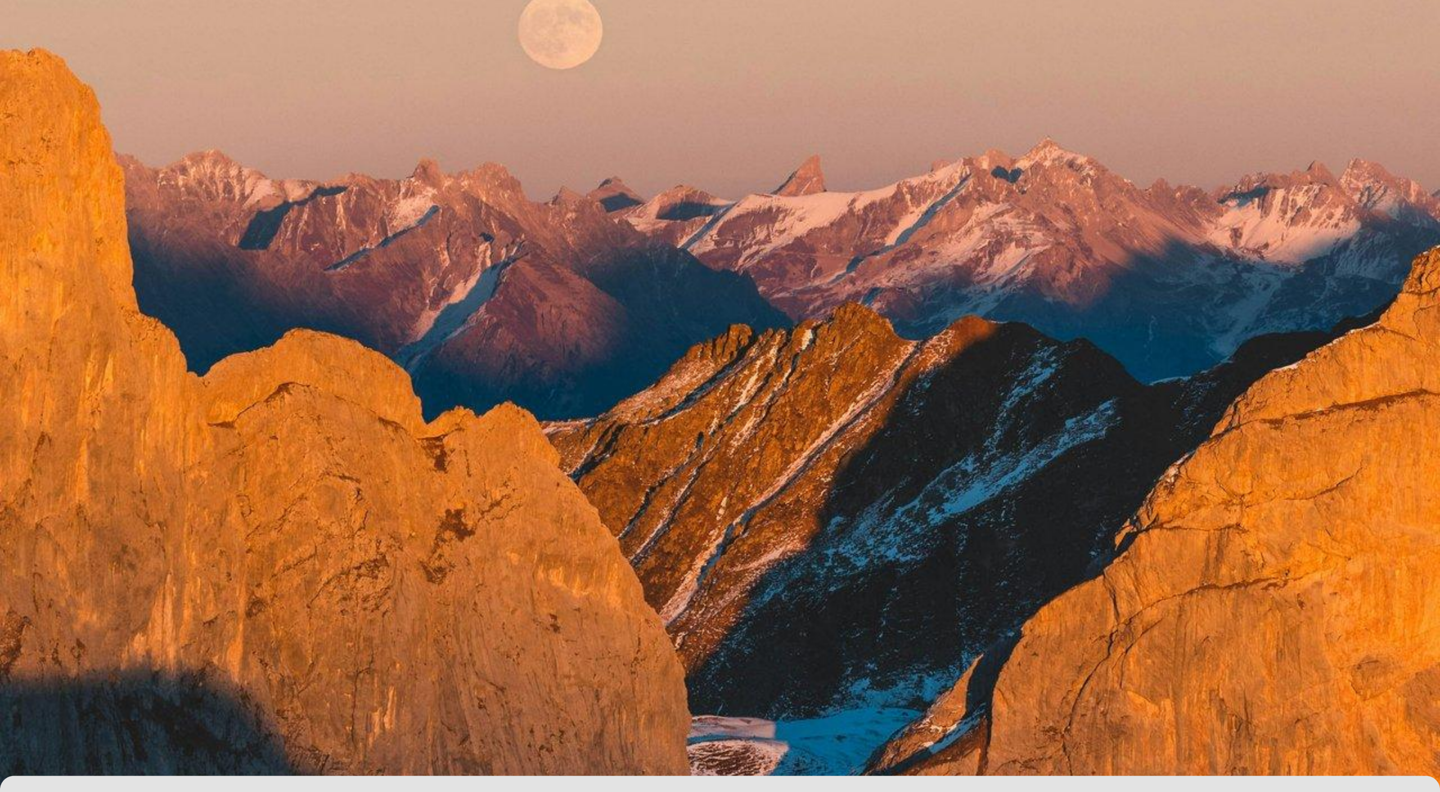
Sustainable Scaling Limits for Carbon Dioxide Removal Pathways

How much carbon removal can we deploy by 2050?



Inside this report

- Understand how much carbon dioxide can be sustainably removed by 2050, with a deep dive into the physical and ecological boundaries that shape global CDR potential.
- Discover conservative and upper-bound estimates for each pathway, grounded in peer-reviewed literature.
- Learn how combining nature-based and engineered solutions is critical for staying within planetary boundaries and achieving Paris-aligned goals

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A deep dive into planetary resource limits

To achieve Paris-aligned climate targets, the world needs to permanently remove between 6 and 16 gigatons (Gt) of CO_2 annually by 2050, in addition to deep cuts in greenhouse gas emissions [1, 2]. Today's carbon dioxide removal (CDR) capacity is minimal by comparison [2, 3], and many projections of future scale fail to account for the physical constraints of our planet [4]. This can lead to inflated, unsustainable estimates [2, 5].

Our analysis establishes defensible global limits for six key CDR pathways: bioenergy with carbon capture and storage (BECCS), biochar, afforestation, reforestation, and revegetation (ARR), mangroves, enhanced rock weathering (ERW), and direct air capture and storage (DACS). For each pathway, we identify the single most limiting resource—such as biomass, land, or low-carbon energy—and use a single-constraint method to calculate conservative estimates for 2050.

The findings are clear. Conservatively, no single CDR technology can meet 2050 requirements without exceeding sustainable resource limits. This underscores the need for a balanced portfolio that combines a mix of all credible available technologies, as outlined in our Global Optimal Portfolio paper.

Method in brief

Our analysis is built on a straightforward, four-step methodology:

1 Identify the limiting constraint

For each pathway, we pinpointed the single most plausible global resource constraint in 2050. For example, our analysis assumes that by mid century, technological maturation and infrastructure build-out will no longer be the primary limitations.

2 Conduct a bottom-up assessment

We performed a bottom-up assessment of global resource availability for each technology, drawing on extensive peer-reviewed literature.

3 Convert to removal potential

We converted resource quantities into annual CO_2 removal potentials using clear, lifecycle-based conversion factors.

4 Interpret, and apply

We interpreted the results in a broader context, including co-benefits, trade-offs, and risks, to inform a realistic view of CDR and its role in an optimal global portfolio.

Why a resource-constrained approach?

Many published estimates of CDR potential assume unconstrained access to land, energy, and biomass, often leading to inflated and unrealistic projections [6]. Integrated assessment models and "technical potential" studies frequently simulate large-scale deployment of technologies like BECCS, without fully accounting for the ecological and social trade-offs that emerge at gigaton scale [7, 8]. Current studies increasingly suggest that earlier estimates of BECCS' potential were far too high. To illustrate the scale of the challenge, removing 10 Gt of CO_2 annually through BECCS would require roughly five times the world's current municipal solid waste as feedstock. When planetary boundaries—such as biosphere integrity, freshwater availability, and land-system change—are respected, recent analyses show that the sustainable potential for BECCS from dedicated biomass plantations outside agricultural land falls to near zero [9]. This example underscores how quickly ecological limits can be approached or exceeded when scaling individual technologies.

Our approach addresses this directly by placing resource constraints at the center of CDR planning. Rather than assuming theoretical maxima, we identify the most likely binding constraint for each pathway and use it to define conservative limits. These limits are transparent, grounded in peer-reviewed literature, and designed to inform actionable strategies for portfolio design and procurement planning. While many pathways face multiple interacting constraints, this single-constraint method provides a clear, operational safeguard for models and procurement teams. The result is a more realistic view of the CDR landscape in 2050, ensuring that deployment remains within ecological limits.

Bioenergy with carbon capture and storage is a climate mitigation technology that produces energy from biomass — through combustion, fermentation, or anaerobic digestion — while capturing the resulting CO_2 and storing it geologically, thereby generating net-negative emissions. In our framework, the feasible deployment of BECCS in 2050 is determined by the availability of sustainably sourced biomass.

To remain conservative, we only include residues and waste biomass stemming from the following sources:

Forest residues

Biomass leftover from forestry, like branches, treetops, and sawdust not used as commercial timber, amounts to about 1.6 Gt/yr of biomass [2, 10, 11, 12].

Agricultural residues

Non-food by-products of farming, including crop residues like straw, husks, and shells, as well as manure, with an estimated potential of 1.3 Gt/yr [2, 13].

Organic municipal waste

The biodegradable fraction of household and urban waste such as food scraps and garden clippings collected through municipal systems, this adds 0.5 Gt/yr [2, 14, 15].

Together, these sources equal to an estimated 6.1 $GtCO_2$/yr[1] 1from sustainable biomass feedstock prior to conversion.

To prevent double-counting across pathways that draw from the same feedstock pool, we allocate 47% of this biomass to BECCS, reserving 53% for biochar. This allocation balances net energy gain, water use, and product sales, while reflecting the centralized nature of large BECCS facilities compared to smaller-scale, dispersed biochar facilities [5]. Assuming a 70% conversion[2] of biomass carbon to geologically stored CO_2, this results in approximately 2.0 Gt CDR/yr of removals for BECCS in the conservative case.

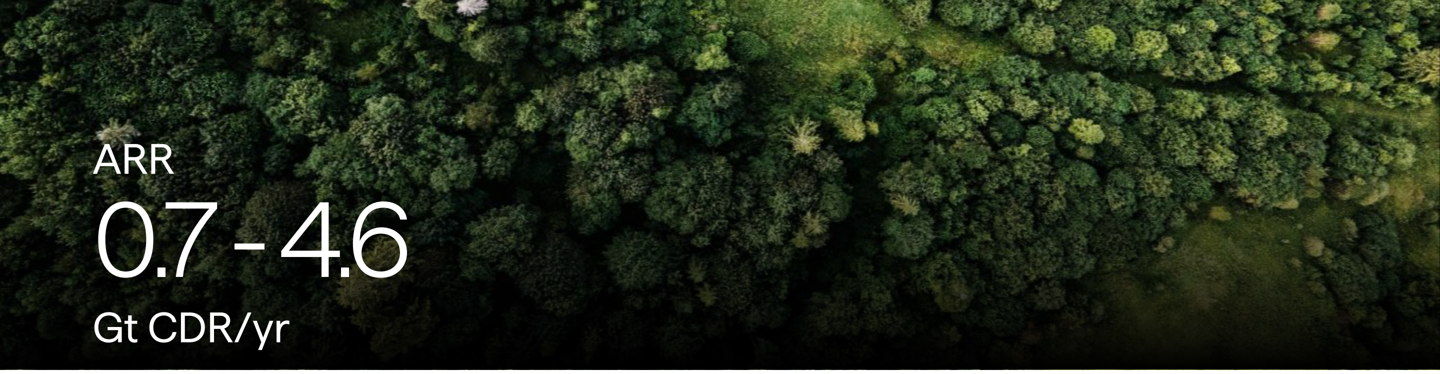
In an upper-bound sensitivity case, we include energy crops grown on about 250 Mha of land that can be made available through dietary shifts and sustainable land use changes. Energy crops are purpose-grown plants such as miscanthus, short-rotation woody crops, and in some regions even corn or sugarcane that are cultivated for energy rather than food. Including such crops adds roughly 4.5 $GtCO_2$/yr of biomass potential [2, 16, 17], increasing the total biomass pool to about 10.6 $GtCO_2$/yr. Applying the same biomass allocation logic and CDR efficiency as the conservative case, this results in an upper-bound case of 3.5 Gt CDR/yr for BECCS. While considering energy crops expands biomass supply, it also introduces significant trade-offs, including increased land and water requirements, fertilizer inputs, competition with food production and risks of indirect land-use change that can release existing carbon stocks. Other studies often report higher BECCS potentials because they assume large-scale deployment of energy crops without imposing such conservative sustainability constraints [6].

[1] 1 Gt of biomass has 0.5 Gt of C, which equals to 1.8 Gt CO_2.
[2] 70% can be claimed as removal after considering LCA deductions, including biomass processing, non-capture emissions, and other grey emissions.

Biochar carbon removal involves heating biomass in the absence of oxygen (pyrolysis) to produce a stable, carbon-rich solid that can be applied to soils or used in construction materials, where it remains stored for centuries or longer. Like BECCS, biochar is primarily limited by the availability of sustainable biomass feedstock, and as such draws on the same pool of sustainably-sourced residues and wastes, so the two approaches must be considered in parallel.

To prevent double counting across pathways that compete for common feedstocks, we apply the same allocation used in the BECCS analysis – 47% of available biomass to BECCS and 53% to biochar [5]. In the conservative case, 53% of the 6.1 $GtCO_2$/yr biomass pool is allocated to biochar; assuming that 30% of biomass carbon remains as stable char after pyrolysis, this yields approximately 0.97 Gt CDR/yr. In the upper-bound case that includes energy crops, the total biomass pool increases to about 10.6 $GtCO_2$/yr and, under the same allocation and conversion assumptions, biochar delivers 1.7 Gt CDR/yr

CDR. This framing ensures coherence across biomass-based routes and avoids inflating totals through implicit double use of the same resource base. We exclude other potential sources of biomass such as aquatic biomass or additional energy crops, which are treated as exploratory due to major sustainability, scalability, and ecological uncertainties. Furthermore, we exclude competing uses of biomass such as sustainable aviation fuels (SAF), which would primarily rely on energy crops and therefore reduce the upper-bound availability for CDR.



Afforestation, reforestation, and revegetation remove CO_2 from the atmosphere by planting new forests on previously non-forested land (afforestation) or restoring forests/vegetation on land that was recently deforested (reforestation/revegetation). The main constraint for ARR is land availability, as large-scale deployment competes with agriculture, settlements, and ecosystems.

In the conservative scenario, we assume 70 Mha of land becomes available for reforestation between 2025 and 2035 by extrapolating recent FAO-reported deforest-ation rates into the next decade. This is a land area roughly equal to 1.5 times the size of the DACH region (Germany, Austria, and Switzerland) or Texas [10]. Applying average sequestration rates of ~9.5 tCO_2/ha/yr[3] to this available land gives a total of 0.67 Gt CDR/yr net.

In the upper-bound scenario, additional land is assumed to become available (see below). Taken together, ARR on these areas could provide up to 4.59 Gt CDR/yr of removals.

[3] sequestration rate taken as the average of temperate/boreal and tropical zone sequestration rates across multiple species

Temperate and boreal zones

180 Mha of abandoned agricultural land is reforested, but cooler climates and shorter growing seasons limit productivity to ~3.9 tCO_2/ha/yr (equivalent to 0.7 $GtCO_2$/yr) [18].

Tropical zones

215 Mha is reforested, where warm, wet conditions drive much faster biomass accumulation of ~15 tCO_2/ha/yr (equivalent to 3.2 $GtCO_2$/yr) [2, 19, 20].

Mangrove restoration removes CO_2 by re-establishing coastal mangrove forests that store large amounts of carbon in both biomass and sediments. The main constraint is the availability of restorable coastal land, since mangroves can only grow in specific intertidal zones and climates.

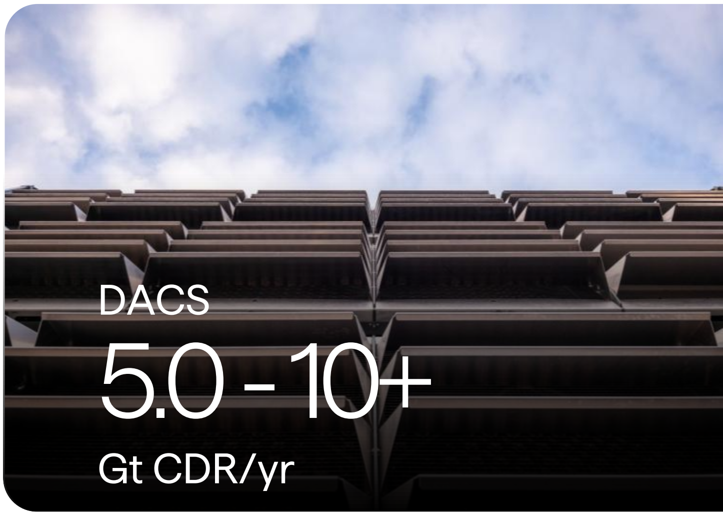
In the conservative case, we consider 0.7 Mha of highly restorable land to be available, an area equivalent to ~17% of Switzerland [21]. This is coastal land previously covered with mangrove forests, where biophysical and social conditions make restoration most feasible. With sequestration rates of ~23 tCO_2/yr [22], this gives 0.016 Gt CDR/yr of removal. In the upper-bound case, we assume interventions can successfully restore mangroves to mid-20th century coverage of approximately 10 Mha [23, 24] (2.5 times Switzerland), resulting in 0.23 Gt CDR/yr CDR. While small in volume, mangroves provide substantial biodiversity and coastal protection co-benefits.

Enhanced Rock Weathering refers to CO_2 capture through reaction of rock material (typically silicates) to form stable carbonates. It's an acceleration of natural rock weathering, with greater rate of sequestration achieved by reducing the size of the rock to a powder and spreading over large areas. . In practice, the application is limited to cropland, where access, spreading of rock, and monitoring of weathering are feasible and there are economic co-benefits. The availability of cropland, in turn, becomes the binding constraint for scaling, i.e., land where application can proceed without harming soils or displacing food production and where climatic and geochemical conditions support sufficient weathering rates. After suitable land, the next limiting factor for ERW scaling would be suitable rock powder. While global reserves of appropriate rock such as basalt are vast, deployment should utilize material that can be mined, processed, and transported with low life-cycle emissions to ensure that ERW interventions retain significant climate benefit.

In the conservative case, 150 Mha (~10% of global cropland) [25] is treated at 10 t/ha/yr [26]. This is broadly consistent with conventional rates of ag-lime application, given ERW application has demonstrated strong fertilizer co-benefits, enabling replacement of ag-lime practices. Since approximately 4 tons of basaltic rock are needed to remove 1 ton of CO_2 [27, 28], this equates to 0.4 Gt CDR/yr net CDR (after LCA adjustments). This corresponds to 1.5 Gt rock material per year, which is equal to roughly 3% of global mine waste [27, 28, 29, 30].

In the upper-bound sensitivity, the treated area expands to 500 Mha (~30% of global cropland) with an application rate of 15 t/ha/yr [26]—still within the broad range of ag-lime practice—yielding 1.88 Gt CDR/yr of removal. This implies 7.5 Gt of rock material moved, about 17% of global mine waste [27, 28, 29, 30]. Covering a larger fraction of cropland becomes unfeasible given accessibility constrictions and increasing distance from sources of rock.

Direct air capture and storage removes CO_2 directly from ambient air using chemical sorbents or solvents, which are regenerated using heat or electricity, after which the captured CO_2 is permanently stored in geological formations. DACS facilities are modular, require relatively little land, and are not constrained by biomass supply chains, meaning that energy availability is the primary scaling constraint. Unlike land-intensive approaches such as ARR, the main challenge for scaling DACS is securing sufficient low-carbon energy to ensure net-negative emissions.



Capturing one ton of CO_2 requires about 2 MWh of electricity (assuming electrified thermal energy) [31]. In the conservative scenario, global renewable electricity generation is projected to reach ~66,900 TWh/year by 2050 [1]. Allocating 15% of this supply to DAC yields ~10,035 TWh/year – about 5 times the current electricity generation of India - sufficient for 5.0 Gt CDR/yr of removals.

In an upper-bound scenario, technical potential estimates for G20 countries' solar and wind resources total ~1,390,247 TWh/year [32]. Allocating 15% of this potential corresponds to 208,537 TWh/year, enough for 104 Gt CDR/yr - a theoretical maximum that illustrates scalability if renewable capacity grows substantially, though real-world deployment would likely be constrained by infrastructure build-out and costs.

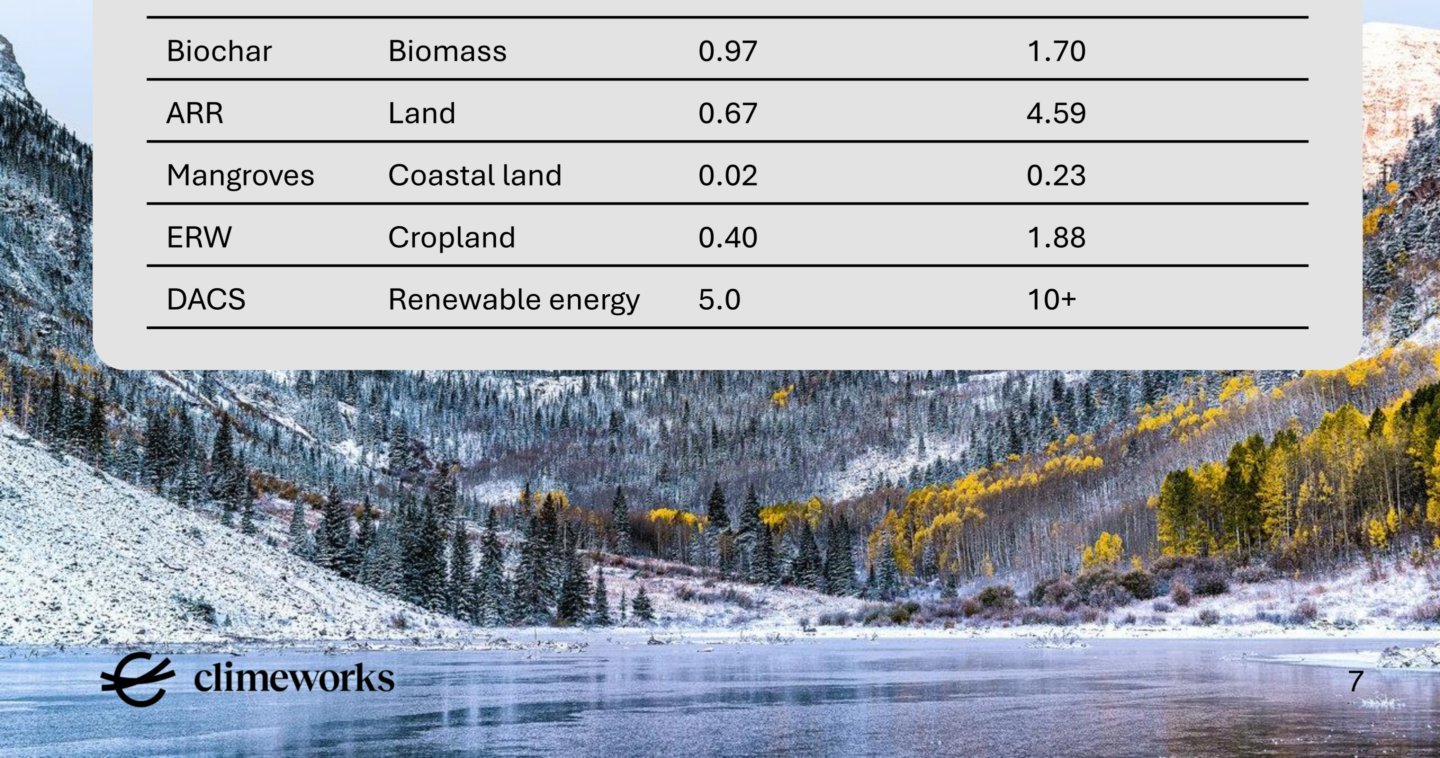
An optimal path forward

Across all pathways, conservative global limits sum to approximately 9 Gt CDR/yr net. This is at the lower end of the 6–16 Gt CDR/yr that most models indicate will be needed by 2050 to compensate for residual and historic emissions. The remaining gap to the upper estimate underscores two realities: first, land- and biomass-based removals alone cannot meet future demand; second, scaling engineered solutions like DACS is essential to close the shortfall.

Our global optimal portfolio analysis demonstrates how combining these approaches within resource constraints provides a realistic path to achieving 2050 CDR targets. By deploying nature-based solutions with higher technology readiness and availability today, immediate impact can be driven, while simultaneously scaling engineered solutions crucial to meeting long-term, gigaton scale demand.

2050 sustainable scaling limits of CDR pathways

Technology	Constraint	Conservative Case ($GtCO_2$/yr)	Upper Bound ($GtCO_2$/yr)
BECCS	Biomass	2.00	3.50
Biochar	Biomass	0.97	1.70
ARR	Land	0.67	4.59
Mangroves	Coastal land	0.02	0.23
ERW	Cropland	0.40	1.88
DACS	Renewable energy	5.0	10+



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