

1 The carbon dioxide removal gap

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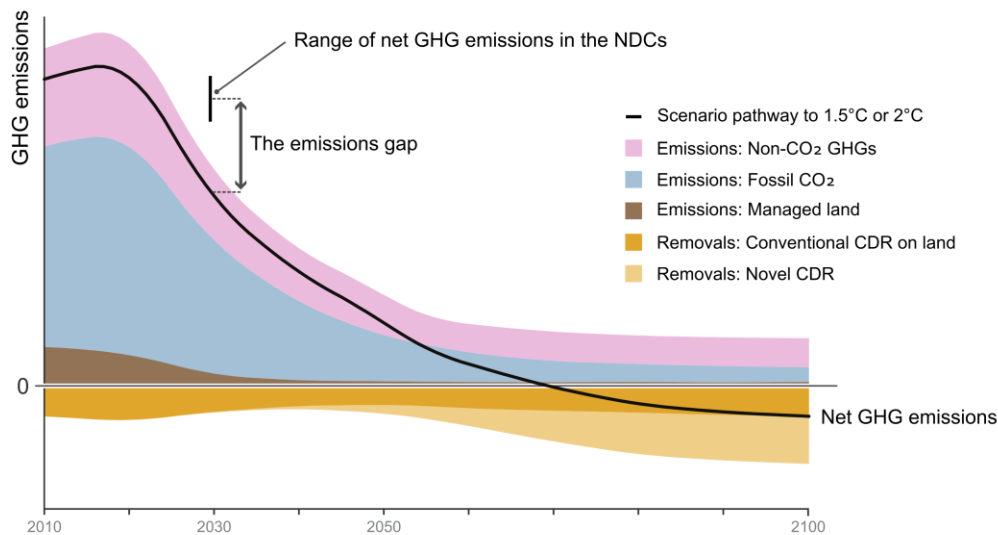
17 **Rapid emissions reductions, including reductions in deforestation-based land emissions, are**
18 **the dominant source of global climate mitigation potential in the coming decades. However,**
19 **carbon dioxide removal (CDR) will also have an important role to play. Despite this, it remains**
20 **unclear if current national proposals for CDR align with temperature targets. Here we show the**
21 **“CDR gap”, i.e. CDR efforts proposed by countries fall short of those in integrated assessment**
22 **model scenarios that limit warming to 1.5°C. However, the most ambitious proposals for CDR**
23 **are close to levels in a low energy demand scenario with the most limited CDR scaling and**
24 **aggressive near-term emissions reductions. Further, we observe that many countries propose**
25 **to expand land-based removals, but none yet commit to significantly scaling novel methods**
26 **such as bioenergy carbon capture and storage, biochar, or direct air carbon capture and**
27 **storage.**

28 CDR can support climate mitigation in three ways ^{1,2}. First, in the short-term, it can reduce net
29 emissions. While many CDR methods are costly and technologically immature, afforestation and land-
30 based removals already make a contribution today. Second, in the mid-term, CDR can
31 counterbalance residual emissions in “hard-to-abate” sectors, allowing countries to reach their stated
32 net-zero CO₂ or greenhouse gas (GHG) emissions objectives. And third, in the long-term, CDR could
33 be used to reach net-negative emissions. This could compensate for historical emissions and allow
34 global temperature exceedance to be reversed (but it wouldn't, however, avoid the impacts
35 associated with an overshoot of 1.5°C, such as biodiversity loss and sea level rise) ³.

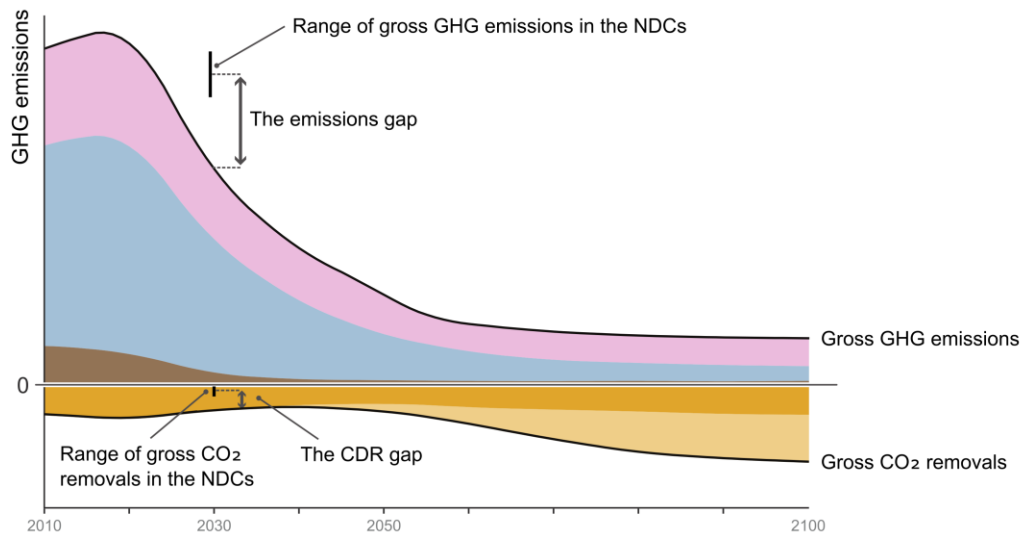
36 Yet despite the apparent importance of CDR, there are few dedicated efforts to track real-world
37 deployments, commitments, policies or related developments in the sector ^{2,4}. By contrast, tracking is
38 widely available for emissions reductions ⁵⁻⁷. In particular, none have evaluated the removal
39 component of the “emissions gap”: a science-policy device for assessing progress towards the Paris

1 Agreement temperature goal, published each year in the Emissions Gap Report ⁷ and supported by
 2 an underlying evidence base ⁸⁻¹⁰. To date the emissions gap has been formulated in terms of net
 3 GHG emissions, with no distinction has been made between gross emissions and removals (Figure
 4 1). This simplifies the assessment to a single aggregated gap and recognises certain empirical
 5 realities: most countries do not distinguish emissions and removals in their targets, and IAM reporting
 6 has tended to combine emissions and removals on managed land as a single net indicator. However,
 7 there are a number of compelling reasons why CDR should be distinguished in the gap analysis.

(a) An assessment of the emissions gap combining emissions and removals



(b) An assessment of the emissions gap separating emissions and removals



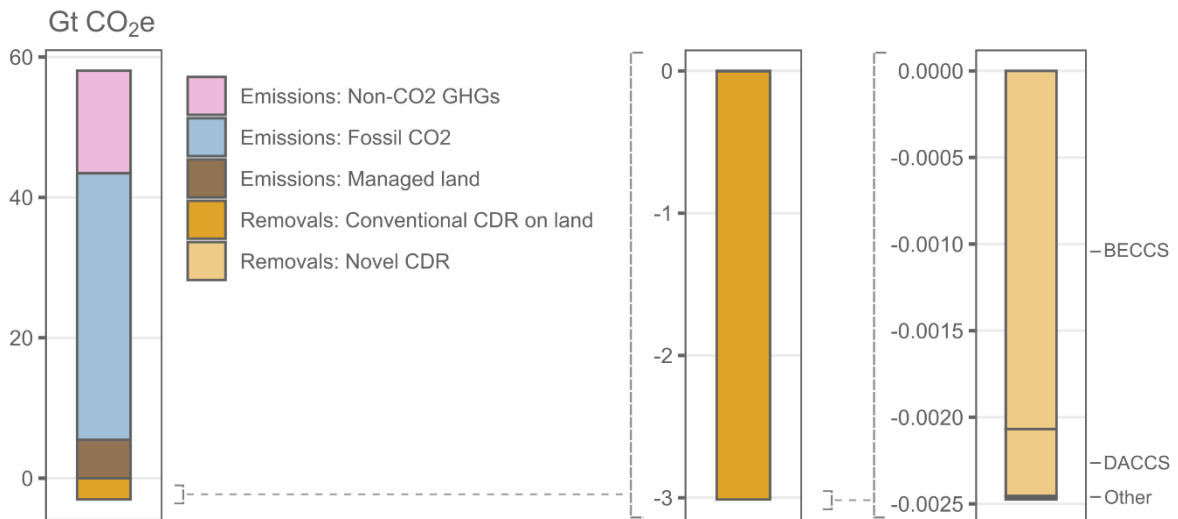
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9 **Figure 1: Combined versus separate assessments of the emissions and CDR gap.** Both panels show a
 10 stylised scenario pathway that reach net zero CO₂ and GHG emissions. Typically the gap would be assessed
 11 against a scenario range and median level, rather than a single scenario.

12 In the first instance, this is a simple transparency issue. As many countries have pledged net-zero
 13 targets, an assessment of their implied emissions and removals will provide a better understanding of
 14 how countries want to achieve these goals ¹¹. In turn, this opens a space for critical reflection on the
 15 fairness and ambition of proposed reductions, levels of residual emissions, and potential

1 overdependence on CDR ^{12–16}. A second reason is that emissions and removals are fundamentally
 2 different categories, involving different technologies, implementation options and risks, with varying
 3 policy and governance requirements including critical issues such as permanence and land use ¹⁷.
 4 Finally, while CDR makes a trivial contribution to climate change mitigation today (Figure 2),
 5 according to scenarios it could become the dominant response in the second half of the 21st century
 6 ². In some countries with large existing land-based removals it could become the dominant response
 7 much sooner.

Global total greenhouse gas emissions and removals



8

9 **Figure 2: Current global CDR versus emissions.** Updated from Powis et al. ¹⁹ (see methods) with additional
 10 emissions data from Crippa et al. ⁶⁷, using global warming potentials with a 100 year time horizon from the IPCC
 11 6th Assessment Report ⁶⁸. Emissions data for 2019 are plotted, while LULUCF removals are the 2011-2020
 12 annual average, and novel CDR removals are an estimate for 2020.

13 In this article we provide a conceptualisation and quantification of the “CDR gap”: the gap between
 14 levels of CDR that are proposed by governments, and levels of CDR in integrated assessment model
 15 (IAM) scenarios that limit warming to 1.5°C. Importantly, our evaluation introduces further normativity
 16 into the assessment of global mitigation pledges by making a judgment regarding the appropriate
 17 division of effort between emissions reductions and removals. Concretely, this judgment manifests in
 18 the scenarios we choose as a point of comparison to national proposals, including the specific
 19 amounts and types of CDR they implement, as well as their rates of emissions reductions. But rather
 20 than obscure this choice by comparing against broad scenario ranges, we instead select individual
 21 scenarios and aim to discuss and justify our particular choices, further opening the discourse on *how*
 22 *much CDR is needed* to meet the Paris Agreement.

23 To estimate the CDR gap, we first organise our analysis around two categories of CDR that differ in
 24 terms of scale, technology readiness and permanence: *conventional CDR on land* and *novel CDR*.
 25 The former consists of methods conventionally defined as removals in the land use, land-use change
 26 and forestry (LULUCF) sector (e.g. afforestation, restoration). Novel CDR comprises all other CDR
 27 methods, such as biochar, direct air carbon capture and storage (DACCS) or bioenergy carbon
 28 capture and storage (BECCS). (In the methods section we further explain our definitions, including the
 29 notable exclusion of removals driven by indirect anthropogenic effects). Whereas conventional CDR
 30 on land methods are already widely adopted and integrated into national climate pledges, novel CDR
 31 methods remain at an early stage of adoption and policy integration ². Studies are now beginning to
 32 report total current CDR deployments following these definitions ^{18,19}, which we estimate as
 33 approximately 3 GtCO₂/yr, of which 99.9% is from conventional CDR on land (Figure 2) ¹⁹.

1 To estimate proposed levels of CDR upscaling by countries, we draw from documents submitted to
2 the UNFCCC: the NDCs and the long-term strategies (also known as the long-term low emissions
3 development strategies). These give insight into levels of CDR in 2030 and 2050, compared to
4 historical inventory-based reporting. There are currently no strict requirements for reporting CDR in
5 either of these documents, so a number of assumptions must be made to extract this information
6 where it is implicit in national targets (see methods).

7 To benchmark levels of CDR proposed by countries, we use the compilation of IAM scenarios vetted
8 by the IPCC 6th Assessment (AR6) Working Group III Report ^{1,20}. While novel CDR such as BECCS is
9 reported in the AR6 scenario database, conventional CDR on land is only inconsistently reported as
10 afforestation and instead tends to be combined with emissions as a net LULUCF flux. We therefore
11 use a novel re-analysis of the IPCC database using the OSCAR model that extracts the removal
12 component of the LULUCF flux in each scenario corresponding to our definition of conventional CDR
13 on land (see methods) ²¹.

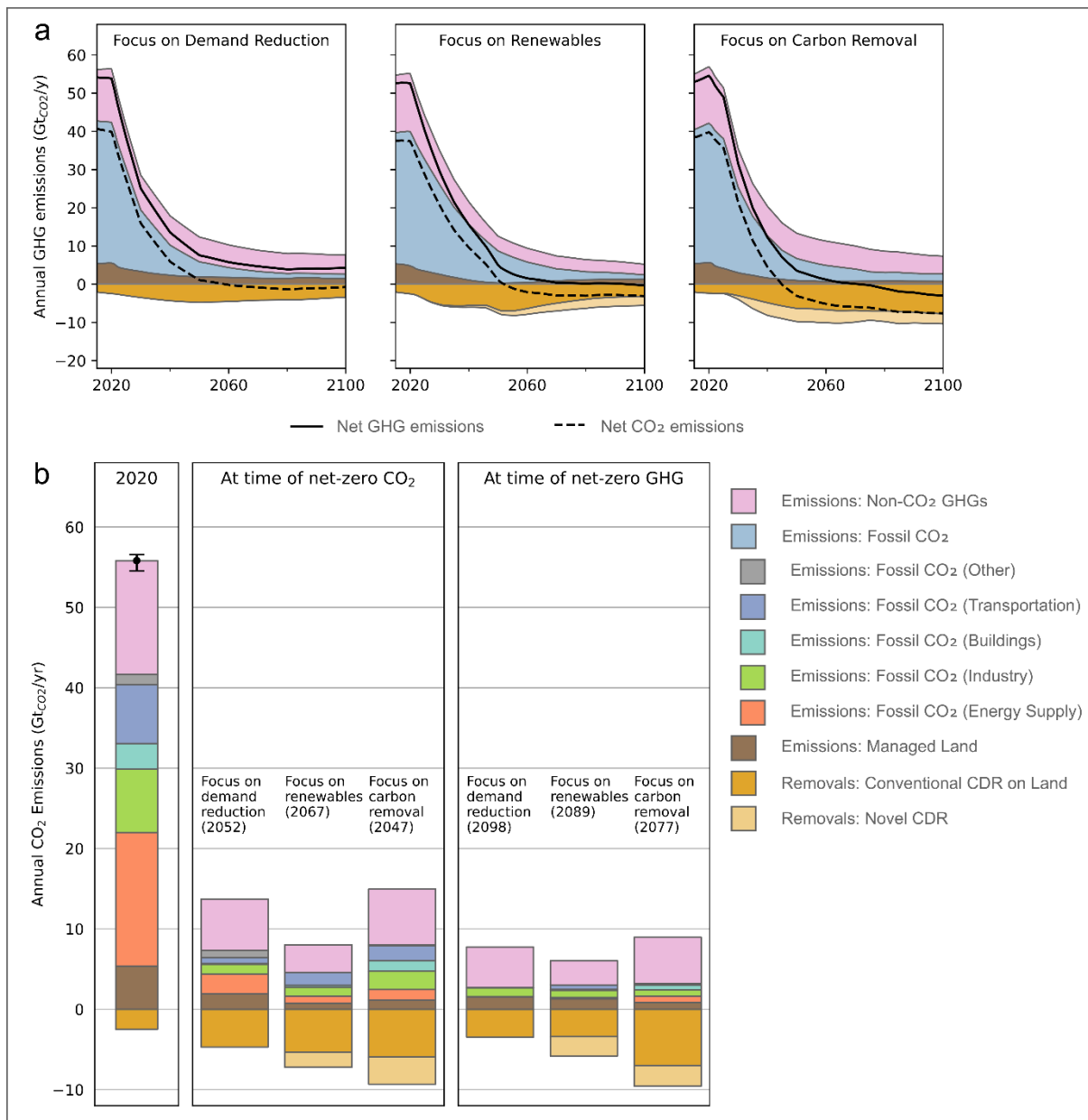
14 *CDR in national mitigation pledges*

15 Our NDC assessment finds that countries' conventional CDR on land will change from -3.0 GtCO₂/yr
16 for the period 2011-2020, i.e. the removals reported in GHG inventories once the indirect effects are
17 factored out in this study (see methods), to approximately -3.1 GtCO₂/yr (unconditional pledges) or
18 about -3.5 GtCO₂/yr (conditional pledges) in 2030. While some countries include novel CDR in their
19 qualitative description of mitigation efforts towards the 2030 pledges, and a few provide initial
20 quantifications (e.g. Korea, Canada, Norway), these are currently not possible to distinguish from
21 avoided emissions (e.g. fossil-based CCS). We therefore estimate zero commitments towards novel
22 CDR by 2030, with no change from current levels of approximately 2 MtCO₂/yr.

23 In the case of the long-term strategies, there is a general acknowledgement that CDR is needed to
24 realise national net zero targets ²². Indeed, most countries include at least a qualitative description of
25 how this type of mitigation effort would be achieved. However, only 40 countries have outlined
26 scenarios in their long-term strategies that depict quantifiable levels of CDR by 2050 (28 if EU
27 countries are combined as one). If we assume that all other countries sustain their current levels of
28 removals, proposed CDR as reflected in the long-term strategies range between -4.6 and -5.0
29 GtCO₂/yr in 2050, the majority of which is conventional CDR on land (85% and 81%, respectively).

30 *CDR in mitigation scenarios*

31 In scenarios that limit warming to below 2°C (see methods for scenario definitions), gross emissions
32 reductions are the dominant mitigation response in the coming three decades. Between 2020 and
33 2050, emissions are reduced by 62 [46-75] %. Subsequently, CDR becomes the main mitigation
34 strategy in the second half of the 21st century, with scenarios cumulating 670 [450-1100] GtCO₂ of
35 removals by 2100. Novel CDR tends to continuously scale up in scenarios throughout the 21st
36 century and accounts for over half of cumulative removals by 2100. By contrast, conventional CDR on
37 land starts from a high baseline but quickly reaches saturation by the mid-century due to land area
38 constraints for afforestation/restoration.



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Figure 3: The three focus scenarios. Panel a depicts the emissions and removals pathways of each scenario in the 21st century. Panel b depicts the residual gross GHG emissions and removals of each scenario at the point of net-zero CO₂ and net-zero GHG emissions. The error bar in panel b depicts the median and interquartile range (sample size: 189) of gross emissions and removals in scenarios, sourced from Byers et al.²⁰ and Gidden et al.²¹.

Reasons why scenarios deploy more CDR	Reasons why scenarios deploy less CDR
<ul style="list-style-type: none"> • Emissions reductions are delayed ^{23,24} • A wider portfolio of CDR methods are available, lowering their costs relative to deep emissions reductions ²⁵⁻²⁷ • The portfolio of mitigation technologies that can lower residual emissions at the point of net-zero CO₂ is more limited (such as CCS for industrial processes) ²⁸ • A more stringent temperature target is applied, lowering the available carbon budget ²⁸ • The scenario is permitted to initially exceed a warming level and compensate for this with net negative emissions later in the century ²⁵ • A temperature target is chosen that has already been exceeded, such as 1°C ²⁹ • For scenarios which use a full-century carbon budget rather than a peak budget ³⁰, values assumed for economic discount rates can push mitigation further into the future ³¹ 	<ul style="list-style-type: none"> • Emissions reductions are faster and implemented without delay ^{23,24} • A wider portfolio of (demand-side) mitigation options are available, with lower costs relative to CDR ^{32,33} • A wider portfolio of mitigation technologies that can lower residual emissions at the point of net-zero CO₂ is available (such as CCS for industrial processes) ²⁸ • A less stringent temperature target is applied, increasing the available carbon budget ²⁸ • Assumptions differ strongly about different limitations to CDR deployment, including both technological progress ³⁴ as well as social and environmental sustainability ³⁵⁻³⁸. Scenarios may limit the speed or total quantity of deployment based on some or all of these considerations.

1 **Table 1: Reasons why CDR deployments vary in scenarios**

2 Scenarios vary considerably in their levels and types of CDR deployment, depending on how policy
3 choices, technology availability, and socio-economic developments shape the speed and depth of
4 gross emissions reductions (Table 1). We therefore highlight three “focus scenarios” that depict
5 different emission reduction and CDR pathways to hold warming below 1.5°C:

- 6 • **Focus on Demand Reduction** - a scenario that reduces global energy demand through
7 efficiency and sufficiency measures, with a low long-term dependency on CDR ³². Annual
8 removals in 2050 are -4.8 GtCO₂, entirely from conventional CDR on land.
- 9 • **Focus on Renewables** - a scenario that rapidly implements a supply-side transformation
10 towards renewable energy ³⁶. Annual removals in 2050 are -7.6 GtCO₂, including a small
11 contribution from novel CDR (-0.91 GtCO₂).
- 12 • **Focus on Carbon Removal** - a scenario with rapid near-term emissions reductions but a
13 subsequent incomplete phase out of fossil fuels, leading to higher residual emissions at net
14 zero CO₂. Annual removals in 2050 are -9.8 GtCO₂, with a large contribution from novel CDR
15 (-3.5 GtCO₂).

16 The first two of these focus scenarios feature CDR levels at the lower end of the range in below 2°C
17 scenarios (see methods), while the latter sits just above the median (see Table 2). Scenarios at the
18 upper end of the below 2°C range (95th percentile) feature CDR deployments of -14 GtCO₂/yr in 2050
19 - levels that likely encounter feasibility constraints in terms of scale-up and bioenergy resource

1 availability³⁵. As all three scenarios hold warming below 1.5°C with no or limited overshoot, they
2 mainly differ in CDR upscaling due to the speed of their near-term reductions and the quantity and
3 type of residual emissions that they need to compensate to reach net zero CO₂ (Figure 3;
4 Supplementary Table 1). We include 2°C (e.g. C3) pathways in the overall scenario range (Figure 4,
5 Table 2), but do not select them as focus scenarios, which would highlight both lower CDR
6 requirements and lower gross emissions reductions, but also higher climate impacts.

7 *The CDR gap*

8 Across both categories of removals, a CDR gap already emerges by 2030 (Table 2). Compared to
9 2011-2020, the conditional NDCs would expand CDR by -0.5 GtCO₂/yr in 2030. This contrasts to an
10 increase of -1 GtCO₂/yr in 2030 in the Focus on Demand Reduction scenario, which has the lowest
11 CDR requirements. The CDR gap in 2050 is then strongly determined by the chosen scenario
12 benchmark. Compared to 2020, additional CDR in 2050 implied by the upper estimate of the long-
13 term mitigation strategies (from 28 countries including the EU, assuming all others sustain current
14 removals) would sum to -1.9 GtCO₂/yr. This approaches levels in the Focus on Demand Reduction
15 scenario (an additional -2.3 GtCO₂/yr), but falls short by multiple gigatons compared to the other focus
16 scenarios. The most ambitious of current CDR plans are therefore close to a conservative level of
17 CDR scaling, albeit one that would need to be coupled with deep, near-term emissions reductions.

18 *The gap in conventional CDR on land*

19 Neither the NDCs in 2030 nor the long-term strategies in 2050 propose levels of conventional CDR on
20 land sufficient to meet those projected in scenarios (Table 2; Figure 4). However, our analysis only
21 captures countries with quantifiable scenarios, which represent about 38% of current conventional
22 CDR on land removals. These countries plan to increase removals by -0.8 to -1.0 GtCO₂/yr, when
23 adjusting the long-term strategies to remove “indirect anthropogenic effects” (see methods). By
24 contrast, the focus scenarios increase conventional CDR on land by an additional -2.3 GtCO₂/yr
25 (Focus on Demand Reduction) to -4.1 GtCO₂/yr (Focus on Renewables).

26 Our analysis assumes that all other countries without quantifiable scenarios - accounting for 62% of
27 current conventional CDR on land – are able to sustain their existing removals. This includes China,
28 India and DR Congo, which all have significant forest conservation and restoration potentials³⁹ and
29 could be instrumental in closing the gap in conventional CDR on land.

30 *The gap in novel CDR*

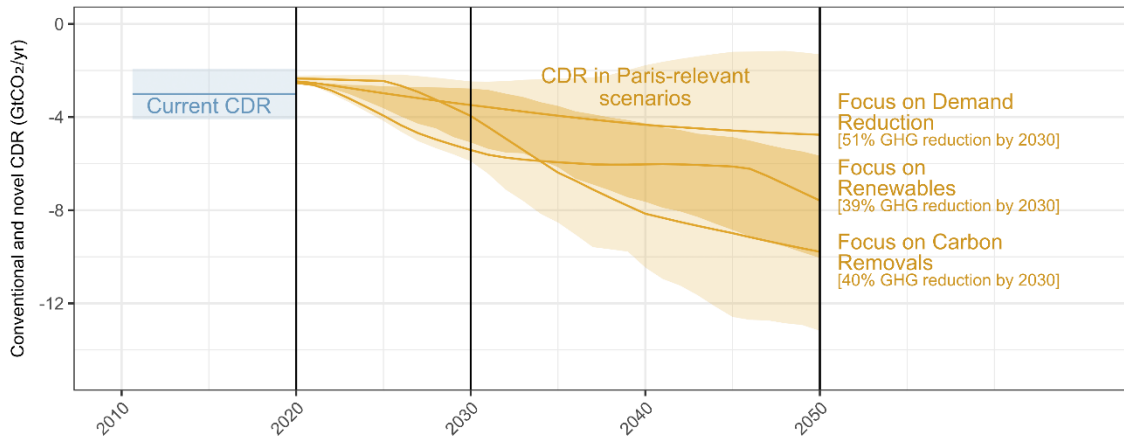
31 No country transparently includes novel CDR as a distinct portion of their pledged mitigation efforts by
32 2030. By contrast, below 2°C scenarios already implement -0.06 GtCO₂/yr of additional novel CDR by
33 2030.

34 Looking forward to 2050, many countries mention novel CDR in their long-term strategies, and some
35 quantify it in their illustrative national scenarios. At the upper estimate, approximately -0.96 GtCO₂/yr
36 of additional novel CDR can be inferred from these scenarios, largely driven by the US (-0.5
37 GtCO₂/yr), Canada (-0.23 GtCO₂/yr) and the EU (-0.08). This compares to the -0.91 GtCO₂/yr of
38 (global) additional novel CDR in the Focus on Renewables scenario and the -3.5 GtCO₂/yr in the
39 Focus on Carbon Removals scenario. There is no gap in novel CDR compared to the Focus on
40 Demand Reduction scenario, which avoids scaling up novel CDR entirely (but does, however,
41 significantly scale up conventional CDR on land).

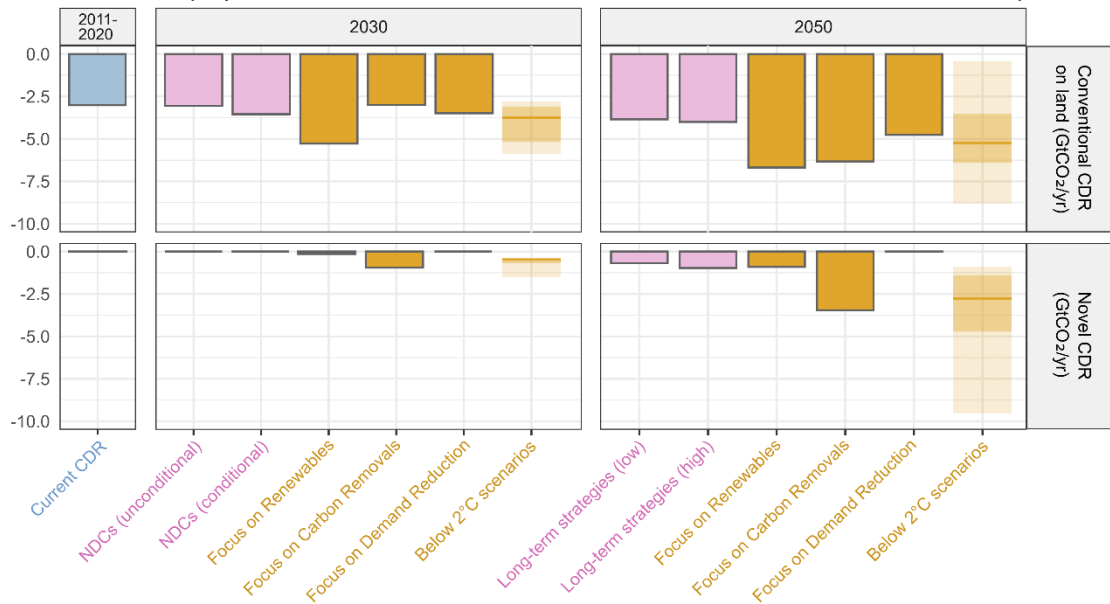
42 Our analysis assumes that countries without quantifiable scenarios do not currently plan to implement
43 novel CDR. This includes China, Norway and Saudi Arabia, which are all developing technology
44 roadmaps towards novel CDR and could contribute to closing the gap.

45

The extent of future carbon dioxide removal depends on the scenario by which climate goals are met



Current and proposed levels of carbon dioxide removal are insufficient to meet the Paris temperature goal



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2 **Figure 4: The carbon dioxide removal gap.** Upper panel: current levels of CDR and levels in Paris-relevant
 3 scenarios up to 2050. The orange shaded areas depict the 5th-95th and 25th-75th percentiles of IPCC C1 and
 4 C3 scenarios that limit warming to below 2°C. The orange lines depict three Focus Pathways that limit warming to
 5 1.5°C, alongside the gross greenhouse gas emissions reductions required by 2030 for each. Lower panel: levels
 6 of current, proposed and scenario-based CDR, split by conventional CDR on land and novel CDR in 2020, 2030
 7 and 2050. Pink bars depict proposed CDR levels in the Nationally Determined Contributions (NDCs) and the
 8 long-term mitigation strategies. Orange bars depict CDR levels in the three focus scenarios, as well as the overall
 9 scenario medians and ranges (5th-95th and 25th-75th percentiles).

1

	Additional total CDR from 2020 (GtCO ₂ /yr)		Additional conventional CDR on land from 2020 (GtCO ₂ /yr)		Additional novel CDR from 2020 (GtCO ₂ /yr)		Gross GHG emissions reductions from 2020 (%)	
	2030	2050	2030	2050	2030	2050	2030	2050
Below 2°C scenarios	-1.1 [0.01 to -3.4]	-4.5 [0.92 to -11]	-0.85 [0.014 to -3]	-2.3 [2.5 to -6]	-0.06 [0 to -1.1]	-2.4 [-0.5 to -9.1]	25 [4.2 - 50]	62 [46 - 75]
Focus on Demand Reduction	-1	-2.3	-1	-2.3	0	0	51	78
Focus on Renewables	-2.9	-5.1	-2.7	-4.1	-0.14	-0.91	39	80
Focus on Carbon Removal	-1.6	-7.4	-0.66	-4.0	-0.95	-3.5	40	77
Nationally Determined Contributions (NDCs)*	[-0.05 to -0.53]	NA	[-0.05 to -0.53]	NA	0	NA	NA	NA
Long-term mitigation strategies	NA	[-1.5 to -1.9]**	NA	[-0.8 to -1.0]**	NA	[0.7-0.96]*	NA	NA

2 **Table 2: Scaling of CDR to 2030 and 2050 in scenarios, NDCs and long-term strategies (GtCO₂/yr).** Below 2°C scenarios refer to categories C1 and
3 C3 in the AR6 scenario database. For these categories the median and 5-95th percentiles are reported. In the lower range of some scenarios
4 conventional CDR on land decreases compared to 2020, which gives rise to negative numbers. The analysis of the NDCs (*) was complemented by other
5 official reports containing information on the country's mitigation targets (e.g National Communications, Biannual Updated Reports, REDD+ documents,
6 national mitigation strategies). The additional CDR in the long term mitigation strategies (*) assumes that countries without a quantifiable strategy
7 preserve their current levels of conventional CDR on land. 111 NDCs (i.e excluding small island states, city states and countries with no land use fluxes)
8 and all long-term strategies up to Nov 2023 (COP28) were considered for the analysis.

1 *Discussion*

2 Our initial quantification of the CDR gap highlights that countries also lack progress in this domain
3 of climate mitigation. While some are planning to scale CDR to meet the temperature goal of the
4 Paris Agreement, together they fall short by hundreds of megatons in 2030, and by hundreds of
5 megatons to multiple gigatons in 2050, depending on the benchmarked scenario. The importance
6 of planning for CDR at scale in 2050 is therefore not currently reflected at the policy level, even
7 under assumptions of rapid and sustained emissions reductions in the short term. However, three
8 important caveats should be noted in this analysis.

9 First, although most countries have committed to net zero targets, they still provide little
10 information on what role CDR will play in reaching them. Within the NDCs, ambiguities and a lack
11 of transparency lead to wide ranging assessments of not only the land use flux and implied
12 removals, but also overall emissions levels^{40,41}. These problems are even more apparent with
13 the long-term strategies, which lack any common reporting structure and where underlying
14 scenarios are illustrative rather than formal commitments¹³. As of COP28, only 68 countries (42
15 when excluding EU countries) have actually submitted a long-term strategy. Further, not all
16 pledges have an associated climate law in their home jurisdictions¹⁰.

17 Nevertheless, the NDCs and long-term strategies are among the few reference points available
18 for evaluating national CDR proposals, and they are the only documents that can be feasibly
19 analysed and aggregated for a global assessment. It is therefore critical that future iterations of
20 these documents contain the required transparency for evaluating national targets on the basis of
21 both gross emissions and removals.

22 Second, IAMs have a prominent role in shaping climate mitigation policy advice and have been
23 subject to a number of criticisms. Discussions have focused on whether sustainable levels of
24 bioenergy use are exceeded in scenarios, whether CDR tends to substitute for short-term
25 emissions reductions, and if the full scope of low demand, low CDR, or 'degrowth' scenarios has
26 yet been explored^{25,42-44}. In addition, IAMs have mainly modelled afforestation, BECCS and
27 DACCS, while other methods have been scarcely explored²⁵. By drawing from scenario
28 evidence, this CDR gap assessment is similarly exposed to such criticisms.

29 In this assessment we take a pragmatic approach, and recognise that IAM scenarios provide the
30 best current evidence available to benchmark country proposals for CDR. We also select specific
31 focus scenarios to increase the transparency in a set of possible CDR futures and their
32 underlying determinants, but orient our selection to scenarios at the lower end of CDR
33 requirements. Other selections are possible - and can be made using the supplementary data file
34 to this article. Alternative approaches for benchmarking CDR levels should also be explored, for
35 instance by assessing the residual emissions associated with bottom-up energy and material
36 requirements for meeting human needs⁴⁵. One area of needed improvement is to separate gross
37 LULUCF emissions and removals in scenario reporting - information that we have sourced here
38 from a re-analysis of the AR6 scenario database²¹.

39 Finally, a recurring concern in the literature is that including CDR in mitigation discussions may
40 deter near-term emissions reductions⁴⁶. States, corporations or other interest groups seeking an
41 excuse for doing very little may exploit the fact that CDR can compensate for emissions,
42 overplaying the quantity of removals that may be achieved at some (later) point in time. Indeed, a
43 variety of claims and discursive strategies beyond CDR are used to excuse or delay climate
44 action, which may help political actors resolve the tension between powerful incumbent fossil
45 interests and increasing domestic or international calls for climate action⁴⁷⁻⁴⁹. Given the
46 commercial stakes at play, scientists therefore face enormous challenges in facilitating a nuanced
47 dialogue on CDR.

1 The assessment we provide of the CDR gap contributes to this dialogue by asking “how much is
2 needed?” and “what are countries planning?”. We believe it is important to situate such questions
3 in the scientific literature and provide a space to critically reflect on them. However, we
4 acknowledge that this will not prevent interest groups from exploiting the integration of CDR in the
5 climate debate. We therefore plainly state: our assessment of CDR in no way underplays the
6 need for rapid, immediate and deep emissions reductions across all sectors, including a rapid
7 decrease in fossil fuel use and the halting of deforestation. Indeed, our analysis reinforces this
8 fact, as the longer such reductions are delayed, the higher future CDR requirements are, and the
9 wider the CDR gap becomes.

10 There are varying challenges to closing the CDR gap. While conventional CDR on land is already
11 well integrated into climate governance, experience has highlighted significant difficulties in
12 monitoring, reporting and verifying ⁵⁰⁻⁵². An over-dependence on land-based removals brings
13 risks for land availability, food production and ownership rights ¹². On the other hand, if designed
14 well they can be integrated with sustainable development and biodiversity objectives ⁵³.
15 Additionally, forest carbon is vulnerable to reversal and expectations that regional sinks can be
16 preserved in the coming decades have been challenged, highlighting the importance of policies
17 that promote sustainable management, prevent illegal removals, and limit the impact of natural
18 disturbances ⁵⁴⁻⁵⁶.

19 Regarding novel CDR, there is little existing capacity and rates of potential scale-up are very
20 high, both in the long-term strategies (up to 0.95 GtCO₂/yr, or 470 times current levels) and in
21 below 2°C scenarios (up to 2.4 GtCO₂/yr, or 1200 times current levels, but with some scenarios at
22 or near 0). Although technology adoption and scale-up rates have been impressive in a number
23 of analogous historical cases ⁵⁷, novel CDR methods like BECCS may face significant headwinds
24 due to high capital costs, a dependency on state-support, and other factors. In our view, near-
25 term policies to support these methods in their formative phase are urgently needed, without
26 which it is difficult to conceive of any gigaton-scale contribution from novel CDR in 2050 and
27 beyond. In addition, regulatory action that robustly defines, monitors, reports and verifies novel
28 CDR is lagging. Importantly, enhanced emissions reductions are needed to reduce our
29 dependence on dramatically scaling up these nascent CDR technologies.

30 To what extent is the CDR gap due to inadequate proposals by countries, versus a failure to
31 specify them in the first place? Our analysis of the long-term strategies covers 28 countries
32 (including the EU), summing to 38% of current removals. Due to this limitation we assume that all
33 other countries are able to sustain their current conventional CDR on land. This is a generous
34 assumption, given how difficult it will be to sustain such removals amid mounting climate impacts
35 ⁵⁴⁻⁵⁶. On the other hand, we may underestimate proposals for novel CDR where national policy
36 making is in its infancy (even though countries would have little incentive to develop concrete
37 plans but exclude these from their communicated targets). Given these uncertainties, it remains
38 important to continuously track new developments and update estimates of the CDR gap as
39 national policies and targets are refined.

40 CDR entails many challenges for designing policy, supporting innovation, and ensuring
41 sustainable, equitable and durable removals. Our analysis shows that scenarios meeting the
42 Paris temperature goal imply a very rapid scale up of CDR, and that governments are not
43 planning for this. A twofold strategy that limits our dependence on CDR through rapid and deep
44 emissions reductions, but aggressively supports and scales CDR implementation is not a
45 contradiction, but a necessary pathway towards successful climate policy.

1 **Methods**

2 Following the IPCC and State of CDR reports, we define CDR as “Human activities capturing CO₂
3 from the atmosphere and storing it durably in geological, land or ocean reservoirs, or in products.
4 This includes human enhancement of natural removal processes, but excludes natural uptake not
5 caused directly by human activities.”^{1,2} Important characteristics of this definition are its
6 unambiguous inclusion of both conventional land-based sinks and emerging CDR methods, as
7 well as requirements for durability and direct human intervention¹⁹.

8 A wide array of CDR technologies have been developed, tested or are in practice today⁵⁸. In this
9 article we follow Smith et al.² and categorise afforestation, reforestation, forest management, soil
10 carbon sequestration, wetland restoration, and durable harvested wood products as *conventional*
11 *CDR on land*. *Novel CDR* comprises all other CDR methods, such as biochar as well as those
12 that store carbon in the lithosphere including direct air carbon capture and storage (DACCS),
13 bioenergy carbon capture and storage (BECCS), and enhanced weathering.

14 *Direct versus indirect anthropogenic CDR*

15 Whereas novel CDR methods are solely the result of direct human intervention, land can remove
16 CO₂ from the atmosphere through a combination of direct anthropogenic effects (such as land
17 use change, forest harvest and regrowth), indirect anthropogenic effects (such as fertilisation
18 because of elevated atmospheric CO₂) and natural effects (such as climate variability). These
19 effects are impossible to disentangle through observations, but can be partitioned using earth
20 system models⁵⁹. The different treatment of indirect anthropogenic effects and of managed land
21 concepts are the main reasons for the major discrepancy between national inventories and global
22 bookkeeping models used in the IPCC assessment reports^{60,61}.

23 In order to keep consistency with the IPCC definition of CDR, we consider CDR on land as only
24 the net direct human-induced removal component occurring in managed areas of forests and
25 soils. (Note: deforestation is human-induced but is categorised as emissions, not CDR, and is
26 therefore excluded). Defining CDR in this way orients policy makers towards addressing those
27 activities under their direct control (e.g. forest and soil management practices) and avoids claims
28 on CDR that result from global factors outside their direct control (e.g. the CO₂-fertilisation effect).

29 To evaluate current conventional CDR on land on this basis, we start from the latest compilation
30 of national LULUCF inventories⁵¹, considering all negative fluxes from forest land and other land
31 uses as removals. A global ratio of direct to indirect anthropogenic removals derived from Powis
32 et al.¹⁹ is then applied to the forest land fluxes to remove the indirect component. The resulting
33 global and national levels of current conventional CDR on land are then taken as the baseline for
34 any changes observed in the NDCs and long-term strategies (described below). Where these
35 documents describe an increase in conventional CDR on land compared to the baseline
36 inventory, we consider this increase as representing direct removals only. Where a decrease is
37 described in the long-term strategies, we preserve the current ratio of direct to indirect removals.
38 The final analysis considers direct anthropogenic removals only, as shown in Supplementary
39 Figure 2.

40 *CDR in national 2030 mitigation pledges*

41 A number of assumptions need to be taken to extract CDR levels from NDCs. First, with the aim
42 of identifying quantifiable conventional CDR on land, and considering the frequent lack of
43 LULUCF information in the NDCs, we gathered as much official information as possible up to a
44 cut-off date of Nov 2023 (i.e. COP28). This included not only NDCs, which we prioritize, but also
45 other relevant national submissions to the UNFCCC where mitigation targets and information on
46 activities and flux disaggregation are usually included, such as long-term mid-century strategies

1 (e.g. USA, Chile), National Communications (e.g. China, Japan, New Zealand), Biennial Update
2 Reports (e.g. Peru), and Forest Reference Emission Levels (e.g. Malaysia, Peru, Mexico).
3 Whenever available, we also considered other national documents, such as climate strategies
4 (e.g. Norway, Chile, Thailand, Philippines, Mexico, Peru), GHG projections (e.g. Brazil) or
5 assessments of national targets (e.g. India). We prioritised documents by ranking countries
6 according to their contribution to global emissions and removals, using the PRIMAP Hist-CR
7 database⁶² and Grassi et al.⁵¹. We searched for this information in 111 of 195 countries
8 reporting under the UNFCCC framework, excluding small island states, city states and countries
9 with no or very low land use fluxes.

10 Second, we followed different strategies to extract information from these documents and
11 estimate the specific contribution of LULUCF removals to national pledges, depending on the
12 level of transparency and information available for each country. As summarised in
13 Supplementary Figure 1, countries can be categorised into three groups:

- 14 • Group A: countries with the least amount of information regarding their headline mitigation
15 target and the contribution of LULUCF. For these countries, we assume that removals in
16 2030 remain consistent with the historic trend (2011-2020). (n=25, historic inventory-based
17 gross removals (2011-2020)=-0.375 GtCO₂/yr, no additional CDR for 2030)
- 18 • Group B1: countries with a specified LULUCF target in 2030, but no information regarding the
19 contribution of removals. We scale the LULUCF target to the historic ratio of emissions and
20 removals (2011-2020). (n=55, historic inventory-based gross removals = -3.45 GtCO₂/yr,
21 additional conditional CDR for 2030= -0.22 GtCO₂/yr)
- 22 • Group B2: countries with a specified LULUCF target in 2030, and with information on the
23 specific contribution of removals. We directly report these removals in our analysis. (n=31,
24 historic inventory-based gross removals (2011-2020) =-3.87 GtCO₂/yr, additional conditional
25 CDR for 2030 = -0.33 GtCO₂/yr).

26 It is relevant to note that the national extra removals (i.e. CDR) are here presented as the
27 difference between committed removals in 2030 (un/conditional) and countries' average removals
28 for the previous decade (2011-2020). This approach offers high temporal coherence between
29 countries' emissions and mitigation commitments in 2030.

30 Historical averages of removals are based on an update (July 2023) of Grassi et al's compiled
31 database of national GHG Inventories obtained from UNFCCC submissions⁵¹. Emissions are
32 calculated as the sum of all positive GHG fluxes detailed in Grassi et al (i.e., forest, deforestation,
33 organic soils and other), while removals are the sum of all negative fluxes. Most emissions come
34 from deforestation and organic soils, while most removals come from forests. The category 'other'
35 is either a removal or an emission, depending on the country as it includes other non-forest land
36 uses (croplands, grasslands, wetlands, settlements). Since not all countries contribute similarly to
37 global mitigation targets, below we provide more insights for several key countries, with additional
38 examples in the supplementary Information Section 1.

39 Brazil: There are several possible scenarios for Brazil's LULUCF commitments in 2030, but none
40 of them are described in their latest NDC (2022). One scenario is presented in the Low Carbon
41 Agriculture Programme (ABC and ABC+), but their targets are considered obsolete (year 2014).
42 We therefore use Brazil's national mitigation projections and mitigation options for 2030 and 2050
43 published by the Ministry of Science and Technology in 2017⁶³. This official report includes land
44 use net emissions for BAU (2030) (298 MtCO₂e) and two commitment scenarios based on two
45 difference prices for mitigation investment (270 and 189 MtCO₂e as unconditional and conditional
46 LULUCF emissions in 2030). Historical removals (2011-2020) are about -400 MtCO₂/y, while the
47 extra removals (i.e., CDR) under conditional commitments that we estimated in 2030 are about -
48 45 MtCO₂/y. Brazil is a Category B1 country (numerical LULUCF target with unspecified
49 removals).

1 Indonesia: Its 2022 NDC submission is highly informative on LULUCF quantitative targets (-500
2 and -729 MtCO₂e (unconditional and conditional committed emissions) and projected BAU (714
3 MtCO₂e). The NDC also describes a list of mitigation activities disaggregated between emission
4 avoidance and removals, to support their claims. Historical removals (2011-2020) are about -370
5 MtCO₂/y, while the extra removals (i.e., CDR) under conditional commitments we estimated in
6 2030 are about -165 MtCO₂/y. Indonesia is a Category B2 country (numerical LULUCF target
7 with specified removals).

8 China: The latest NDC includes the target to 'increase forest stock volume by around 6 billion
9 cubic metres in 2030 from the 2005 level', which is not easily translated into a CO₂ sink value.
10 However, LULUCF targets are better covered in the Third Biennial Update Report 3 (2018),
11 where forest sink projections are specified for 2030 as BAU (2030) -410 MtCO₂e (range: 390-430
12 MtCO₂e), and two forest sink targets are presented under two scenarios of action that preserve
13 the same commitment for forests sinks (-495 MtCO₂e) (range:470-520 MtCO₂e). To allow the
14 comparison of the target with the LULUCF historical trend, forest sink targets are then
15 complemented by the average sink of other non-forest land uses for the period 2011-2020,
16 raising the committed sink to -806 MtCO₂e/y for 2030. Due to China's current large sink of about
17 -1135 MtCO₂e (average 2011-2020), their LULUCF targets for 2030 translate into a weakening of
18 removals, i.e. an increase in net emissions (ca. 326 MtCO₂/y), which significantly reduce the
19 global LULUCF sink commitments. China is Category B2 country (numerical LULUCF target with
20 specified removals).

21 *CDR in national 2050 mitigation pledges*

22 To calculate CDR in national 2050 mitigation pledges, we rely upon information in the long-term
23 strategies as analysed in Smith et al. ^{13,64}, reading all submissions up to Nov 2023 (i.e. COP28).
24 We identify the subset of these that have quantified scenarios describing how they will reach their
25 stated climate objective (e.g. net zero GHG emissions). Often these scenarios are depicted in a
26 figure or a table, where the contribution of novel or conventional CDR on land is included as a
27 portion of the mitigation effort. If the long-term strategy does not include such quantitative
28 material, we assume that any current removals (i.e. from conventional CDR on land) are
29 sustained until 2050. As in the NDCs, most countries describe the total LULUCF flux in their
30 scenarios, rather than providing a breakdown of emissions and removals in this sector. We count
31 the entirety of these fluxes in 2050 as removals. In other words, we assume zero deforestation.
32 This assumption is consistent with the text and framing of the long-term strategies. For example,
33 no countries describe deforestation in their scenarios, and a number of them - such as Cambodia
34 and Colombia - explicitly pledge zero deforestation. However, we acknowledge that it is a
35 simplification.

36 In the case of the European Union, we discard all member state documents and instead rely upon
37 modelling studies performed by the European Commission describing EU-wide pathways to net-
38 zero by the mid-century ⁶⁵. While these were published prior to the United Kingdom formally
39 leaving the European Union, we continue to include the UK long-term strategy separately.

40 *Scenario selection and re-analysis*

41 Our selection of IAM scenarios draws from the latest IPCC 6th Assessment Report (AR6) vetted
42 scenario database ²⁰. We use the C1 and C3 scenario categories, which are together referred to
43 as "below 2°C scenarios" in the main manuscript. These scenarios can be considered those most
44 relevant to, but not necessarily all consistent with, the Paris Agreement temperature goal.

45 We use the scenario re-analysis provided by Gidden et al. ²¹ that splits emissions and removals in
46 the land use sector. Their analysis is conducted by running the OSCAR bookkeeping model using
47 variables reported in the AR6 scenario database - including forest land area, cropland area and

- 1 forestry activity - to evaluate the direct anthropogenic removals on managed land. These scenario
- 2 projections follow and extend the experimental setup used for the 2021 Global Carbon Budget ⁶⁶.
- 3

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8 **Data availability**

9 The data for this article is available at <https://doi.org/10.5281/zenodo.10821849>. All raw and
10 processed data is freely accessible, with the exception of complete national-level CDR estimates
11 in 2030 (i.e. from the NDCs and other national documents) which will be made available upon
12 reasonable request.

13 **Code availability**

14 The code for this article is available at <https://doi.org/10.5281/zenodo.10821849>.

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22 **Author contributions**

23 W.F.L., G.N., S.M.S., O.G., K.R. and J.C.M conceived the idea for the paper. W.F.L., T.G.,
24 R.M.RC, G.G., M.G., C.M.P., Y.P., J.S., N.E.V. and H.S. contributed to data gathering and the
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26 paper.

27 **Competing interests**

28 The authors declare no competing interests