# The carbon dioxide removal gap

*William F. Lamb[1,2,*], Thomas Gasser[3], Rosa M. Roman-Cuesta[4], Giacomo Grassi[4], Matthew J. Gidden[3], Carter M. Powis[5], Oliver Geden[6], Gregory Nemet[7], Yoga Pratama[3], Keywan Riahi[3], Stephen M Smith[5], Jan Steinhauser[3], Naomi E. Vaughan[8,9], Harry Smith[8,9], Jan C. Minx[1,2]*

*[1] Mercator Research Institute on Global Commons and Climate Change (MCC)*

*[2] Priestley International Centre for Climate, University of Leeds*

*[3] International Institute for Applied Systems Analysis (IIASA)*

*[4] Joint Research Centre, European Commission*

*[5] School of Enterprise and the Environment, University of Oxford*

*[6] German Institute for International and Security Affairs (SWP)*

*[7] University of Wisconsin-Madison*

*[8] School of Environmental Sciences, University of East Anglia, Norwich NR4 7TJ, UK*

*[9] Tyndall Centre for Climate Change Research, University of East Anglia, Norwich NR4 7TJ, UK*

*Corresponding author (lamb@mcc-berlin.net)

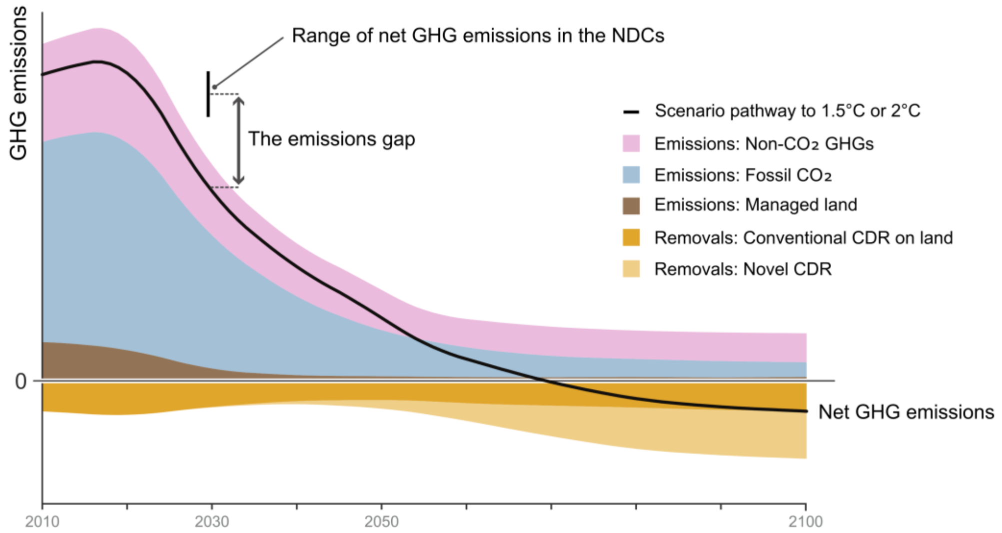
**Rapid emissions reductions, including reductions in deforestation-based land emissions, are the dominant source of global climate mitigation potential in the coming decades. However, carbon dioxide removal (CDR) will also have an important role to play. Despite this, it remains unclear if current national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

CDR can support climate mitigation in three ways [1,2]. First, in the short-term, it can reduce net emissions. While many CDR methods are costly and technologically immature, afforestation and land-based removals already make a contribution today. Second, in the mid-term, CDR can counterbalance residual emissions in "hard-to-abate" sectors, allowing countries to reach their stated net-zero $CO_2$ or greenhouse gas (GHG) emissions objectives. And third, in the long-term, CDR could be used to reach net-negative emissions. This could compensate for historical emissions and allow global temperature exceedance to be reversed (but it wouldn't, however, avoid the impacts associated with an overshoot of 1.5°C, such as biodiversity loss and sea level rise) [3].

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

Agreement temperature goal, published each year in the Emissions Gap Report [7] and supported by an underlying evidence base [8–10]. To date the emissions gap has been formulated in terms of net GHG emissions, with no distinction has been made between gross emissions and removals (Figure 1). This simplifies the assessment to a single aggregated gap and recognises certain empirical realities: most countries do not distinguish emissions and removals in their targets, and IAM reporting has tended to combine emissions and removals on managed land as a single net indicator. However, 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**

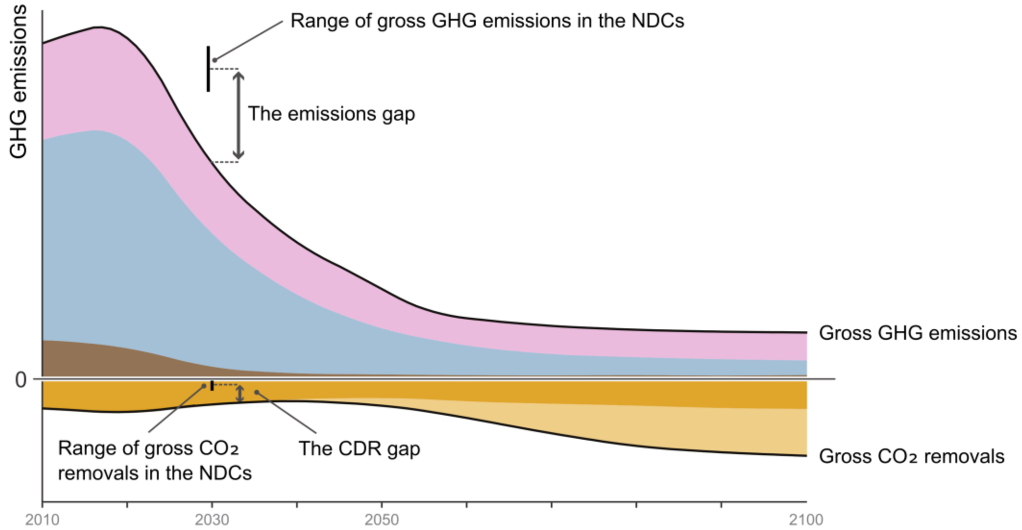


**Figure 1: Combined versus separate assessments of the emissions and CDR gap.** Both panels show a stylised scenario pathway that reach net zero $CO_2$ and GHG emissions. Typically the gap would be assessed against a scenario range and median level, rather than a single scenario.

In the first instance, this is a simple transparency issue. As many countries have pledged net-zero targets, an assessment of their implied emissions and removals will provide a better understanding of how countries want to achieve these goals [11]. In turn, this opens a space for critical reflection on the fairness and ambition of proposed reductions, levels of residual emissions, and potential overdependence on CDR [12–16]. A second reason is that emissions and removals are fundamentally different categories, involving different technologies, implementation options and risks, with varying policy and governance requirements including critical issues such as permanence and land use [17]. Finally, while CDR makes a trivial contribution to climate change mitigation today (Figure 2), according to scenarios it could become the dominant response in the second half of the 21st century [2]. In some countries with large existing land-based removals it could become the dominant response much sooner.

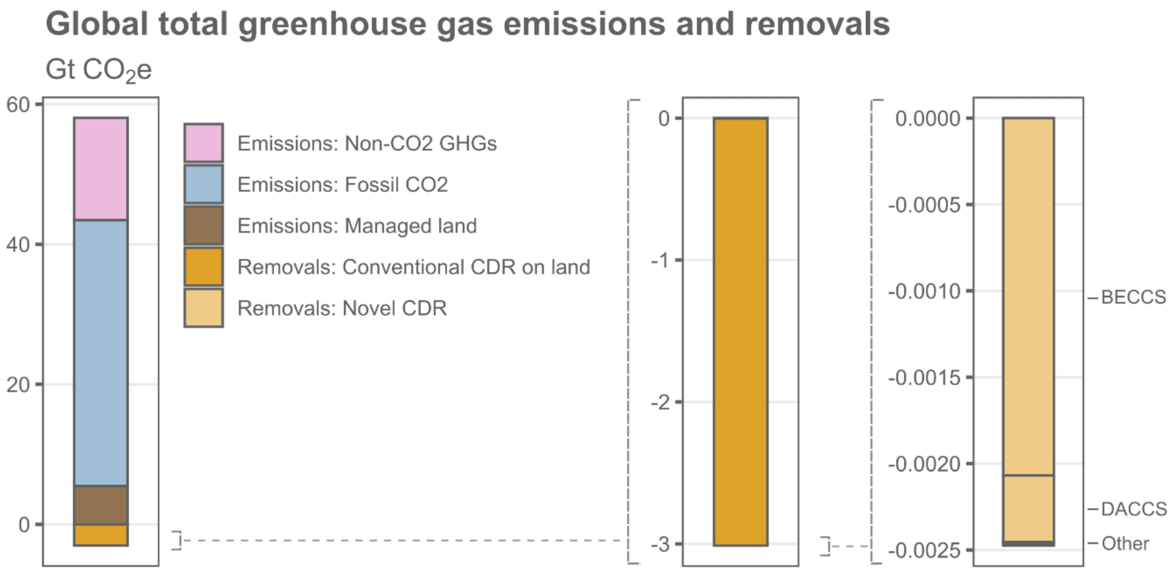


**Figure 2: Current global CDR versus emissions.** Updated from Powis et al. [19] (see methods) with additional emissions data from Crippa et al. [67], using global warming potentials with a 100 year time horizon from the IPCC 6th Assessment Report [68]. Emissions data for 2019 are plotted, while LULUCF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

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

To estimate the CDR gap, we first organise our analysis around two categories of CDR that differ in terms of scale, technology readiness and permanence: *conventional CDR on land* and *novel CDR*. The former consists of methods conventionally defined as removals in the land use, land-use change and forestry (LULUCF) sector (e.g. afforestation, restoration). Novel CDR comprises all other CDR methods, such as biochar, direct air carbon capture and storage (DACCS) or bioenergy carbon capture and storage (BECCS). (In the methods section we further explain our definitions, including the notable exclusion of removals driven by indirect anthropogenic effects). Whereas conventional CDR on land methods are already widely adopted and integrated into national climate pledges, novel CDR methods remain at an early stage of adoption and policy integration [2]. Studies are now beginning to report total current CDR deployments following these definitions [18,19], which we estimate as approximately 3 $GtCO_2$/yr, of which 99.9% is from conventional CDR on land (Figure 2) [19].

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

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

### *CDR in national mitigation pledges*

Our NDC assessment finds that countries' conventional CDR on land will change from -3.0 $GtCO_2$/yr for the period 2011-2020, i.e. the removals reported in GHG inventories once the indirect effects are factored out in this study (see methods), to approximately -3.1 $GtCO_2$/yr (unconditional pledges) or about -3.5 $GtCO_2$/yr (conditional pledges) in 2030. While some countries include novel CDR in their qualitative description of mitigation efforts towards the 2030 pledges, and a few provide initial quantifications (e.g. Korea, Canada, Norway), these are currently not possible to distinguish from avoided emissions (e.g. fossil-based CCS). We therefore estimate zero commitments towards novel CDR by 2030, with no change from current levels of approximately 2 $MtCO_2$/yr.

In the case of the long-term strategies, there is a general acknowledgement that CDR is needed to realise national net zero targets [22]. Indeed, most countries include at least a qualitative description of how this type of mitigation effort would be achieved. However, only 40 countries have outlined scenarios in their long-term strategies that depict quantifiable levels of CDR by 2050 (28 if EU countries are combined as one). If we assume that all other countries sustain their current levels of removals, proposed CDR as reflected in the long-term strategies range between -4.6 and -5.0 $GtCO_2$/yr in 2050, the majority of which is conventional CDR on land (85% and 81%, respectively).

### *CDR in mitigation scenarios*

In scenarios that limit warming to below 2°C (see methods for scenario definitions), gross emissions reductions are the dominant mitigation response in the coming three decades. Between 2020 and 2050, emissions are reduced by 62 [46-75] %. Subsequently, CDR becomes the main mitigation strategy in the second half of the 21st century, with scenarios cumulating 670 [450-1100] $GtCO_2$ of removals by 2100. Novel CDR tends to continuously scale up in scenarios throughout the 21st century and accounts for over half of cumulative removals by 2100. By contrast, conventional CDR on land starts from a high baseline but quickly reaches saturation by the mid-century due to land area constraints for afforestation/restoration.

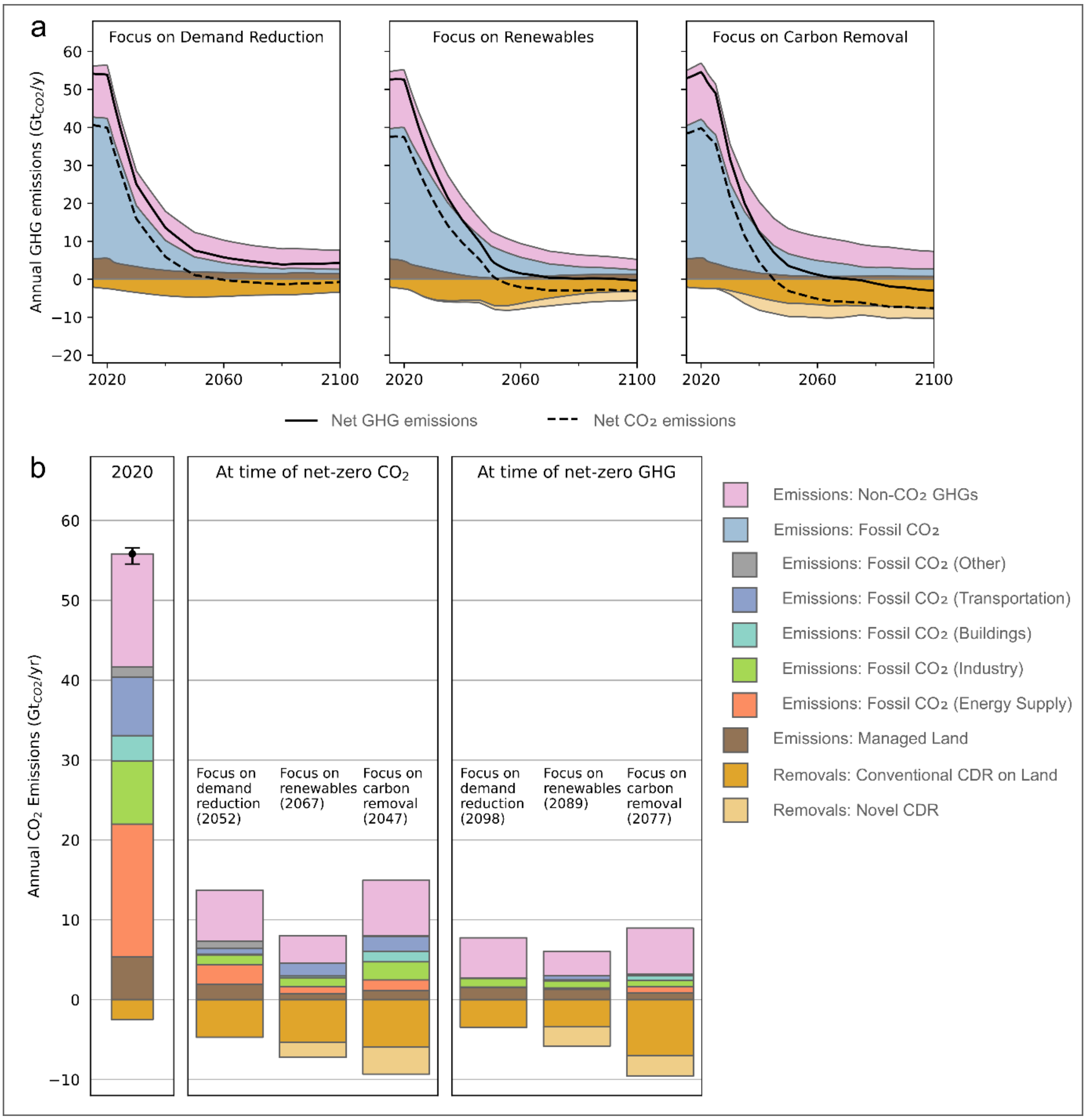


**Figure 3: The three focus scenarios.** Panel a depicts the emissions and removals pathways of each scenario in the 21st century. Panel b depicts the residual gross GHG emissions and removals of each scenario at the point of net-zero $CO_2$ and net-zero GHG emissions. The error bar in panel b depicts 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 |
|---|---|
| ● Emissions reductions are delayed [23,24] | ● Emissions reductions are faster and implemented without delay [23,24] |
| ● A wider portfolio of CDR methods are available, lowering their costs relative to deep emissions reductions [25–27] | ● A wider portfolio of (demand-side) mitigation options are available, with lower costs relative to CDR [32,33] |
| ● The portfolio of mitigation technologies that can lower residual emissions at the point of net-zero $CO_2$ is more limited (such as CCS for industrial processes) [28] | ● A wider portfolio of mitigation technologies that can lower residual emissions at the point of net-zero $CO_2$ is available (such as CCS for industrial processes) [28] |
| ● A more stringent temperature target is applied, lowering the available carbon budget [28] | ● A less stringent temperature target is applied, increasing 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]<br>● A temperature target is chosen that has already been exceeded, such as 1°C [29]<br>● 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] | ● 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. |

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

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

- **Focus on Demand Reduction** - a scenario that reduces global energy demand through efficiency and sufficiency measures, with a low long-term dependency on CDR [32]. Annual removals in 2050 are -4.8 $GtCO_2$, entirely from conventional CDR on land.

- **Focus on Renewables** - a scenario that rapidly implements a supply-side transformation towards renewable energy [36]. Annual removals in 2050 are -7.6 $GtCO_2$, including a small contribution from novel CDR (-0.91 $GtCO_2$).

- **Focus on Carbon Removal** - a scenario with rapid near-term emissions reductions but a subsequent incomplete phase out of fossil fuels, leading to higher residual emissions at net zero $CO_2$. Annual removals in 2050 are -9.8 $GtCO_2$, with a large contribution from novel CDR (-3.5 $GtCO_2$).

The first two of these focus scenarios feature CDR levels at the lower end of the range in below 2°C scenarios (see methods), while the latter sits just above the median (see Table 2). Scenarios at the upper end of the below 2°C range (95th percentile) feature CDR deployments of -14 $GtCO_2$/yr in 2050 - levels that likely encounter feasibility constraints in terms of scale-up and bioenergy resource availability [35]. As all three scenarios hold warming below 1.5°C with no or limited overshoot, they mainly differ in CDR upscaling due to the speed of their near-term reductions and the quantity and type of residual emissions that they need to compensate to reach net zero $CO_2$ (Figure 3; Supplementary Table 1). We include 2°C (e.g. C3) pathways in the overall scenario range (Figure 4, Table 2), but do not select them as focus scenarios, which would highlight both lower CDR requirements and lower gross emissions reductions, but also higher climate impacts.

### *The CDR gap*

Across both categories of removals, a CDR gap already emerges by 2030 (Table 2). Compared to 2011-2020, the conditional NDCs would expand CDR by -0.5 $GtCO_2$/yr in 2030. This contrasts to an increase of -1 $GtCO_2$/yr in 2030 in the Focus on Demand Reduction scenario, which has the lowest CDR requirements. The CDR gap in 2050 is then strongly determined by the chosen scenario benchmark. Compared to 2020, additional CDR in 2050 implied by the upper estimate of the long-term mitigation strategies (from 28 countries including the EU, assuming all others sustain current removals) would sum to -1.9 $GtCO_2$/yr. This approaches levels in the Focus on Demand Reduction scenario (an additional -2.3 $GtCO_2$/yr), but falls short by multiple gigatons compared to the other focus scenarios. The most ambitious of current CDR plans are therefore close to a conservative level of CDR scaling, albeit one that would need to be coupled with deep, near-term emissions reductions.

### *The gap in conventional CDR on land*

Neither the NDCs in 2030 nor the long-term strategies in 2050 propose levels of conventional CDR on land sufficient to meet those projected in scenarios (Table 2; Figure 4). However, our analysis only captures countries with quantifiable scenarios, which represent about 38% of current conventional CDR on land removals. These countries plan to increase removals by -0.8 to -1.0 $GtCO_2$/yr, when adjusting the long-term strategies to remove “indirect anthropogenic effects” (see methods). By contrast, the focus scenarios increase conventional CDR on land by an additional -2.3 $GtCO_2$/yr (Focus on Demand Reduction) to -4.1 $GtCO_2$/yr (Focus on Renewables).

Our analysis assumes that all other countries without quantifiable scenarios - accounting for 62% of current conventional CDR on land – are able to sustain their existing removals. This includes China, India and DR Congo, which all have significant forest conservation and restoration potentials [39] and could be instrumental in closing the gap in conventional CDR on land.

### *The gap in novel CDR*

No country transparently includes novel CDR as a distinct portion of their pledged mitigation efforts by 2030. By contrast, below 2°C scenarios already implement -0.06 $GtCO_2$/yr of additional novel CDR by 2030.

Looking forward to 2050, many countries mention novel CDR in their long-term strategies, and some quantify it in their illustrative national scenarios. At the upper estimate, approximately -0.96 $GtCO_2$/yr of additional novel CDR can be inferred from these scenarios, largely driven by the US (-0.5 $GtCO_2$/yr), Canada (-0.23 $GtCO_2$/yr) and the EU (-0.08). This compares to the -0.91 $GtCO_2$/yr of (global) additional novel CDR in the Focus on Renewables scenario and the -3.5 $GtCO_2$/yr in the Focus on Carbon Removals scenario. There is no gap in novel CDR compared to the Focus on Demand Reduction scenario, which avoids scaling up novel CDR entirely (but does, however, significantly scale up conventional CDR on land).

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

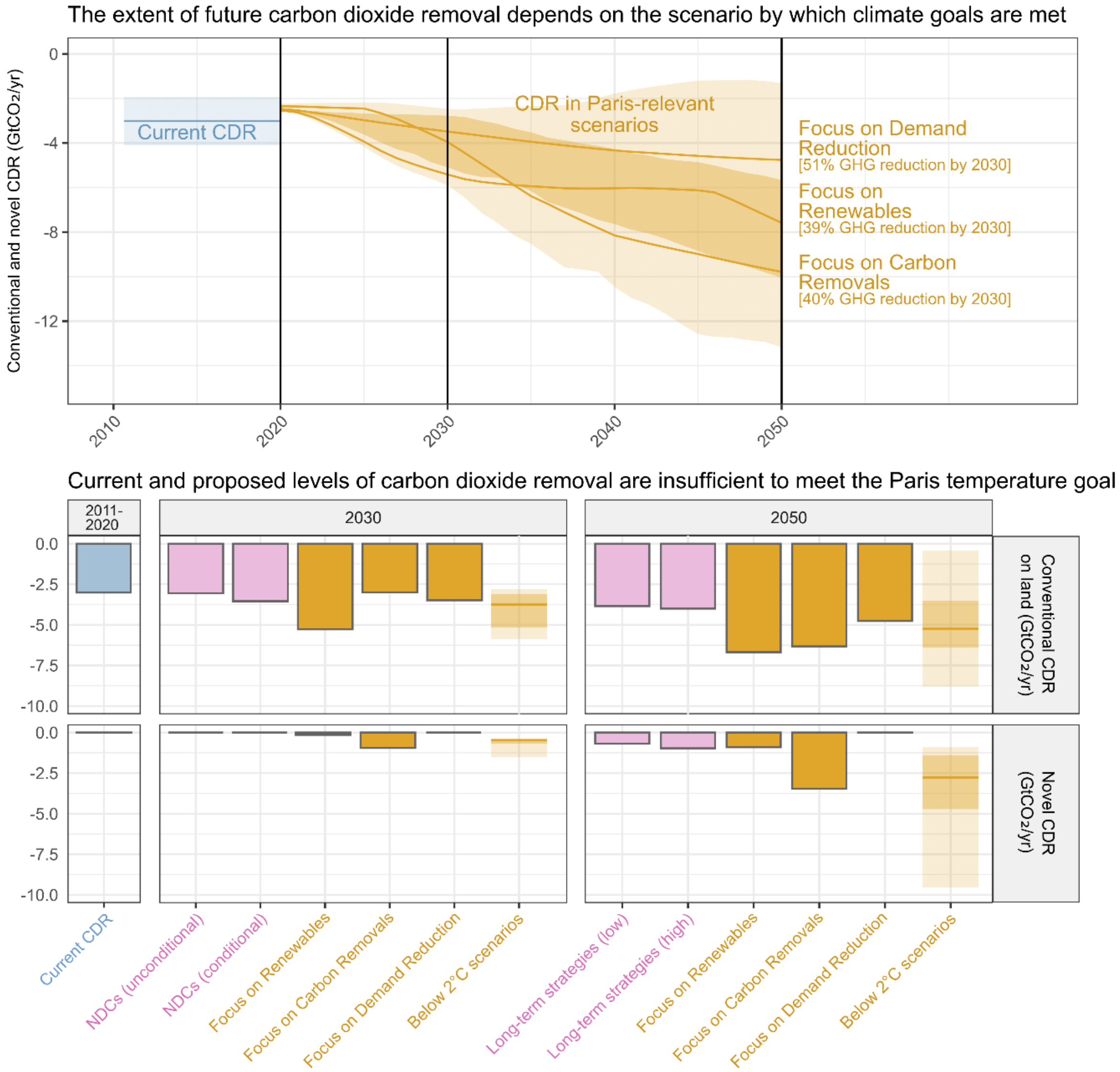


**Figure 4: The carbon dioxide removal gap.** Upper panel: current levels of CDR and levels in Paris-relevant scenarios up to 2050. The orange shaded areas depict the 5th-95th and 25th-75th percentiles of IPCC C1 and C3 scenarios that limit warming to below 2°C. The orange lines depict three Focus Pathways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

|  | 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<br>[0.01 to -3.4] | -4.5<br>[0.92 to -11] | -0.85<br>[0.014 to -3] | -2.3<br>[2.5 to -6] | -0.06<br>[0 to -1.1] | -2.4<br>[-0.5 to -9.1] | 25<br>[4.2 - 50] | 62<br>[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 |

**Table 2: Scaling of CDR to 2030 and 2050 in scenarios, NDCs and long-term strategies (GtCO$_2$/yr).** Below 2°C scenarios refer to categories C1 and C3 in the AR6 scenario database. For these categories the median and 5-95th percentiles are reported. In the lower range of some scenarios conventional CDR on land decreases compared to 2020, which gives rise to negative numbers. The analysis of the NDCs (*) was complemented by other official reports containing information on the country's mitigation targets (e.g National Communications, Biannual Updated Reports, REDD+ documents, national mitigation strategies). The additional CDR in the long term mitigation strategies (*) assumes that countries without a quantifiable strategy 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) and all long-term strategies up to Nov 2023 (COP28) were considered for the analysis.

### *Discussion*

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

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

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

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

In this assessment we take a pragmatic approach, and recognise that IAM scenarios provide the best current evidence available to benchmark country proposals for CDR. We also select specific focus scenarios to increase the transparency in a set of possible CDR futures and their underlying determinants, but orient our selection to scenarios at the lower end of CDR requirements. Other selections are possible - and can be made using the supplementary data file to this article. Alternative approaches for benchmarking CDR levels should also be explored, for instance by assessing the residual emissions associated with bottom-up energy and material requirements for meeting human needs [45]. One area of needed improvement is to separate gross LULUCF emissions and removals in scenario reporting - information that we have sourced here from a re-analysis of the AR6 scenario database [21].

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

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

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

Regarding novel CDR, there is little existing capacity and rates of potential scale-up are very high, both in the long-term strategies (up to 0.95 $GtCO_2$/yr, or 470 times current levels) and in below 2°C scenarios (up to 2.4 $GtCO_2$/yr, or 1200 times current levels, but with some scenarios at or near 0). Although technology adoption and scale-up rates have been impressive in a number of analogous historical cases [57], novel CDR methods like BECCS may face significant headwinds due to high capital costs, a dependency on state-support, and other factors. In our view, near-term policies to support these methods in their formative phase are urgently needed, without which it is difficult to conceive of any gigaton-scale contribution from novel CDR in 2050 and beyond. In addition, regulatory action that robustly defines, monitors, reports and verifies novel CDR is lagging. Importantly, enhanced emissions reductions are needed to reduce our dependence on dramatically scaling up these nascent CDR technologies.

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

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

## Methods

Following the IPCC and State of CDR reports, we define CDR as “Human activities capturing $CO_2$ from the atmosphere and storing it durably in geological, land or ocean reservoirs, or in products. This includes human enhancement of natural removal processes, but excludes natural uptake not caused directly by human activities.” [1,2]. Important characteristics of this definition are its unambiguous inclusion of both conventional land-based sinks and emerging CDR methods, as well as requirements for durability and direct human intervention [19].

A wide array of CDR technologies have been developed, tested or are in practice today [58]. In this article we follow Smith et al. [2] and categorise afforestation, reforestation, forest management, soil carbon sequestration, wetland restoration, and durable harvested wood products as *conventional CDR on land*. *Novel CDR* comprises all other CDR methods, such as biochar as well as those that store carbon in the lithosphere including direct air carbon capture and storage (DACCS), bioenergy carbon capture and storage (BECCS), and enhanced weathering.

### *Direct versus indirect anthropogenic CDR*

Whereas novel CDR methods are solely the result of direct human intervention, land can remove $CO_2$ from the atmosphere through a combination of direct anthropogenic effects (such as land use change, forest harvest and regrowth), indirect anthropogenic effects (such as fertilisation because of elevated atmospheric $CO_2$) and natural effects (such as climate variability). These effects are impossible to disentangle through observations, but can be partitioned using earth system models [59]. The different treatment of indirect anthropogenic effects and of managed land concepts are the main reasons for the major discrepancy between national inventories and global bookkeeping models used in the IPCC assessment reports [60,61].

In order to keep consistency with the IPCC definition of CDR, we consider CDR on land as only the net direct human-induced removal component occurring in managed areas of forests and soils. (Note: deforestation is human-induced but is categorised as emissions, not CDR, and is therefore excluded). Defining CDR in this way orients policy makers towards addressing those activities under their direct control (e.g. forest and soil management practices) and avoids claims on CDR that result from global factors outside their direct control (e.g. the $CO_2$-fertilisation effect).

To evaluate current conventional CDR on land on this basis, we start from the latest compilation of national LULUCF inventories [51], considering all negative fluxes from forest land and other land uses as removals. A global ratio of direct to indirect anthropogenic removals derived from Powis et al.[19] is then applied to the forest land fluxes to remove the indirect component. The resulting global and national levels of current conventional CDR on land are then taken as the baseline for any changes observed in the NDCs and long-term strategies (described below). Where these documents describe an increase in conventional CDR on land compared to the baseline inventory, we consider this increase as representing direct removals only. Where a decrease is described in the long-term strategies, we preserve the current ratio of direct to indirect removals. The final analysis considers direct anthropogenic removals only, as shown in Supplementary Figure 2.

### *CDR in national 2030 mitigation pledges*

A number of assumptions need to be taken to extract CDR levels from NDCs. First, with the aim of identifying quantifiable conventional CDR on land, and considering the frequent lack of LULUCF information in the NDCs, we gathered as much official information as possible up to a cut-off date of Nov 2023 (i.e. COP28). This included not only NDCs, which we prioritize, but also other relevant national submissions to the UNFCCC where mitigation targets and information on activities and flux disaggregation are usually included, such as long-term mid-century strategies (e.g. USA, Chile), National Communications (e.g. China, Japan, New Zealand), Biennial Update Reports (e.g. Peru), and Forest Reference Emission Levels (e.g. Malaysia, Peru, Mexico). Whenever available, we also considered other national documents, such as climate strategies (e.g. Norway, Chile, Thailand, Philippines, Mexico, Peru), GHG projections (e.g. Brazil) or assessments of national targets (e.g. India). We prioritised documents by ranking countries according to their contribution to global emissions and removals, using the PRIMAP Hist-CR database [62] and Grassi et al. [51]. We searched for this information in 111 of 195 countries reporting under the UNFCCC framework, excluding small island states, city states and countries with no or very low land use fluxes.

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

- Group A: countries with the least amount of information regarding their headline mitigation target and the contribution of LULUCF. For these countries, we assume that removals in 2030 remain consistent with the historic trend (2011-2020). (n=25, historic inventory-based gross removals (2011-2020)=-0.375 $GtCO_2$/yr, no additional CDR for 2030)
- Group B1: countries with a specified LULUCF target in 2030, but no information regarding the contribution of removals. We scale the LULUCF target to the historic ration of emissions and removals (2011-2020). (n=55, historic inventory-based gross removals = -3.45 $GtCO_2$/yr, additional conditional CDR for 2030= -0.22 $GtCO_2$/yr)
- Group B2: countries with a specified LULUCF target in 2030, and with information on the specific contribution of removals. We directly report these removals in our analysis. (n=31, historic inventory-based gross removals (2011-2020) =-3.87 $GtCO_2$/yr, additional conditional CDR for 2030 = -0.33 $GtCO_2$/yr).

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

Historical averages of removals are based on an update (July 2023) of Grassi et al's compiled database of national GHG Inventories obtained from UNFCCC submissions [51]. Emissions are calculated as the sum of all positive GHG fluxes detailed in Grassi et al (i.e., forest, deforestation, organic soils and other), while removals are the sum of all negative fluxes. Most emissions come from deforestation and organic soils, while most removals come from forests. The category 'other' is either a removal or an emission, depending on the country as it includes other non-forest land uses (croplands, grasslands, wetlands, settlements). Since not all countries contribute similarly to global mitigation targets, below we provide more insights for several key countries, with additional examples in the supplementary Information Section 1.

Brazil: There are several possible scenarios for Brazil's LULUCF commitments in 2030, but none of them are described in their latest NDC (2022). One scenario is presented in the Low Carbon Agriculture Programme (ABC and ABC+), but their targets are considered obsolete (year 2014). We therefore use Brazil's national mitigation projections and mitigation options for 2030 and 2050 published by the Ministry of Science and Technology in 2017 [63]. This official report includes land use net emissions for BAU (2030) (298 MtCO2e) and two commitment scenarios based on two difference prices for mitigation investment (270 and 189 MtCO2e as unconditional and conditional LULUCF emissions in 2030). Historical removals (2011-2020) are about -400 MtCO2/y, while the extra removals (i.e., CDR) under conditional commitments that we estimated in 2030 are about -45 MtCO2/y. Brazil is a Category B1 country (numerical LULUCF target with unspecified removals).

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

China: The latest NDC includes the target to ‘increase forest stock volume by around 6 billion cubic metres in 2030 from the 2005 level’, which is not easily translated into a $CO_2$ sink value. However, LULUCF targets are better covered in the Third Biennial Update Report 3 (2018), where forest sink projections are specified for 2030 as BAU (2030) -410 MtCO2e (range: 390-430 MtCO2e), and two forest sink targets are presented under two scenarios of action that preserve the same commitment for forests sinks (-495 MtCO2e) (range:470-520 MtCO2e). To allow the comparison of the target with the LULUCF historical trend, forest sink targets are then complemented by the average sink of other non-forest land uses for the period 2011-2020, raising the committed sink to -806 MtCO2e/y for 2030. Due to China’s current large sink of about -1135 MtCO2e (average 2011-2020), their LULUCF targets for 2030 translate into a weakening of removals, i.e. an increase in net emissions (ca. 326 MtCO2/y), which significantly reduce the global LULUCF sink commitments. China is Category B2 country (numerical LULUCF target with specified removals).

### *CDR in national 2050 mitigation pledges*

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

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

### *Scenario selection and re-analysis*

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

We use the scenario re-analysis provided by Gidden et al. [21] that splits emissions and removals in the land use sector. Their analysis is conducted by running the OSCAR bookkeeping model using variables reported in the AR6 scenario database - including forest land area, cropland area and forestry activity - to evaluate the direct anthropogenic removals on managed land. These scenario projections follow and extend the experimental setup used for the 2021 Global Carbon Budget [66].

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## Data availability

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

## Code availability

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

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## Author contributions

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., 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 analysis. W.F.L. wrote the paper. All authors contributed to drafting, reviewing and editing the paper.

## Competing interests

The authors declare no competing interests