basically asking for removing carbon dioxide from the atmosphere which will be equivalent of one-quarter of all carbon emissions at present,” and the journalist wrote, “This amounts to about 10 billion tonnes of carbon dioxide removed from the atmosphere and disposed of each year." The number next appeared in the National Academy of Science (NAS) report where the authors selected 10 Gt CO_2 yr^{-1} from the AR5/Fuss et al. (2018) range and reported it as what was "needed" based on "every recent analysis of solutions to the climate problem." From that point forward, 10 Gt CO_2 yr^{-1} continued to propagate, with multiple sources citing the NAS report (Figure 1A).

The convergence of the discourse on a single benchmark obscured a broader finding: both the IPCC ensemble and non-IPCC primary sources included pathways that met temperature goals with minimal or no CDR (Figures 1A, 1B). In the non-IPCC sources, 12 studies incorporated runs that explicitly minimized CDR through aggressive mitigation scenarios, altered carbon price trajectories, sustainability and feasibility constraints on CDR use, or stringent definitions of hard-to-avoid emissions (SI Table 1). When CDR was explicitly minimized, the maximum reported 2050 rate was 6.5 Gt CO_2 yr^{-1}, nine studies reported a maximum rate at or below 5 Gt CO_2 yr^{-1}, and two met a 1.5°C target using no CDR (published in 2018 and 2022) (Figure 1C). Yet these low-CDR pathways did not enter the downstream discourse: of the 25 estimates that relied on citations and reported a 2050 rate, only five reported CDR magnitudes below 5 Gt CO_2 yr^{-1} (EASAC, MIT, APS, Heinrich Böll, Carbon Market Watch).

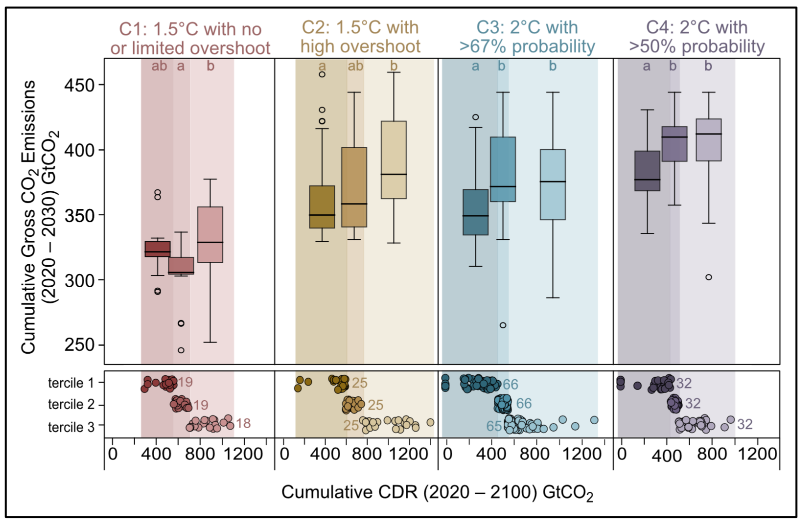

Figure 2 | AR6 Scenario Variables Correlated with End-of-Century Cumulative CDR Use. (**Bottom Panel**) End of century cumulative CDR (2020–2100) for AR6 scenarios divided into terciles (low, mid, high) for each temperature category C1–C4. Numbers next to each group indicate scenario count within each tercile. Of the 50 scenario variables tested, five had significantly different and monotonically changing median values across the CDR terciles when integrated over either near-term (2020-2030) or mid-term (2020-205) time windows (see text). One variable-window combination is plotted here: (**Top Panel**) near-term cumulative gross CO_2 emissions (2020–2030) for each CDR tercile. Letters above boxplots indicate results of pairwise statistical comparisons; groups sharing a letter are not significantly different.

CDR in AR6 Correlates with Near-Term Mitigation and Offsets Continued Emissions

Given that the CDR benchmark predominantly traces back to the IPCC, I analyzed the scenario ensembles from the most recent assessment report (AR6) to understand what characteristics correlate with CDR magnitude. The central finding is that end-of-century CDR deployment is more closely linked to the energy system trajectory of the 2020s than to characteristics later in the century — specifically, scenarios with higher cumulative CDR had higher near-term emissions and greater mid-century fossil energy persistence.

To determine this, I grouped scenarios into terciles based on end-of-century cumulative CDR (2020–2100) within each temperature category (C1–C4) and tested 50 scenario variables for significantly different and monotonically changing medians across the terciles. Each variable was integrated across three time windows (2020–2030, 2020–2050, 2020–2100) to identify when correlation emerged (see Methods). Five variables showed significant monotonic trends in at least three temperature categories. Four were significant in the near-term window (2020–2030): gross CO_2 emissions (Figure 2), net F-gas emissions, net Kyoto gas emissions, and primary energy from gas. Two were significant in the mid-term window (2020–2050): primary energy from gas and fossil-source electricity generation. No variables were significant in the long-term window (2020–2100). In all cases, scenarios with higher cumulative CDR had higher cumulative emissions or greater fossil energy.

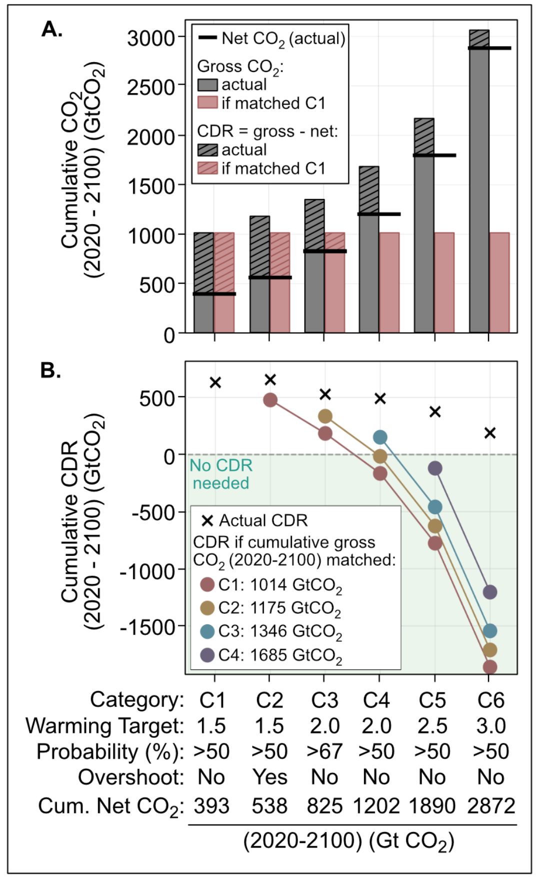

Figure 3 | Counterfactual CDR under mitigation assumptions of stricter temperature categories. **(A)** Example counterfactual using C1 as the reference category. Gray bars show median cumulative gross CO_2 emissions (2020–2100) for each temperature category; red bars show C1 median gross emissions applied to each category. Black lines indicate median cumulative net CO_2 emissions, which remain unchanged in the counterfactual. Hatched regions show CDR (gross minus net CO_2): black for actual, red for counterfactual CDR. Where the red bar falls below the net CO_2 line, no CDR is required. These counterfactual CDR values correspond to the red (C1) line in (B). **(B)** Counterfactual CDR for all reference categories (C1-C4), as described in (A). Black 'X' shows actual median cumulative CDR. Values below the dashed line (green shading) indicate no CDR is required. All calculations use category medians; see Methods.

Having established that CDR deployment correlates with fossil fuel use, I next examined whether it varied with temperature targets. Strikingly, in the median AR6 scenarios, warmer temperature targets did not imply less CDR deployment. Instead, the additional budget space was filled by continued emissions. This pattern emerged from a counterfactual analysis where I tested how much CDR would be required if a given temperature category achieved the same emissions reductions as a more stringent category. I held median end-of-century cumulative net CO_2 emissions constant for each temperature category while substituting median cumulative gross CO_2 emissions from a stricter category (Figure 3A). The difference is the counterfactual CDR required. For categories C3 through C6, the counterfactual CDR was notably less than the median amount used in the ensemble, and in several cases no CDR was required (Figure 3B). For example, if the median C4 scenario adopted cumulative gross emissions of the median C1 or C2 scenario, the temperature target could be met or exceeded without CDR.

Thus, the IPCC CDR magnitudes anchoring the downstream discourse (Figure 1C) do not reflect temperature targets but rather the near-term and mid-century mitigation trajectories embedded in the underlying scenarios — scenarios in which, on median, CDR offsets continued emissions.

CDR framing hardened, risk discussion declined, and CDR type narrowed as estimates reached NGO and industry sectors

In addition to CDR magnitude, I tracked how CDR was framed, how risks were discussed, and what types of CDR were considered. I found that all three of these characteristics evolved as the original studies were cited and estimates moved out of government and academic sectors into NGO and industry sectors.

CDR framing shifted from conditional/exploratory to promotional/advocacy across the IPCC citation chain (see Methods for category definitions). Three of the five original IPCC sources (AR5, Fuss et al., and SR1.5) discussed CDR in a conditional and exploratory way (Figure 4A) using language such as "scenarios typically rely on" and "deployment is projected to range from." AR6 had a more prescriptive/definitive framing (e.g., "CDR is a necessary element") while the State of CDR report used more pragmatic/cautious language. Only one of the 29 sources that cited these primary IPCC sources used conditional language to frame CDR (Figure 4A). The majority used prescriptive/definitive (31%) or promotional/advocacy (21%) framing, with the remainder using neutral/descriptive or pragmatic/cautious.

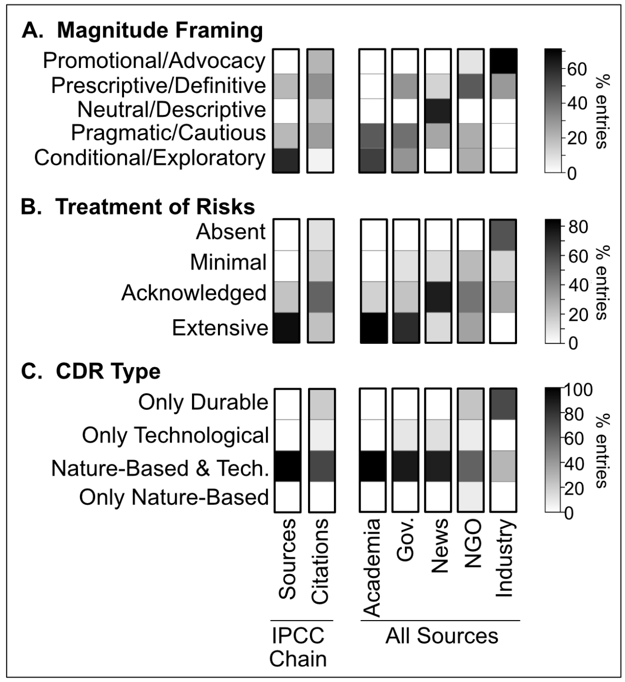

Figure 4 | CDR magnitude framing, risk treatment, and CDR type. Each panel shows the distribution of assigned entries as percent of entries within each group. Left columns show IPCC sources and their citations (see Figure 1A); right columns show all 51 sources grouped by sector. (**A**) Magnitude framing. (**B**) Treatment of risks associated with CDR deployment. (**C**) Specified CDR type. Note that 'Only Durable' implies technological CDR and is thus a more stringent category than 'Only Technological.' Classification criteria and entry details are provided in Methods and Supplementary Table 1.

Looking across all 51 sources, this shift toward prescriptive and promotional framing was largely driven by NGO and industry sources (Figure 4A). Academic sources maintained conditional or cautious framing throughout, and media sources predominantly used neutral/descriptive language. In contrast, nearly half of NGO sources used prescriptive/definitive framing, and all industry sources used either prescriptive/definitive or promotional/advocacy framing.

Discussion of CDR risks also diminished as estimates moved from academic and government sources into news, NGO, and industry contexts. Within the IPCC citation chain, four of the five original sources included extensive discussion of risk, highlighting that "depending on future CDR is inherently risky" (State of CDR). AR6 acknowledged CDR risks but did not extensively discuss them, which was the approach followed by most of the downstream sources (Figure 4B). Across all 51 sources, academic and government sources most consistently included extensive risk discussion, while industry sources largely omitted risk entirely.

A requirement that CDR encompass only technological and durable methods appeared in publications as CDR estimates reached NGO and industry sectors. For all original sources in the IPCC chain, the reported CDR magnitudes reflected both nature-based and technological forms of removal. However, nearly 30% of the sources citing the IPCC chain narrowed the reported magnitudes to only technological and/or durable forms of CDR—excluding the nature-based approaches used in the original scenarios. Across all 51 sources, this narrowing of CDR type was driven by the NGO and industry sectors, where ~30% and ~70% of sources, respectively, specified technological or durable CDR (Figure 4C). The durability requirement was added during translation, not derived from the underlying scenarios.

Across all three dimensions — framing, risk, and CDR type — the pattern was consistent: qualifying information present in the original sources was not preserved as estimates moved into NGO and industry sectors, which are the sectors most directly shaping investment and policy (Figure 4).

DISCUSSION

The analysis reveals that the CDR discourse has converged on a benchmark drawn from the upper end of an ensemble in which, on median, CDR served to offset continued emissions. As this benchmark propagated, it was stripped of its conditionality, risk context, and diversity of approaches. The result is a policy and investment landscape organized around a CDR target that is biased high, disconnected from the mitigation choices that shape CDR magnitude, and narrowed to exclude approaches that the scenarios themselves relied upon.

The IPCC is the primary conduit through which CDR estimates reach policy, corporate, and media contexts (Figure 1A). This role is appropriate, but consequential. In the AR6 database, CDR magnitude was driven by a cost-optimization framework[71] that treats near-term emissions reductions and future carbon removal as interchangeable, favoring delayed mitigation paired with future CDR deployment[72]. Thus, CDR in the median scenarios remained largely unchanged as temperature targets relaxed; the additional carbon-budget space was filled by continued emissions rather than by reduced CDR dependence (Figure 3). The cost-optimization framework produced scenarios requiring CDR to deploy at speeds and scales not yet demonstrated[26,28–30,32]. When deployment constraints were imposed or economic assumptions altered, CDR requirements dropped substantially and in some cases were eliminated entirely (Figure 1C), demonstrating that it is possible to meet temperature goals with less CDR than indicated by either the median AR6 scenarios or the 10 Gt benchmark.

NGO and industry sources predominantly drove the shift in CDR framing from conditional to prescriptive, the diminishment of risk discussion, and the narrowing of CDR toward durable approaches (Figure 4). These shifts, particularly the durability requirement, are consistent with the needs of carbon markets where CDR is used to offset fossil emissions. In an offsetting framework, the lifetime of the CO_2 removal must match the atmospheric lifetime of the emission it compensates[73]. In this context, a 1,000-year removal requirement is justified. But a blanket durability requirement conflates two distinct CDR roles[1,74]: offsetting ongoing or residual emissions and reducing atmospheric CO_2 burden. When CDR is deployed to reduce atmospheric CO_2 concentrations, rather than to offset emissions, the relevant criteria are speed, scale, and cost[75]. In this context, durability is a less relevant criterion because temporary removals deliver a net climate benefit even if the stored carbon is eventually re-released [76,77]. The current discourse inappropriately applies the logic of offsetting to all forms of CDR.

By narrowing CDR to durable methods, the discourse excludes the approaches most capable of delivering near-term atmospheric CO_2 reduction. Nature-based CDR is already operating at gigatonne scale[24], is cheaper and faster to deploy than most technological alternatives[24,78], and the AR6 scenarios themselves show it deploying first[79]. Yet, the narrowing od CDR is being institutionalized. NOAA now defines CDR as requiring "long-duration (100–1,000 years) storage"[80], and the CDR pavilion at COP30 was organized around scaling "permanent carbon removals" [81]. A CDR strategy that draws on the full range of available approaches and matches durability to purpose would be more resilient, more deployable, and more likely to succeed than one constrained to a single category.

More broadly, the current CDR discourse is not structured to support informed decision-making about climate pathways. Rather than converging on a single CDR target with a single durability standard, the discourse should present CDR in the context of its associated mitigation pathway — with the costs, risks, and feasibility of both the mitigation and removal components characterized, and with durability requirements matched to the role CDR is playing. At a minimum, CDR magnitude should be reported as conditional on its associated mitigation pathway: not “we need X Gt” but “given mitigation trajectory Y, X Gt would be required.”

This reorientation is urgent because near-term mitigation decisions are correlated with future CDR requirements (Figure 2): the actions taken, or not taken, in the next decade will shape the scale of removal required by the end of the century. The consequences of getting the mitigation-CDR balance wrong are asymmetric: deeper near-term mitigation reduces future CDR dependence but requires faster economic transformation[82], while weaker near-term mitigation demands CDR deployment at speeds and scales that may be unachievable[26,28,30,32], and if that deployment fails, the consequences are irreversible and disproportionately borne by future generations[33].

With AR7 now underway, there is an opportunity to build a CDR discourse that better supports informed decision-making by reporting CDR magnitude alongside its associated mitigation assumptions so that the connection between them is explicit, including feasibility and risk assessment alongside deployment estimates, giving comparable visibility to scenarios that achieve climate goals with minimal CDR, and disaggregating CDR by type to preserve the diversity of the modeled portfolio. In addition, reporting emissions reductions and CDR as separate objectives — rather than as interchangeable components of a net target — would make visible, and potentially prevent, the substitution dynamic that produced the CDR-dependent scenarios in the first place.

This paper does not argue against CDR research, investment, or deployment. It argues for a pivot toward unanswered questions about feasibility, costs, risks, and likelihood of success. A CDR agenda oriented around these issues, rather than around reaching a single benchmark, would restore what the current discourse has lost: the ability to compare mitigation-CDR pathways and course-correct as both mitigation progress and CDR feasibility become clearer.

ONLINE METHODS

Literature analysis

<u>Source identification and coding</u>
I constructed a dataset of sources making quantitative claims about CDR magnitude (Gt CO_2 yr^{-1} or cumulative Gt CO_2) intended to inform climate policy, investment, or public understanding. Sources were identified in two ways. The first was an expert-identified seed set of 33 sources drawn from the author's domain knowledge. The second involved queries of four databases (Policy Commons, ProQuest, Web of Science, Factiva) chosen to capture academic, grey literature, and media sources.

Queries were designed around two requirements: CDR-related terms (e.g., 'carbon dioxide removal,' 'negative emissions') in the source title, and magnitude-related terms (e.g., 'gigaton,' 'Gt CO_2,' 'billion tons') in the title, abstract, or full text depending on database capabilities. Exact query syntax was adapted to each platform. Resulting sources were screened against pre-specified inclusion criteria and then manually reviewed. Criteria required each source to (a) contain a quantitative CDR magnitude claim, AND either: (b) generate an independent CDR estimate through original analysis; (c) represent a new organizational voice not already captured in the dataset; or (d) represent an organization's shift in framing or magnitude relative to existing entries.

All searches were restricted to the period 2017–2025. The temporal scope began in 2017 because this is when CDR magnitudes first appeared in documents translating IPCC findings for policy audiences, including the UNEP Emissions Gap Report. The IPCC Fifth Assessment Report (AR5, 2014) is the one exception. AR5 was the first IPCC report to include scenarios with CDR. It did not contain aggregate CDR values and was not used to support CDR claims until ~2017. A gap in source coverage in 2020 reflects a drop in CDR-magnitude discourse between the SR1.5 response wave (2018–2019) and the AR6/net-zero policy wave (2021–2022), compounded by the postponement of COP26 due to the COVID pandemic; it is not a search artifact.

Policy Commons yielded 330 results, Web of Science Core Collection yielded 107 results, ProQuest (searched across 76 databases, excluding wire feeds, dissertations, and conference proceedings) yielded 298 non-news and 69 news/media results after deduplication, and Factiva (searched across major English-language outlets including the Wall Street Journal, New York Times, Financial Times, Guardian, Washington Post, BBC, Associated Press, TIME, Carbon Brief, E&E Daily, Climate Home News, and Platts sources) yielded 84 unique results. AI (Claude, Opus 4.6, Anthropic) was used to apply the pre-specified inclusion criteria to titles and abstracts across these ~800 results, classifying sources into tiers for manual review. The author then reviewed titles across all tiers to confirm prioritization, followed by abstract screening of top-tier sources to identify the final set for in-depth manual review. This process yielded ~60 (Policy Commons), 4 (Web of Science), 28 non-news and 37 news/media (ProQuest), and 4 (Factiva) sources for manual review. All four studies retained from Web of Science were also captured by ProQuest, confirming convergent coverage across databases. For media and news sources, an additional selection step was applied: when multiple outlets published similar coverage in the same year, higher-circulation outlets were preferred; when same-year coverage represented distinct framings (e.g., promotional versus critical), both were retained to capture the range of discourse.

The database search effort identified 18 additional sources for inclusion in the study that were not in the initial expert-identified set, yielding a final dataset of 51 sources spanning 2017–2025 (plus AR5 as pre-period context). This dataset is not intended as a comprehensive census of all CDR discourse but rather tracks the translation pathway through which CDR magnitude claims moved from primary scientific sources into policy, corporate, and public contexts. The approach was designed to capture the sources that shaped downstream claims rather than to achieve exhaustive coverage.

<u>Source classification</u>

Each source was classified by sector based on its discursive function rather than institutional affiliation alone. A university-affiliated report written as a policy brief was classified as NGO/Advocacy if its primary function was to advocate for specific CDR approaches, while a peer-reviewed paper from the same institution was classified as Academic/Research. Five sector categories were used: Academic/Research, Policy/Government, NGO/Advocacy, Industry/Corporate, and News/Media.

<u>Coding framework</u>

Each source entry was coded along three dimensions using language quoted directly from the source text, not inferred from source identity or assumed from institutional affiliation. The coding taxonomies were developed through iterative discussion with AI (Claude, Opus 4.6, Anthropic), which also reviewed source documents and proposed coding classifications. All final coding decisions were made by the author.

Magnitude framing was coded on a five-tier scale:

- *Conditional/Exploratory*: CDR presented as one pathway among many; uses language such as "could," "may," "scenarios show," "depending on"
- *Neutral/Descriptive*: presents CDR magnitude information without advocacy; acknowledges CDR role factually
- *Pragmatic/Cautious*: accepts CDR necessity but with explicit concerns, caveats, or emphasis on emissions reductions as priority
- *Prescriptive/Definitive*: states CDR "will be needed," is "unavoidable," "necessary," or "must" be deployed; declarative statements of necessity
- *Promotional/Advocacy*: actively promotes CDR adoption or investment; frames CDR as a market opportunity; mobilizes actors to participate

Treatment of CDR risks and limitations was coded on a four-level scale: *Extensive* (risks are a central concern, potentially motivating CDR minimization); *Acknowledged* (risks mentioned substantively but not central); *Minimal* (brief or passing mention); and *Absent* (no discussion of risks or limitations).

CDR type was coded as: *Nature-based Only* (afforestation, soil carbon, ocean-based biological approaches); *Nature-based & Technological* (both categories discussed); *Technological Only* (DACCS, BECCS, enhanced weathering, ocean alkalinity enhancement; durability is not a specific requirement); or *Durable Only* (specifies permanence/durability requirements; implies technological CDR).

<u>Citation network analysis</u>

For each source, I identified the origin of its CDR magnitude claim. Sources were classified as: *Primary Source* (generates an original CDR estimate through independent analysis or model runs); *Cited Source* (cites a specific primary source for its magnitude claim); *Cited Citation* (cites an intermediary that itself cited a primary source, representing second-order propagation); or *Unclear* (states a magnitude without identifiable citation).

AR6 scenario analysis

Scenario data were obtained from the IPCC AR6 Working Group III scenario database hosted by IIASA. I analyzed scenarios across categories C1 through C6: C1 (limit warming to 1.5°C with no or limited overshoot, >50% probability), C2 (return warming to 1.5°C after high overshoot, >50% probability), C3 (limit warming to 2°C, >67% probability), C4 (limit warming to 2°C, >50% probability), C5 (limit warming to 2.5°C, >50% probability), and C6 (limit warming to 3°C, >50% probability)[1].

CDR and emissions variable definitions

Total CDR for each scenario was computed as the sum of four carbon sequestration variables reported in the AR6 database

- 'Carbon Sequestration|CCS|Biomass',
- 'Carbon Sequestration|Direct Air Capture',
- 'Carbon Sequestration|Enhanced Weathering', and
- 'Carbon Sequestration|Land Use'.

Gross CO_2 emissions were computed as 'Emissions|CO_2' (net) plus total CDR.

Data cleaning

Using approaches published by Prütz et al.[83], scenarios were excluded if: (a) 'Carbon Sequestration|Land Use' exceeded 1000 Mt CO_2 yr^{-1} in 2020, indicating implausible baseline land-use sequestration; (b) they reported zero land-use sequestration data but negative AFOLU CO_2 emissions, indicating CDR activity was not captured by the sequestration variables; (c) the sum of 'Emissions|CO_2|AFOLU' and 'Carbon Sequestration|Land Use' was less than −1 Mt CO_2 in any year, indicating internal inconsistency in land-sector accounting; or (d) computed gross CO_2 emissions were negative in any year, which is physically implausible. These filters removed scenarios with inconsistent or implausible CDR accounting. Cumulative values across years were computed by trapezoidal integration of decadal time series reported at 10-year intervals.

Tercile analysis

Within each scenario category (C1–C4), scenarios were divided into terciles (low, mid, high) based on cumulative CDR (2020–2100). I used cumulative CDR (2020–2100) rather than deployment rates at individual time points because cumulative removal is the quantity directly constrained by the carbon budget and reflects the full pathway rather than a single snapshot. I then compared 50 pathway variables across terciles. Variables encompassed emissions, energy sources across primary, secondary and final forms of energy, energy investment, and economic policy costs. Cumulative values of pathway variables were calculated for three time windows, 2020–2030, 2020-2050, and 2020-2100, to identify whether variables correlated with CDR in a time-dependent manner. In addition, the price of carbon at 2030, 2050, and 2100 was compared across terciles. Group differences were tested using the Kruskal-Wallis H-test, with post-hoc pairwise comparisons conducted using Dunn's test with Bonferroni correction. Statistical significance was set at a p-value of 0.05. Pathway variables were required to have all three tercile groups represented, with each group containing at least 10% of the category's scenarios to ensure robust comparisons.

To identify variables that consistently distinguished low- from high-CDR scenarios, I applied progressively stringent filters. The strictest required a variable to show a statistically significant Kruskal-Wallis result ($p < 0.05$) with monotonically ordered group medians (consistently increasing or decreasing from low to high CDR terciles) across all four scenario categories (C1–C4) for a given time window (cumulative variables) or time point (price of carbon). No variables met this criterion. Under a slightly relaxed filter requiring monotonic trends in at least three of four categories, six variables qualified:

- 2020 – 2030 cumulative values
    - ‘Emissions|CO2|Gross’
    - ‘Emissions|F-Gases’
    - ‘Emissions|Kyoto Gases’
    - ‘Primary Energy|Gas’
- 2020 – 2050 cumulative values
    - ‘Primary Energy|Gas’
    - ‘Secondary Energy|Electricity|Fossil’

<u>Counterfactual analysis</u>

To assess how CDR requirements changed under alternative decarbonization assumptions, I computed the cumulative CDR that would be required if a less ambitious scenario category achieved the gross emissions level of a stricter category while maintaining its own net CO_2 constraint. For each category, I first computed three median values from the scenario outputs: cumulative gross CO_2 emissions, cumulative CDR, and cumulative net CO_2 emissions, all across 2020–2100. The counterfactual CDR for target category *i* under the decarbonization assumption of reference category *r* was then:

CDR_counterfactual(i,r) = median cumulative gross CO_2(r) – median cumulative net CO_2(i)

Counterfactuals were computed only for target categories less ambitious than the reference (e.g., C1 gross emissions applied to C2–C6, C2 to C3–C6, etc.), using four reference categories (C1–C4) and all six categories (C1–C6) as targets. When CDR_counterfactual is negative, the reference category's gross emissions would satisfy the target category's cumulative net CO_2 constraint without requiring any CDR.

Data and code availability

Scenario data from the IIASA AR6 scenario database are publicly available at [URL]. Analysis code and the complete source dataset will be made available upon publication at [repository URL]. AI (Claude, Opus 4.6, Anthropic) assisted with Python code development for the AR6 scenario analysis.

AI disclosure

AI (Claude, Opus 4.6, Anthropic) assisted with manuscript development. The author produced original drafts, outlines, and analytical content; AI was used to help organize and synthesize this material, provide structural feedback, and refine text. AI use in source screening and coding taxonomy development is described in the relevant methods sections above. The core findings, analytical framework, data analysis, final coding decisions, and intellectual direction of the study are the author's own.

Limitations
The study's media and grey literature sources are predominantly English-language, drawn from US and UK outlets. While the policy and corporate sources in the analysis include non-Anglophone institutions (e.g., the EU CRCF), the media set does not capture how CDR magnitude claims were translated in non-English-language outlets. CDR discourse in other linguistic and regional contexts may follow different translation patterns.

ACKNOWLEDGEMENTS
This work was funded, in part, by National Science Foundation awards: 2422780 and 2419565. Thank you to Claire Zarakas, Freya Chay, Tyler Kukla, and Chris Allen at Carbon Plan, and Anne Thompson at Portland State University for helpful discussions and manuscript feedback.

REFERENCES
1. IPCC. Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. doi:10.1017/9781009157926 (2022).
2. CDR.fyi. CDR.fyi. https://www.cdr.fyi/ (2025).
3. Bezos Earth Fund & RMI. Scaling Technological Greenhouse Gas Removal: A Global Roadmap to 2050. https://www.bezosearthfund.org/uploads/scaling-technological-ghg-removal-roadmap-2050.pdf (2024).
4. World Economic Forum. Carbon Dioxide Removal: Best Practice Guidelines. https://www3.weforum.org/docs/WEF_Carbon_Dioxide_Removal_Best_Practice_Guidelines_2023.pdf (2024).
5. Carbon Removal Alliance. Carbon Removal Alliance. https://www.carbonremovalalliance.org/ (2025).
6. National Academies of Sciences, Engineering, and Medicine. Negative Emissions Technologies and Reliable Sequestration: A Research Agenda. 25259 https://www.nap.edu/catalog/25259 (2019) doi:10.17226/25259.
7. Boyd, J., Joiner, E., Krupnick, A. & Toman, M. Policy Incentives to Scale Carbon Dioxide Removal: Analysis and Recommendations. (2024).
8. Foster, J. 4 ways carbon capture can help fight climate change. Vital Signs by Environmental Defense Fund https://vitalsigns.edf.org/story/4-ways-carbon-capture-can-help-fight-climate-change (2023).
9. Nichols, R. Investors Are Betting Big on Carbon Removal Technology. The Reality Is More Complicated. TIME (2022).
10. Hook, L. & Hodgson, C. Carbon removal 'unavoidable' as climate change alarm bells ring. Financial Times (2022).

11. 1PointFive. Addressing emissions with direct air capture and carbon sequestration. 1PointFive https://www.1pointfive.com/ (2026).

12. Sartor, D., Wood, I., Weaver, E., Kahsar, R. & See, G. What We Really Mean by "The Massive Scale" Required for CDR in Climate Goals. RMI https://rmi.org/what-we-really-mean-by-the-massive-scale-required-for-cdr-in-climate-goals/ (2024).

13. Founding Members. Stripe, Alphabet, Shopify, Meta, and McKinsey launch advance market commitment to buy $1B of carbon removal by 2030. Frontier Climate https://frontierclimate.com/writing/launch (2022).

14. Mannion, P., Parry, E., Patel, M., Ringvold, E. & Scott, J. Carbon Removals: How to Scale a New Gigatone Industry. (2023).

15. Mistry, K. et al. Scaling CDR: Demand Drivers for Durable Carbon Removal. https://web-assets.bcg.com/15/ca/ebf8d43f42bba0ec028b1c826fe8/what-does-the-future-of-durable-cdr-hold-june-2024.pdf (2024).

16. Kronk, B. H. The Road to Scaling Durable Carbon Removal Will Be Long and Expensive. Wall Street Journal (2025).

17. World Resources Institute. Carbon Removal FAQs. https://www.wri.org/initiatives/carbon-removal/frequently-asked-questions-about-carbon-removal (2025).

18. Abouelnaga, M. Carbon Dioxide Removal: Pathways and Policy Needs. (2021).

19. Carbon Direct & Microsoft. Criteria for High-Quality Carbon Dioxide Removal: 2025 Edition. https://www.carbon-direct.com/criteria/2025-edition (2025).

20. Viloria, E., Avornic, R., Delerce, S. & Loopesko, L. Funding CDR Research, Development & Innovation for a Net Zero Competitive EU. https://carbongap.org/eu-carbon-removal-funding/ (2025).

21. Carbon180.org. Carbon Removal Funding Tracker. Carbon180 https://carbon180.org/ (2024).

22. Directorate-General for Climate Action. EU sets world's first voluntary standard for permanent carbon removals - Climate Action. Climate Action Department, European Commission (2026).

23. Friedlingstein, P. et al. Global Carbon Budget 2024. Earth System Science Data **17**, 965–1039 (2025).

24. Smith, S. M. et al. The State of Carbon Dioxide Removal - 2nd Edition. https://osf.io/f85qj/ (2024).

25. Cox, E., Spence, E. & Pidgeon, N. Public perceptions of carbon dioxide removal in the United States and the United Kingdom. Nat. Clim. Chang. **10**, 744–749 (2020).

26. McLaren, D. & Corry, O. Carbon Dioxide Removal: What Is Sustainable and Just? Environment: Science and Policy for Sustainable Development **67**, 59–69 (2025).

27. Honegger, M., Michaelowa, A. & Roy, J. Potential implications of carbon dioxide removal for the sustainable development goals. Climate Policy **21**, 678–698 (2021).

28. Smith, P. et al. Biophysical and economic limits to negative CO2 emissions. Nature Clim Change **6**, 42–50 (2016).

29. Rockström, J. et al. The world's biggest gamble. Earth's Future **4**, 465–470 (2016).

30. Günther, P. & Ekardt, F. Human Rights and Large-Scale Carbon Dioxide Removal: Potential Limits to BECCS and DACCS Deployment. Land **11**, 2153 (2022).

31. Ampah, J. D. et al. Deployment expectations of multi-gigatonne scale carbon removal could have adverse impacts on Asia's energy-water-land nexus. Nat Commun **15**, 6342 (2024).

32. Deprez, A. et al. Sustainability limits needed for CO_2 removal. Science **383**, 484–486 (2024).

33. Hollnaicher, S. On economic modeling of carbon dioxide removal: values, bias, and norms for good policy-advising modeling. Glob. Sustain. **5**, e18 (2022).

34. Keller, D. P. et al. The Effects of Carbon Dioxide Removal on the Carbon Cycle. Curr Clim Change Rep **4**, 250–265 (2018).

35. Zickfeld, K., Azevedo, D., Mathesius, S. & Matthews, H. D. Asymmetry in the climate–carbon cycle response to positive and negative CO2 emissions. Nat. Clim. Chang. **11**, 613–617 (2021).

36. Lenton, T. M. et al. Climate tipping points — too risky to bet against. Nature **575**, 592–595 (2019).

37. Solomon, S., Plattner, G.-K., Knutti, R. & Friedlingstein, P. Irreversible climate change due to carbon dioxide emissions. Proceedings of the National Academy of Sciences **106**, 1704–1709 (2009).

38. Buck, H. J., Carton, W., Lund, J. F. & Markusson, N. Why residual emissions matter right now. Nat. Clim. Chang. **13**, 351–358 (2023).

39. Bergman, A. & Rinberg, A. The Case for Carbon Dioxide Removal: From Science to Justice. in Carbon Dioxide Removal Primer (eds Wilcox, J., Kolosz, B. & Freeman, J.) (cdrprimer.org, 2021).

40. IEA. Net Zero by 2050 - A Roadmap for the Global Energy Sector. https://www.iea.org/reports/net-zero-by-2050 (2021).

41. Strefler, J. et al. Between Scylla and Charybdis: Delayed mitigation narrows the passage between large-scale CDR and high costs. Environ. Res. Lett. **13**, 044015 (2018).

42. IPCC. Climate Change 2014: Mitigation of Climate Change Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. (2014).

43. IPCC. Global Warming of 1.5°C: IPCC Special Report on Impacts of Global Warming of 1.5°C above Pre-Industrial Levels in Context of Strengthening Response to Climate Change, Sustainable Development, and Efforts to Eradicate Poverty. https://www.cambridge.org/core/product/identifier/9781009157940/type/book (2018) doi:10.1017/9781009157940.

44. Fuss, S. et al. Negative emissions—Part 2: Costs, potentials and side effects. Environ. Res. Lett. **13**, 063002 (2018).

45. van Vuuren, D. P. et al. Alternative pathways to the 1.5 °C target reduce the need for negative emission technologies. Nature Clim Change **8**, 391–397 (2018).

46. Grubler, A. et al. A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. Nat Energy **3**, 515–527 (2018).

47. Holz, C., Siegel, L. S., Johnston, E., Jones, A. P. & Sterman, J. Ratcheting ambition to limit warming to 1.5 °C – trade-offs between emission reductions and carbon dioxide removal. Environ. Res. Lett. **13**, 064028 (2018).

48. Strefler, J. et al. Alternative carbon price trajectories can avoid excessive carbon removal. Nat Commun **12**, 2264 (2021).

49. Sers, M. R. Ecological macroeconomic assessment of meeting a carbon budget without negative emissions. Global Sustainability **5**, e6 (2022).

50. Energy Transitions Commission. Mind the Gap: How Carbon Dioxide Removals Must Complement Deep Decarbonisation to Keep 1.5°C Alive. (2022).

51. Lamb, W. F. et al. State of Carbon Dioxide Removal - 1st Edition. https://doi.org/10.17605/OSF.IO/W3B4Z (2023) doi:10.17605/OSF.IO/W3B4Z.

52. Climate Action Tracker. Methodology for 1.5°C Compatible Sectoral Benchmarks. (2023).

53. Ampah, J. D. et al. Prioritizing Non-Carbon Dioxide Removal Mitigation Strategies Could Reduce the Negative Impacts Associated with Large-Scale Reliance on Negative Emissions. Environ. Sci. Technol. **58**, 3755–3765 (2024).

54. Fuhrman, J. et al. Ambitious efforts on residual emissions can reduce CO2 removal and lower peak temperatures in a net-zero future. Environ. Res. Lett. **19**, 064012 (2024).

55. Climate Analytics & PIK. Rescuing1.5°C: New Evidence on the Highest Possible Ambition to Deliver the Paris Agreement. https://ca1-clm.edcdn.com/publications/Rescuing1.5%C2%BAC.pdf?v=1762362849 (2025).

56. Monteith, S., Aldrete, L. & Lau, T. Achieving Global Climate Goals by 2050: Pathways to 1.5 oC Future. https://www.climateworks.org/wp-content/uploads/2023/04/ClimateWorks_Climate_Mitigation_Report_042623.pdf (2023).

57. Nawaz, S. et al. Agenda for a Progressive Political Economy of Carbon Removal. (2024).

58. Meyer, R. The Dawn of a New Climate Industry. Heatmap News (2023).

59. Nogrady, B. Negative emissions tech: can more trees, carbon capture or biochar solve our CO2 problem? The Guardian (2017).

60. United Nations Environment Programme. The Emissions Gap Report 2017: A UN Environment Synthesis Report. (UN, 2017). doi:10.18356/1cf881fb-en.

61. Levin, K., Mulligan, J. & Ellison, G. Taking Greenhouse Gases from the Sky: 7 Things to Know About Carbon Removal. World Resources Institute Insights (2018).

62. Royal Society & Royal Academy of Engineering. Greenhouse Gas Removal: A Comprehensive Assessment | Policy Commons. https://policycommons.net/artifacts/1745448/report/2477250/view/ (2018).

63. Holz, C. Modelling 1.5°C-Compliant Mitigation Scenarios Without Carbon Dioxide Removal. (2018).

64. EASAC. Forest Bioenergy, Carbon Capture, and CO2 Removal: An EASAC Update. https://easac.eu/fileadmin/PDF_s/reports_statements/Negative_Carbon/EASAC_Commentary_Forest_Bioenergy_Feb_2019_FINAL.pdf (2019).

65. Temple, J. Carbon removal hype is becoming a dangerous distraction. MIT Technology Review (2021).

66. Plumer, B. Energy Department Aims to Slash Cost of Removing Carbon From the Air. The New York Times (2021).

67. U.S. DOE. Strategic Vision: The Role of Fossil Energy and Carbon Management in Achieving Net Zero Greenhouse Gas Emissions. https://www.energy.gov/sites/default/files/2022-04/2022-Strategic-Vision-The-Role-of-Fossil-Energy-and-Carbon-Management-in-Achieving-Net-Zero-Greenhouse-Gas-Emissions_Updated-4.28.22.pdf (2022).

68. Mundy, S. We need to talk about carbon removal. Financial Times (2024).

69. Taylor, W., Marston, B., Rosner, R. & Wurtele, J. Atmospheric Carbon Dioxide Removal: A Physical Science Perspective. PRX Energy **4**, 017001 (2025).

70. Stoefs, W. & De Simone, F. The Bare Necessities: Essential Principles to Design Sensible Carbon Removal Policies. https://policycommons.net/artifacts/20430198/essential-principles-for-sensible-carbon-removal-policies/21330721/view/?search=Gt (2023).

71. IPCC. Annex III: Scenarios and Modelling Methods. in IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change 1841–1908 (Cambridge University Press, 2023). doi:10.1017/9781009157926.022.

72. Grant, N., Hawkes, A., Mittal, S. & Gambhir, A. Confronting mitigation deterrence in low-carbon scenarios. Environ. Res. Lett. **16**, 064099 (2021).

73. Brunner, C., Hausfather, Z. & Knutti, R. Durability of carbon dioxide removal is critical for Paris climate goals. Commun Earth Environ **5**, 645 (2024).

74. Allen, C., Chay, F., Khan, A. & Simonelli, L. Recentering Goals: A Guide to CDR Policymaking for a Net-Negative World. https://files.carbonplan.org/CDR-Policy-Report.pdf (2026).

75. Streck, C. et al. Considering durability in carbon dioxide removal strategies for climate change mitigation. Climate Policy **26**, 493–501 (2026).

76. Matthews, H. D., Zickfeld, K., Koch, A. & Luers, A. Accounting for the climate benefit of temporary carbon storage in nature. Nat Commun **14**, 5485 (2023).

77. Matthews, H. D. et al. Temporary nature-based carbon removal can lower peak warming in a well-below 2 °C scenario. Commun Earth Environ **3**, 65 (2022).

78. Busch, J. et al. Potential for low-cost carbon dioxide removal through tropical reforestation. Nat. Clim. Chang. **9**, 463–466 (2019).

79. Ganti, G. et al. Evaluating the near- and long-term role of carbon dioxide removal in meeting global climate objectives. Commun Earth Environ **5**, 377 (2024).

80. NOAA Science Council. Carbon dioxide removal: NOAA State of the Science factsheet. https://www.climate.gov/news-features/understanding-climate/carbon-dioxide-removal-noaa-state-science-factsheet (2024).

81. CDR30. COP30: Brazil November 2025. https://cdr30.org/ (2026).

82. Campiglio, E. & van der Ploeg, F. Macrofinancial Risks of the Transition to a Low-Carbon Economy. Review of Environmental Economics and Policy **16**, 173–195 (2022).

83. Prütz, R., Strefler, J., Rogelj, J. & Fuss, S. Understanding the carbon dioxide removal range in 1.5 °C compatible and high overshoot pathways. Environ. Res. Commun. **5**, 041005 (2023).