The carbon dioxide removal gap

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Abstract

Rapid emissions reductions, including reductions in deforestation-based land emissions, are the dominant source of global mitigation potential in the coming decades [1]. But in addition, carbon dioxide removal (CDR) will have an important role to play. Here we benchmark proposed CDR in the Nationally Determined Contributions (NDCs) and the long-term mitigation strategies against levels in integrated assessment scenarios that meet the temperature goal of the Paris Agreement. Our analysis finds a “CDR gap”, i.e. levels proposed by countries fall short of those in virtually all scenarios that limit warming to 1.5°C - including in low energy demand scenarios 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.

Introduction

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, enabling countries to compensate for historical emissions or allowing for the reversal of global temperature overshoot [3].

Yet despite the apparent importance of CDR for achieving the Paris climate goals, 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 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 (IAM) scenarios that limit warming to 1.5°C or 2°C.

The CDR gap is closely related to the “emissions gap” concept, 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. In other words, 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.

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, overdependence on CDR, and the potential for net negative emissions [12–15]. 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. In addition, a lack of policy support today in many parts of the world may limit the long-term prospects for sustainably scaling up CDR methods, which for some, could take decades to reach technological maturity. 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.

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). 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]. A first estimate of total current CDR deployments following these definitions found removals of approximately 2 $GtCO_2$ per year, of which 99.9% is from conventional CDR on land (Figure 2) [16].

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, respectively. 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 [1,19]. 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) [20].

Results

CDR in national mitigation pledges

Our NDC assessment finds that countries plan to increase conventional CDR on land by 2030, from 2 $GtCO_2$ per year in 2020, to approximately 2.1 $GtCO_2$ per year in unconditional and about 2.6 $GtCO_2$ per year in conditional pledges. As it stands, no countries currently describe contributions from novel CDR methods, even if several include it in their qualitative description of mitigation efforts.

In the case of the long-term strategies, there is a general acknowledgement that CDR is needed to realise national net zero targets [21]. Indeed, most countries include at least a qualitative description of how this type of mitigation effort would be achieved. However, only 31 countries have outlined scenarios in their long-term strategies that depict quantifiable levels of CDR by 2050 (19 if EU countries are combined as one). Taking just these countries, projected removals across their scenarios range between 2.5 and 3.6 $GtCO_2$ in 2050, the majority of which is conventional CDR on land (78%-73%).

CDR in mitigation scenarios

In scenarios that limit warming to 1.5°C or 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 72 [61–79] % in 1.5°C scenarios and 59 [45–70] % in 2°C scenarios, Subsequently, CDR becomes the main mitigation strategy in the second half of the 21st century, with 1.5°C scenarios cumulating 770 [450–1200] $GtCO_2$ of removals by 2100 and 2°C scenarios cumulating 650 [460–1100] $GtCO_2$. Novel CDR tends to continuously scale up in scenarios throughout the 21st century and accounts for over half of 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/reforestation.

Table 1
Reasons why CDR deployments vary in scenarios

Reasons why scenarios deploy more CDR	Reasons why scenarios deploy less CDR
● Emissions reductions are delayed [22,23]	● Emissions reductions are faster and implemented without delay [22,23]
● A wider portfolio of CDR methods are available, lowering their costs relative to emissions reductions [24,25]	● A wider portfolio of (demand-side) mitigation options are available, with lower costs relative to CDR [28,29]
● 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) [26]	● 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) [26]
● A more stringent temperature target is applied, lowering the available carbon budget [26]	● A less stringent temperature target is applied, increasing the available carbon budget [26]
● The scenario is permitted to initially exceed a warming target and compensate for this with net negative emissions later in the century (*overshoot*) [24]	
● A temperature target is chosen that has already been overshot, such as 1°C [27]	

Scenarios vary considerably in their levels 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). While our analysis covers the whole range of Paris-relevant scenarios, we highlight three "focus scenarios" 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 [28]. 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 [30]. 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. 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 our ensemble, while the latter sits just above the median (see Table 2). Scenarios at the upper end of the range (95th percentile) feature CDR deployments of 14 $GtCO_2$ per year in 2050 - levels that likely encounter feasibility constraints in terms of scale-up and bioenergy resource availability [31]. We do not select 2°C pathways, 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 and significantly widens by 2050 (Table 2). Compared to 2020, the conditional NDCs would expand CDR by 0.65 $GtCO_2$ per year in 2030. This contrasts to an increase of 1 $GtCO_2$ per year in 2030 in the Focus on Demand Reduction scenario, which has the lowest CDR requirements. The CDR gap then widens by 2050, but is strongly determined by the number of quantifiable long-term strategies published by countries, as well as the chosen scenario benchmark. Compared to 2020, additional CDR removals in 2050 implied by the upper estimate of the long-term mitigation strategies would sum to 1.6 $GtCO_2$ per year. This is equivalent to levels in the Focus on Demand Reduction scenario, but falls short by multiple gigatons compared to the other focus scenarios.

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; Fig. 3). However, the exclusion of countries with large forested areas, such as Brazil, India and China makes the latter comparison problematic.

Another perspective that takes into account the limited data available for the long-term strategies is to consider scale-up rates for those countries with quantifiable scenarios. Here conventional CDR on land would expand between 3.6 to 4.9 times between 2020 and 2050. This is significantly higher than equivalent scale up rates in scenarios, implying that this subset of countries may be over-dependent on conventional CDR on land, at the expense of deep emissions reductions and low residual emissions [13,14].

The gap in novel CDR

No countries include novel CDR in their pledged mitigation efforts by 2030. By contrast, 1.5°C scenarios already implement 0.32 $GtCO_2$ per year 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 0.97 $GtCO_2$ per year of additional novel CDR can be inferred from these scenarios, largely driven by the US (0.5 $GtCO_2$ per year), the EU (0.26 $GtCO_2$ per year) and Canada (0.2 $GtCO_2$ per year). This compares to the 0.91 $GtCO_2$ per year of (global) additional novel CDR in the Focus on Renewables scenario and the 3.5 $GtCO_2$ per year in the Focus on Carbon Removals scenario. Again, as only a limited number of countries have submitted a quantifiable long-term strategy, these numbers are not directly comparable. In fact, it excludes a number of countries that are developing technology roadmaps towards novel CDR deployment such as China, Norway, Australia, and Saudi Arabia.

The Focus on Demand Reduction scenarios avoids scaling up novel CDR entirely. Compared to this benchmark, there is no gap in novel CDR. However, if countries were to follow this pathway then gross GHG emissions would need to be almost halved by 2030, compared to 2020. By contrast, emissions have progressively increased since 2020[7], pushing this and other low-CDR pathways further out of reach.

Table 2

Scaling of CDR to 2030 and 2050 in scenarios, NDCs and long-term strategies ($GtCO_2$ per year). 1.5°C and 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 additional CDR in the long term mitigation strategies (*) includes the difference due to missing data for countries that have not submitted a quantifiable strategy.

	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**
1.5°C scenarios	2.6 [0.77–5.4]	6.7 [2.8–14]	1.6 [-0.0045–3.3]	2.9 [-0.41–6.1]	0.32 [0.048–2.2]	3.8 [0.91–12]	44 [30–56]	72 [61–79]
2°C scenarios	0.72 [-0.011–3.2]	3.8 [-1.8–10]	0.7 [-0.054–2.9]	1.3 [-3.5–5.9]	0.039 [0–0.72]	2 [0.47–7.9]	19 [4.1–45]	59 [45–70]
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)	[0.1 to 0.65]	NA	[0.1 to 0.65]	NA	0	NA	NA	NA
Long-term mitigation strategies	NA	[0.54 to 1.6]*	NA	[0 to 0.65]*	NA	[0.57–0.97]*	NA	NA

Discussion

Our initial quantification of the CDR gap highlights that countries are also failing 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 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.

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 [32,33]. 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]. Only 68 countries (42 excluding EU countries) have actually submitted a long-term strategy. Further, not all pledges have legal status 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 ones that can be feasibly 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 [24,34–36]. In addition, IAMs have mainly modelled afforestation, BECCS and DACCS, while other technologies have been scarcely explored [24]. 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 scenario selections are possible - and can be made using the supplementary data file to this article. Alternative approaches for benchmarking CDR levels may also be possible, for instance by assessing the residual emissions associated with bottom-up energy and material requirements for meeting human needs [37]. 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 [20].

Finally, a recurring concern in the literature is that including CDR in mitigation discussions may deter near-term emissions reductions [38]. 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 [39–41]. 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 CDR discourses. 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 [42–44]. 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 [45]. 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 [46,47].

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 970 $MtCO_2$ per year, or 480 times current levels) and in 1.5°C scenarios (up to 3.8 $GtCO_2$ per year, or 1300 times current levels, but with a wide interquartile range). Near-term policies to support these methods in their formative phase is therefore urgently needed, without which it is difficult to conceive of scenarios where they deliver gigatons in 2050 and beyond. In addition, regulatory action that robustly defines, monitors, reports and verifies novel CDR is lagging.

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 show 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 methods is not a contradiction, but a necessary pathway towards successful climate policy.

Methods

Definition of CDR

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 [16].

A wide array of CDR technologies have been developed, tested or are in practice today [48]. In this article we follow Smith et al. [2] and categorise afforestation, reforestation, forestry management, soil carbon sequestration, wetland restoration, and durable harvested wood products as *conventional CDR on land* (Fig. 4). *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.

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 [49]. 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 [50,51]. 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 (e.g. afforestation/reforestation). (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). However, as we discuss below, this has implications for assessing CDR in the NDCs and long-term strategies, which are oriented around the inventory definition and can include indirect effects.

Scenario selection and re-analysis

Our selection of IAM scenarios draws from the latest IPCC 6th Assessment Report (AR6) vetted scenario database [19]. We use the C1 and C3 scenario categories, which are referred to as "1.5°C scenarios" and "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. [20] 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 [52].

CDR in national mitigation pledges

A number of assumptions need to be taken to extract CDR from NDCs. First, we read all NDC submissions up to July 2022, checking whether they include any quantified removals from novel CDR. Second, focusing on conventional CDR on land, we prioritise reading the NDCs by ranking countries according to the absolute sum of their current emissions and removals using the PRIMAP Hist-CR database [53] and Grassi et al. [43]. We then identify any instances where pledged targets include specific contributions from the LULUCF sector. To derive the split of emissions and removals in these LULUCF specific targets, we assume the proportion of emissions and removals remains consistent with the historical trend. We then re-base all NDCs to historical national inventory data from Grassi et al. [43] and assume that current removals stay constant in countries that have not specified LULUCF targets. In some individual cases, we interpret additional measures in the NDCs that are not under the headline target, such as forest area expansions. The method closely follows that of Grassi et al. [42].

In the case of the long-term strategies, we read all documents up to June 2023 and identify the subset that have stated objectives or scenarios for implementing novel or conventional CDR on land. As in the NDCs, most countries describe the total LULUCF flux in their scenarios. 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.

The NDCs and long-term strategies are oriented around national inventories and hence include indirect anthropogenic effects, such as CO_2 fertilisation. We therefore remove indirect effects in the NDCs and long-term strategies to render them comparable with the estimates of current and scenario-based CDR. We do this by distinguishing (1) maintained current sinks and (2) newly proposed sinks in the NDC pledge or long-term strategy scenario. These can be distinguished from the document texts or by cross-referencing them with current national inventories. For (1), we apply a ratio of direct to direct and indirect removals (2.0/6.4), as identified in Powis et al. [16]. Note that we apply a global ratio of direct to direct and indirect removals, which obscures differing contributions of indirect effects by region or biome. For (2), we preserve the original value, as newly proposed afforestation or regeneration implies largely direct removals.

Declarations

The authors have no conflicts of interest to declare.

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Figures

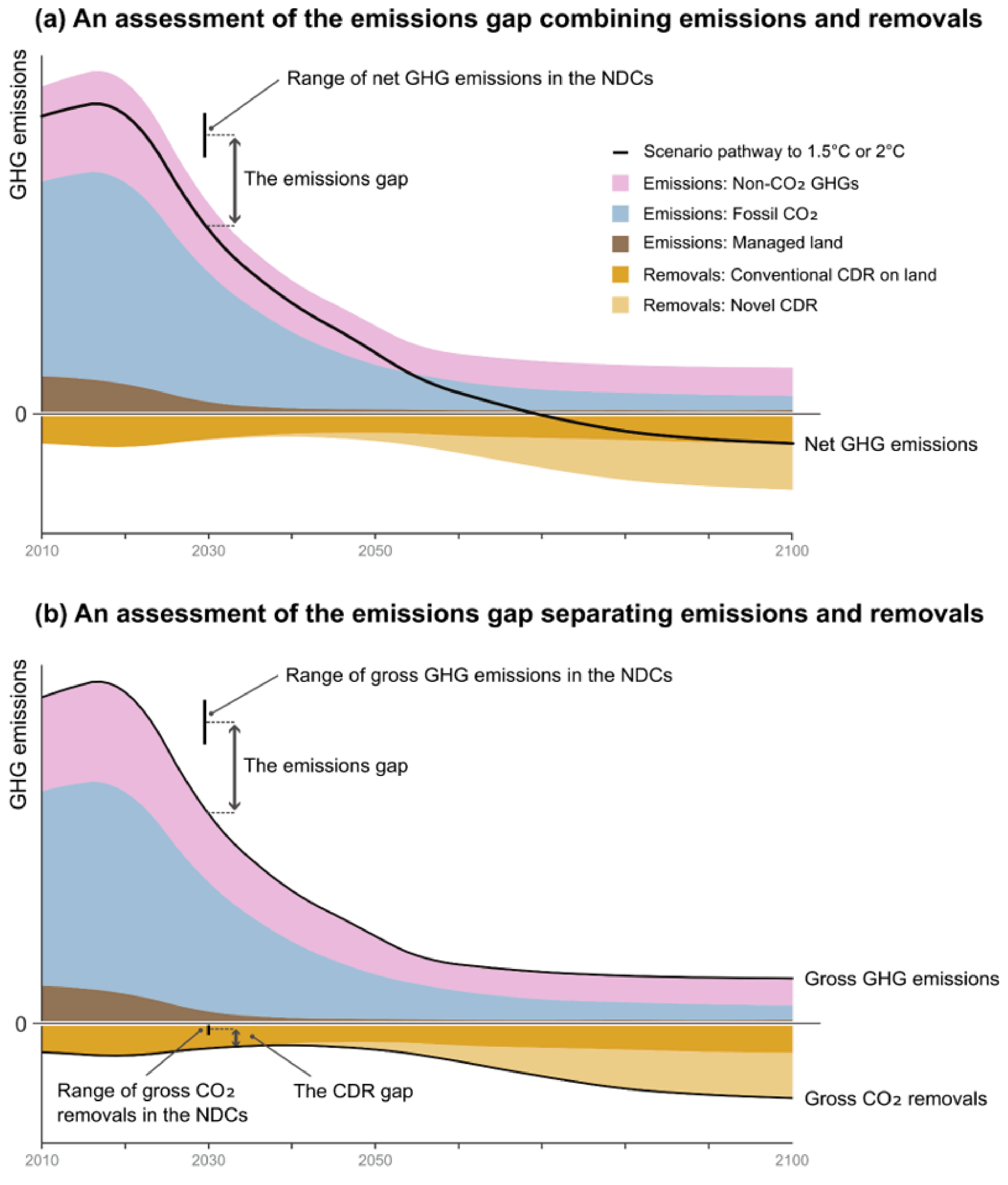

Figure 1

Combined (a) versus separate (b) assessments of the emissions and CDR gap. *Both panels show a stylised scenario pathway that holds warming to 1.5°C or 2°C. Typically the gap would be assessed against a scenario range and median level, rather than a single scenario.*

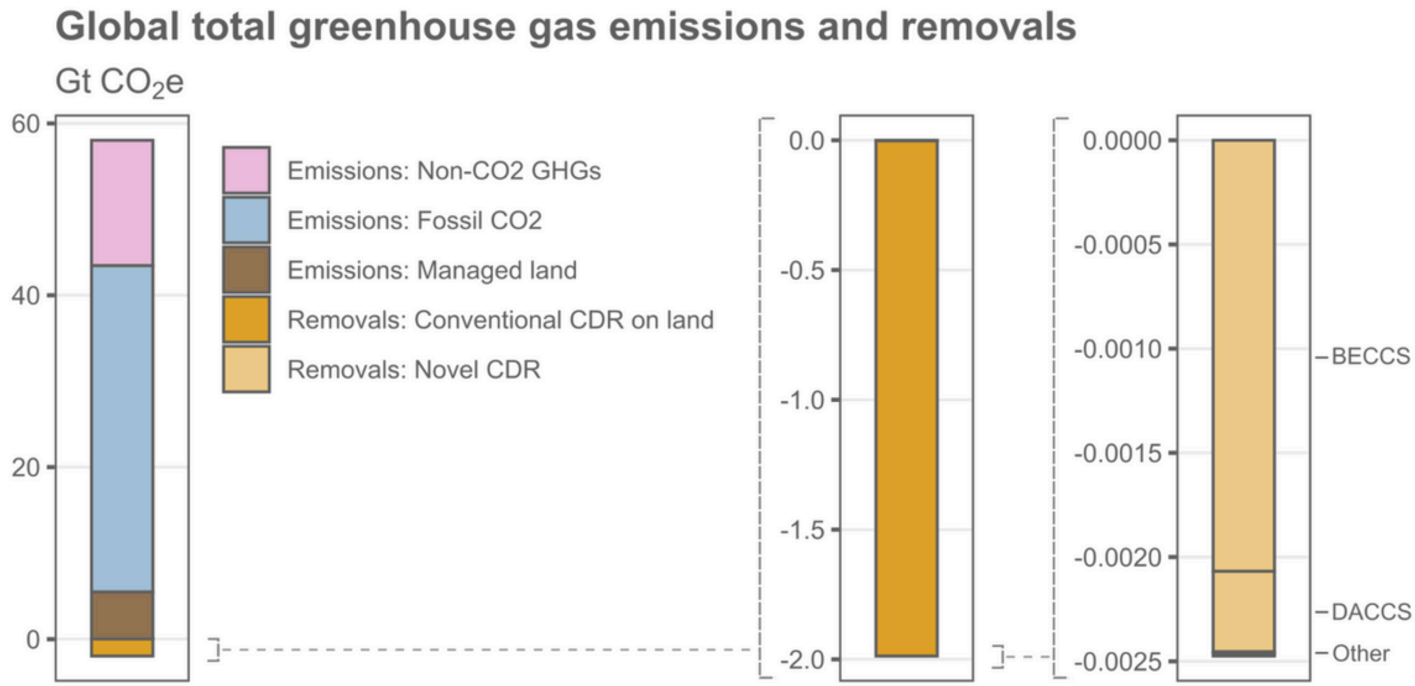

Figure 2

Current global CDR versus emissions. Reproduced from Powis et al. [16] with additional emissions data from Crippa et al. [17], using global warming potentials with a 100 year time horizon from the IPCC 6th Assessment Report [18]. Emissions data for 2019 are plotted, while removals are up to 2020.

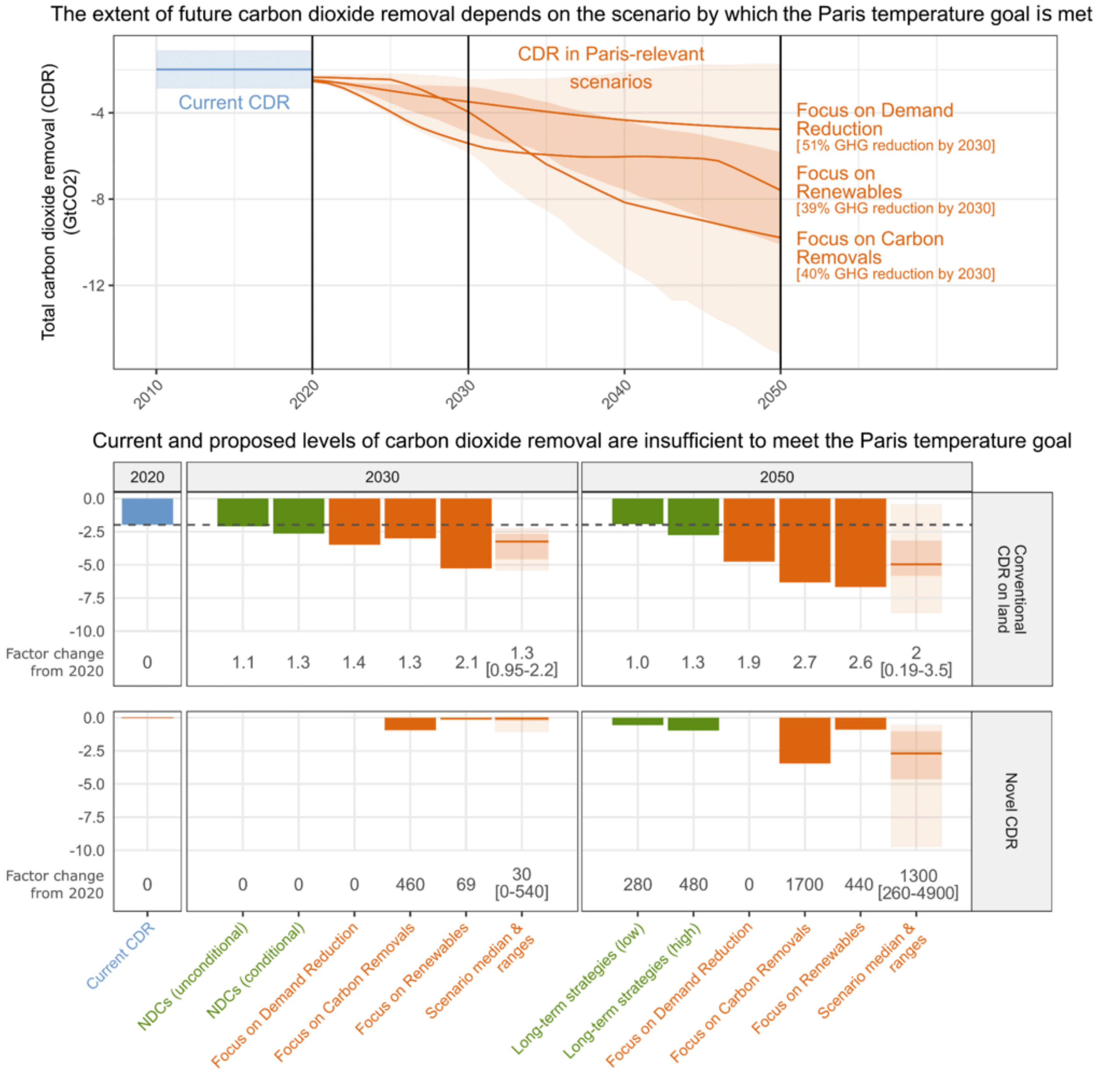

Figure 3

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. Green 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 (5th-95th and 25th-75th percentiles). The factor change from 2020 is also depicted for each category.

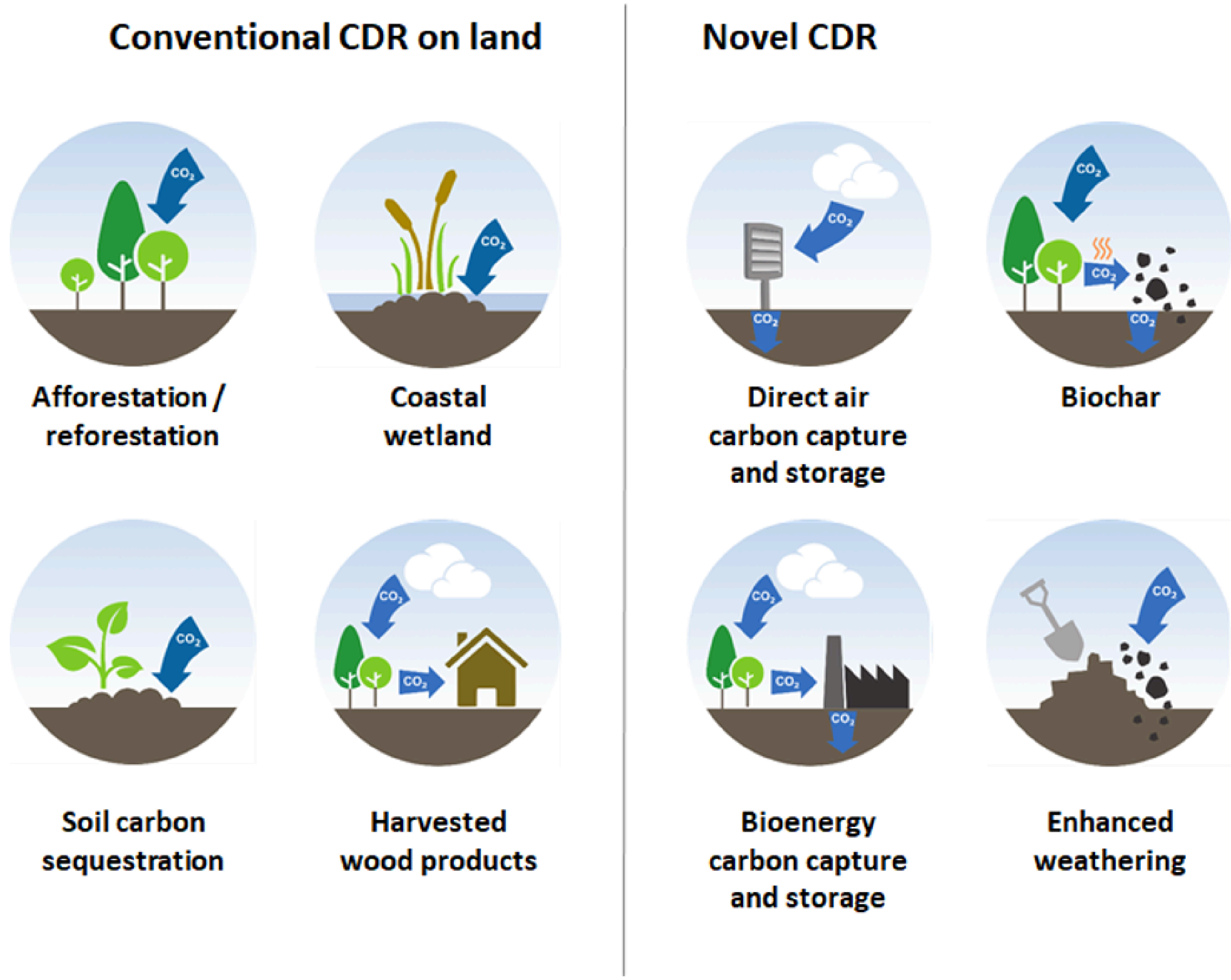

Figure 4

Conventional versus novel carbon dioxide removal methods