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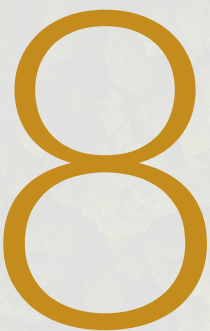
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**Cite as:** Gidden, M. J., Roe, S., Ganti, G., Gasser, T., Hasegawa, T., Lamb, W. F., Ochi, Y., Strefler, J., Vaughan, N. E. Chapter 8: Paris-consistent CDR scenarios. in **The State of Carbon Dioxide Removal 2024 – 2nd Edition** (eds. Smith, S. M. et al.). <https://www.stateofcdr.org>, doi:10.17605/OSF.IO/8XK7H (2024).



# Chapter 8 | Paris-consistent CDR scenarios

Long-term, gigaton-scale carbon dioxide removal (CDR) could be consistent with sustainability objectives if paired with ambitious emission reductions. Scenarios that are more aligned with sustainable development deploy less cumulative CDR and much less novel CDR than other mitigation scenarios.

## Key insights

- On average, scenarios that limit warming to 2°C or less reduce current emissions by 34 Gt per year by 2050. A set of scenarios that are more aligned with sustainable development go further, reducing emissions by an extra 7 Gt per year, or more than 10% of today's emission levels. This report considers the more sustainable scenarios to be "Paris consistent".
- The median total levels of CDR in 2050 are similar in all scenarios that limit temperature rise below 2°C as well as in Paris-consistent scenarios with sustainability limits (7.5–7.8 Gt of carbon dioxide (CO<sub>2</sub>) per year). The range of CDR in 1.5–2°C scenarios in 2050 is 6–10 GtCO<sub>2</sub> per year, and the range in Paris-consistent scenarios is 7–9 GtCO<sub>2</sub> per year. All scenarios assessed in this report use CDR to achieve net zero CO<sub>2</sub> emissions and, in some cases, net zero greenhouse gas emissions.
- Scenarios that limit global temperature rise to 1.5°C and the Paris-consistent scenarios deploy less CDR cumulatively by the time of net zero CO<sub>2</sub> emissions (190 GtCO<sub>2</sub> and 170 GtCO<sub>2</sub>, respectively) compared to the 2°C scenarios (330 GtCO<sub>2</sub>). The Paris-consistent scenarios tend to deploy more conventional CDR, whereas other scenarios deploy comparatively more novel CDR.
- Depending on future CDR is inherently risky for many reasons, and scenario evidence shows that limiting residual emissions is a more robust and sustainable strategy, and thus should be a key objective at all levels of climate policymaking.
- Novel CDR poses significant risks in terms of scalability. Some novel CDR methods have high environmental and ecosystem risks, while others have potential to generate co-benefits, but it is often difficult to determine the scale at which potential benefits outweigh potential negative impacts. Conventional CDR, when well planned and implemented with sustainability considerations, can provide significant benefits to humans and nature beyond climate change mitigation. If poorly executed, it can also

pose risks to sustainable development, such as to biodiversity and food security.

- Most scenarios continue to optimize solely for climate change mitigation and cost, too often producing unsustainable futures including very high levels of CDR that may jeopardize the attainment of other global goals. It is vital that CDR policy and strategy explicitly integrate sustainable development considerations to address risks and maximize co-benefits.

This chapter looks at the levels of CDR needed to achieve the Paris temperature goal of limiting warming to well below 2°C and striving to limit it to 1.5°C (Article 2.1a), while achieving a balance between sources and sinks of greenhouse gases (Article 4.1). The Paris Agreement also states that any response to climate change must be taken “in the context of sustainable development and efforts to eradicate poverty” (Article 2.1). Sustainability across multiple dimensions is thus paramount to delivering the mitigation goals laid out in the Paris Agreement. Section 8.1 of this chapter looks at the levels of CDR needed to achieve the Paris temperature goal in line with sustainability criteria. Section 8.2 examines the amount of residual emissions – or the remaining positive emissions that would need to be compensated by CDR to reach net zero carbon dioxide (CO<sub>2</sub>) – that exist by sector in Paris-consistent scenarios. Section 8.3 highlights the role, risks and co-benefits of conventional and novel CDR, including areas of uncertainty in accounting for removals. Section 8.4 outlines the needs and key elements for the further development of more-sustainable scenarios.

### 8.1 Future scenarios

#### **Meeting the Paris temperature goal will require strong emission reductions and the sustainable scale-up of CDR.**

While the causes of anthropogenic climate change are well known to be the continued emissions of CO<sub>2</sub> and other greenhouse gases through fossil fuel use and land-use change, the human and economic impacts of transitioning away from current energy systems, energy consumption patterns and agricultural practices depend strongly on the national policies and strategies employed to do so. Scientists who study these different transition strategies strive to develop a consistent set of plausible assumptions about the future evolution of demographics, economic growth and technological progress, among many other factors. Techno-economic models are then used to generate quantifications of the needed energy and economy transitions consistent with these storylines. A future scenario consists of a coherent storyline of a plausible future, a wide variety of input assumptions for a model, and the output of a model. Most commonly, models called integrated assessment models (IAMs) are used to produce these scenarios in the context of climate change mitigation (see Box 8.2). This report refers to *scenarios* as the combined set of storylines, input and output of a given model framework.

*The State of Carbon Dioxide Removal* 1<sup>st</sup> edition assessed future CDR deployment based purely on the temperature outcomes of each provided scenario. It followed the same

temperature classifications used by the IPCC, which included scenarios that limit global temperature rise to 1.5°C with 50% probability, scenarios that exceed a temperature rise of 1.5°C but then return to that level by the end of the century, and scenarios that limit temperature rise to 2°C with 67% probability (referred to by the IPCC as *C1*, *C2* and *C3 scenarios*, respectively). The first edition went beyond assessments by the IPCC and disaggregated the total amount of conventional CDR and the total amount of novel CDR in scenarios (see Chapter 1 – Introduction, for definitions) and highlighted three illustrative scenarios to show different mitigation profiles and their trajectories (see Box 8.1).

This edition of the report builds on that previous analysis in several ways:

- Expands the scenarios assessed to include more recently published scenarios than those available in the IPCC’s Sixth Assessment Report (AR6) Working Group III database
- Includes a new subset of scenarios that use sustainable development criteria
- Provides a deeper dive into the role of residual emissions and into the potential risks and co-benefits associated with conventional and novel CDR

As in the first edition, this edition refers to all 1.5–2°C scenarios as *Paris-relevant scenarios*. Whereas the first edition referred to 1.5°C (i.e. IPCC C1) scenarios as *Paris-consistent scenarios*, this edition includes a set of sustainability criteria to assess Paris consistency, among which is limiting temperature rise to below 2°C with at least 67% probability.

New for this edition of the report, all the analysis and data are provided in an open-access *State of Carbon Dioxide Removal* data portal, which will be updated for subsequent editions as new scenario evidence is made available (accessible via <https://portal.stateofcdr.org/>).

### Expanded scenarios

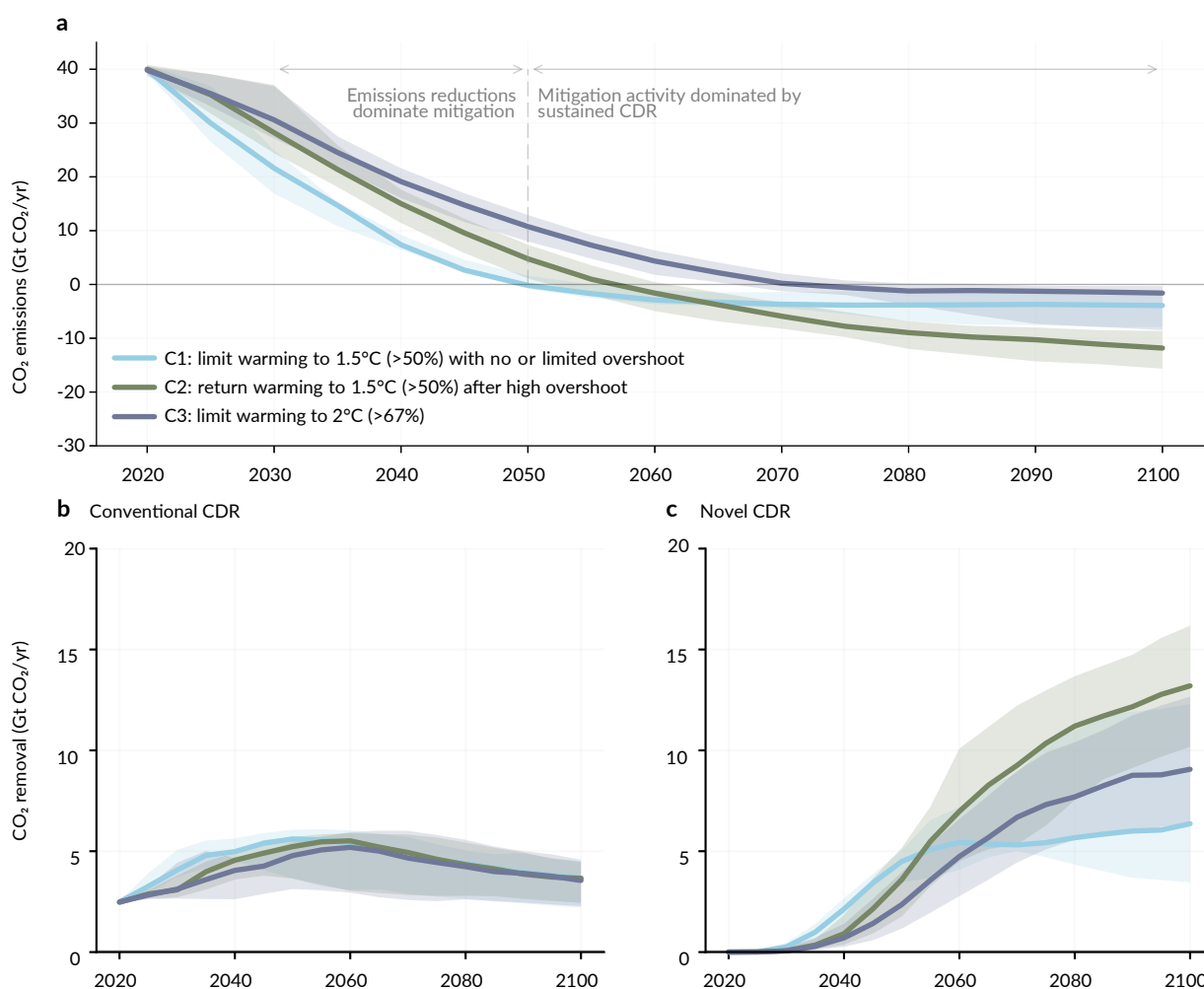
This report has collected additional scenarios from peer-reviewed publications for which data were publicly available in common data formats.<sup>333–335</sup> Each newly assessed scenario was provided a climate assessment (i.e. temperature pathway) consistent with approaches by the IPCC. As part of this analysis, when sufficient land-use change data were available, estimates were made for conventional CDR following the methods laid out in Gidden et al., 2023.<sup>336</sup> Where possible, estimates were also made for novel CDR: bioenergy with carbon capture and storage (BECCS), direct air carbon capture and storage (DACCS), enhanced rock weathering, and other methods (Table 8.1, Figure 8.1).

This report finds that the majority of scenarios used in the IPCC’s AR6 depend on BECCS as the only novel CDR option, while newer scenarios (since AR6) are increasingly exploring future pathways that include DACCS, enhanced rock weathering and other novel methods (Table 8.1).

	Total number of 1.5–2°C scenarios (number assessed)	Number of scenarios with conventional CDR <sup>a</sup> (number for which CDR estimated)	Number of scenarios with novel CDR			
			BECCS	DACCS	ERW	Biochar
Scenarios in the AR6 database	540 (407)	530 (407)	516	146	4	1
New scenarios since AR6	90 (48)	90 (48)	85	71	11	0

<sup>a</sup> Scenarios are considered to include conventional CDR if this value can be estimated using the methodology in Gidden et al., 2023.<sup>336</sup>

**Table 8.1** Carbon dioxide removal (CDR) portfolios included in the scenarios in this assessment. AR6 = Sixth Assessment Report; BECCS = bioenergy with carbon capture and storage; DACCS = direct air carbon capture and storage; ERW = enhanced rock weathering.



**Figure 8.1** The median and interquartile ranges of (a) carbon dioxide (CO<sub>2</sub>) emissions and (b, c) carbon dioxide removal (CDR) values across IPCC Sixth Assessment Report scenarios and new scenarios since the Sixth Assessment Report.

## Sustainable scenarios

This analysis also looked at a subset of scenarios that are more likely than other scenarios to achieve multiple sustainable development outcomes, with the aim of better understanding how future CDR could be deployed in the context of social and environmental sustainability.

The scenarios assessed by the IPCC as well as the expanded scenarios assessed in this chapter (described in the previous section) come from the published literature, including studies from individual modelling groups and from small and large multi-model comparisons. Each study seeks to inform and further mitigation science, focusing on a specific research question. Some studies ask more general questions, such as how to bridge the gap between current nationally determined contributions and emission pathways aligned with the Paris Agreement<sup>337</sup> or what the cost implications are of meeting climate targets while avoiding overshooting those targets.<sup>338</sup> Other studies are more explicit, considering specific questions about the environmental impacts of CDR<sup>139</sup> or investigating how to meet different Sustainable Development Goals (SDGs), including – under SDG 13 – the 1.5°C target.<sup>339</sup> However, no multi-model comparison studies were found to date that systematically explore the implications of CDR deployment for meeting multiple SDGs.

Because the data provided by scenario producers are limited, it is impossible to precisely say if a given SDG is met under that scenario (and not all SDGs have explicitly quantified goals). Therefore, to identify the required subset of scenarios that are more likely to achieve multiple sustainable development outcomes, a number of criteria rooted in the sustainability literature were applied to each existing scenario (see Chapter 8 Technical Appendix). Broad conclusions were then drawn regarding CDR deployment in that subset of scenarios. The sustainability criteria considered and evaluated at the time when each scenario achieved net zero CO<sub>2</sub> emissions were:

- Halting deforestation and conversion of ecosystems and protecting biodiversity and ecosystem services (SDG 15)<sup>340</sup>
- Reducing the population at risk of hunger (SDG 2)<sup>341</sup>
- Limiting the increase of global energy demand while enhancing equitable access to energy (SDGs 7, 12)<sup>339</sup>
- Limiting reliance on energy from biomass to reduce land and water resource needs (SDGs 7, 15)<sup>8,342</sup>
- Keeping temperature rise well below 2°C and striving to limit it to 1.5°C (SDG 13)

Combining both temperature outcomes and dimensions of sustainability, a new “Paris-consistent” range of CDR was assessed based on this subset of more sustainable scenarios (Table 8.2, Figure 8.2). The collection of scenarios assessed does not reflect a statistical sample but rather an unstructured ensemble in which no single scenario is more likely to occur than another; however, robust conclusions can be drawn by analysing the distributions of results.<sup>343</sup> Of the 34 scenarios that meet all sustainability criteria, ten scenarios deploy at least three CDR methods, and 24 deploy only BECCS and afforestation/reforestation.

Scenarios	2035 (GtCO <sub>2</sub> e per year [25-75th percentile])				2050 (GtCO <sub>2</sub> e per year [25-75th percentile])				At net zero CO <sub>2</sub> emissions (GtCO <sub>2</sub> per year [25-75th percentile])		
	Gross emission reductions from 2020	Total CDR	Conventional CDR	Novel CDR	Gross emission reductions from 2020	Total CDR	Conventional CDR	Novel CDR	Cumulative total CDR	Cumulative conventional CDR	Cumulative novel CDR
C1	30 [26, 32]	6.1 [4.9, 7.0]	4.8 [4.2, 5.5]	1.0 [0.53, 1.4]	39 [38, 42]	8.9 [7.6, 11]	5.6 [3.6, 6.1]	4.5 [3.4, 5.1]	190 [150, 260]	140 [120, 180]	51 [43, 89]
C2	21 [16, 26]	4.5 [3.5, 5.5]	4.0 [3.1, 4.5]	0.35 [0.15, 0.65]	35 [33, 39]	8.1 [6.6, 10]	5.2 [3.6, 5.7]	3.6 [1.8, 5.2]	220 [190, 250]	150 [110, 180]	64 [40, 120]
C3	19 [14, 22]	4.1 [3.2, 5.4]	3.6 [2.6, 5.0]	0.28 [0.11, 0.73]	32 [29, 34]	6.4 [5.6, 9.1]	4.8 [3.1, 5.4]	2.4 [1.2, 4]	330 [260, 440]	210 [150, 260]	140 [79, 270]
C1–C3	21 [16, 26]	4.6 [3.6, 5.9]	3.9 [3.0, 5.0]	0.43 [0.16, 0.99]	34 [30, 39]	7.5 [5.9, 10]	5 [3.3, 5.8]	3.2 [1.6, 4.6]	260 [200, 360]	170 [130, 230]	96 [48, 200]
More sustainable scenarios (within C1–C3)	31 [28, 34]	5.1 [4.6, 5.8]	4.5 [4.4, 4.9]	0.30 [0.15, 0.66]	41 [39, 43]	7.8 [6.6, 8.9]	5.7 [5.2, 5.9]	1.9 [1, 3.7]	170 [140, 210]	150 [130, 160]	22 [15, 53]
1.5°C with no novel CDR	34	3.9	3.9	0	45	4.8	4.8	0	130	130	0
1.5°C with higher novel CDR	29	6.4	3.9	2.5	43	9.8	6.3	3.5	160	110	50
1.5°C with higher conventional CDR	27	5.9	5.6	0.3	40	7.6	6.7	0.9	300	265	35

**Table 8.2** Carbon dioxide removal (CDR) and emission reductions across different scenarios (See technical annex section A8.2 for 2030 values). Cumulative values start in 2020. All values rounded to two significant digits.

Stringent emission reductions play the strongest role in all scenarios that limit warming to 2°C or less. The 1.5°C scenarios reduce current sources of emissions compared with modelled 2020 levels by 30 (26 to 32) Gt per year by 2035 and 39 (38 to 42) Gt per year by 2050. The 2°C scenarios see emission reductions of 19 (14 to 22) Gt per year by 2035 and 32 (29 to 34) Gt per year by 2050. However, the more sustainable scenarios tend to include stronger gross emission reductions than the full scenario set, declining by 31 (28 to 34) Gt per year by 2035 and by 41 (39 to 43) Gt per year by 2050. In other words, this report's set of more sustainable scenarios further reduces sources of emissions by more than 10% of today's emission levels compared with the median of all assessed scenarios that limit warming to 2°C or less. Enhanced sectoral transformation, shifting dietary preferences, and reduced demand for products and services in certain sectors are critical components in minimizing residual emissions in these more sustainable scenarios (see Section 8.2).

Similar levels of total CDR in 2050 are seen across both the full scenario set and the more sustainable scenarios, reaching around 7.5–8 GtCO<sub>2</sub> by mid-century. However, 1.5°C scenarios and the Paris-consistent scenarios deploy less CDR cumulatively by the time of net zero CO<sub>2</sub> emissions (190 GtCO<sub>2</sub> and 170 GtCO<sub>2</sub>, respectively) compared with the 2°C scenarios (330 GtCO<sub>2</sub>). The type of CDR deployed also varies by scenario type. In general, both scenario sets see a ramping up of both conventional and novel CDR in the near term. However, by 2050 the more sustainable scenarios have a stronger dependence on conventional CDR and a relatively weaker dependence on novel CDR than the full set of scenarios. Among the more sustainable scenarios that deploy at least two types of novel CDR, BECCS contributes around 42% of total annual novel removals at the time of net zero CO<sub>2</sub> emissions.

### Box 8.1 Focus scenarios

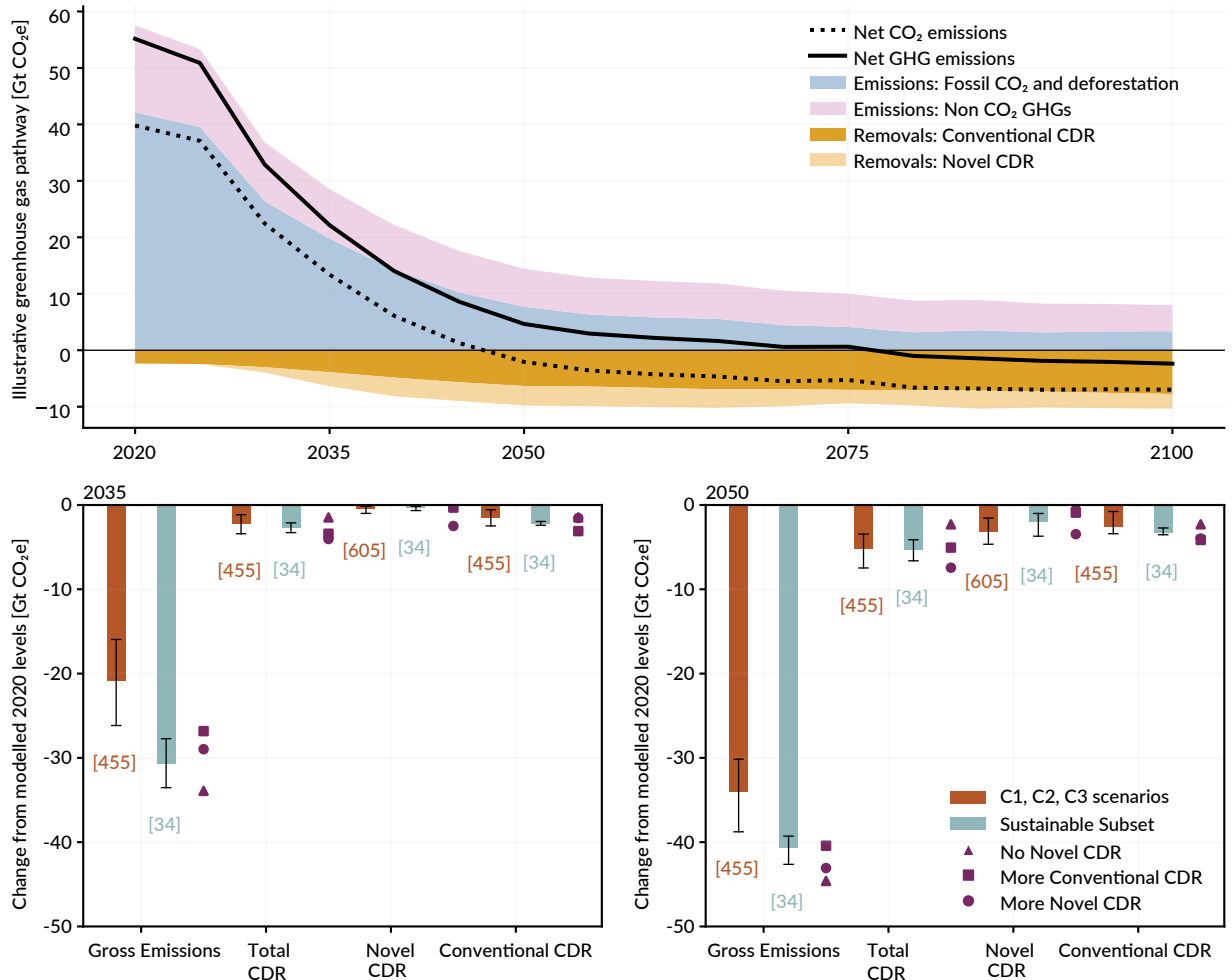
*The State of Carbon Dioxide Removal* 1<sup>st</sup> edition introduced three focus scenarios that highlighted the role of CDR: one focused on demand reduction, one on renewable energy, and one on expanding conventional and novel CDR. Each focus scenario was assessed as a 1.5°C with no or limited overshoot scenario (C1 category) by the IPCC in AR6.

While these distinctions were useful, the naming conventions were felt to detract from the message around their CDR characteristics. In any given scenario, multiple mitigation levers are used to achieve net emission reductions and limit global temperature rise. For example, the *Focus on Renewables* scenario also includes substantial dietary shifts away from meat-based diets and towards the EAT–Lancet diet<sup>344</sup> that includes more vegetable and plant-based proteins, among many other levers, resulting in a scenario with significantly more-sustainable outcomes.

As such, these focus scenarios have been renamed for this second edition of the report based on their CDR characteristics (2030 Total, Conventional, and Novel CDR values shown) as follows:

- Focus on Demand Reduction<sup>345</sup> → 1.5°C with no novel CDR (3.5, 3.5, 0 GtCO<sub>2</sub>)

- Focus on Renewables<sup>339</sup> → 1.5°C with higher conventional CDR (4, 3, 1 GtCO<sub>2</sub>)
- Focus on CDR<sup>346</sup> → 1.5°C with higher novel CDR (5.4, 5.3, 0.1 GtCO<sub>2</sub>)



**Figure 8.2** The more sustainable scenarios see stronger gross emission reductions, more conventional carbon dioxide removal (CDR) (with potentially strong co-benefits), and less novel CDR (with potentially greater risks) by 2050. Gross emission reductions include all greenhouse gases (GHGs).

## 8.2 Residual emissions across sectors

**CDR counterbalances residual emissions in hard-to-transition sectors, including the agricultural and industrial process sectors. Low residual emission scenarios are most aligned with sustainability outcomes.**

The scenarios assessed in this report seek to show future pathways that limit global temperature rise by reducing net CO<sub>2</sub> emissions, and in some cases greenhouse gas emissions, to net-negative levels. Because scenarios try to find cost-effective solutions (see Box 8.2), in some cases they can determine that it is less costly to deploy a given CDR technology than it is to further reduce emissions in a given sector. CDR thus plays three primary roles in scenarios:

- Helping draw down near-term net emissions, largely through conventional CDR
- Counterbalancing remaining positive CO<sub>2</sub> emissions at the time net zero CO<sub>2</sub> is reached, generally through strategies involving both novel CDR and conventional CDR
- Further helping draw down net-negative CO<sub>2</sub> emissions to achieve net zero greenhouse gas emissions by maintaining levels of conventional CDR and expanding further levels of novel CDR

### Box 8.2 IAMs and scenario collections

IAMs bring together representations of multiple systems, including energy supply and demand, economies, and the environment, to study the effect of potential sociodemographic and policy futures. Scenarios generated by IAMs are one of the primary sources of scenarios in the IPCC AR6 database. IAMs use input drivers such as future trajectories of population, gross domestic product and urbanization, as well as a wealth of techno-economic assumptions. These assumptions can hew to certain narratives or storylines, for example a “middle of the road” future, or a “fossil-fuelled” future, or a “sustainability-focused” future.<sup>347</sup>

Different modelling teams choose different values across a wide range of assumptions, such as for technology costs, technology potential and economic discount rates. Models can also have fundamentally different structures, from least-cost or maximum-utility optimization to more simulation-based approaches, as well as fundamentally different levels of representation that focus more on the economy (e.g. computable general equilibrium) or more on fine-grained processes (e.g. bottom-up techno-economic models). Because of the diversity of approaches and assumptions, models may prefer certain types of mitigation solutions over others.<sup>348</sup>

IAMs are regularly used to study the range of different policy tools and the technology development needed to achieve certain policy aims. In the context of IPCC AR6, these policy aims are normally related to specified temperature outcomes governed by negotiations under the UNFCCC. However, IAMs are also used to investigate how to achieve other targets, such as the SDGs, and scenarios generated with IAMs are regularly produced without setting any specific climate target at all. Scenarios are neither predictive nor prescriptive; they are meant to show how different outcomes can be arrived at.

One must use caution when querying unstructured ensembles (or sets) of scenarios (i.e. collections of scenarios that are not coordinated to answer a specific research question), such as the IPCC AR6 Working Group III database. In many cases, scenarios submitted to the AR6 database come from structured intermodel comparison projects, in which multiple models harmonize input assumptions to answer a given research question. In the context of CDR, such projects may have included specific diagnostic scenarios, where certain CDR methods are turned on or off to study how a given climate target could be achieved if that CDR method were unavailable in the future, and the diagnostic conditions specified could affect the outcomes assessed from an unstructured scenario ensemble. In addition, these

scenarios in unstructured ensembles may or may not explicitly consider other sustainability constraints, such as protecting biodiversity. Indeed, some scenarios may explicitly be designed such that they violate sustainability constraints to study what may happen in worst-case outcomes (e.g. in a fossil-fuelled future). This has led to some critique of the IPCC's assessment using scenarios generally,<sup>349</sup> and there are growing calls to develop better methods to perform scenario assessment.<sup>350</sup>

Residual emissions are the emissions that would need to be compensated by CDR to reach net zero CO<sub>2</sub>. A precise definition of residual emissions remains elusive, as they are a future unknown quantity that depends on the success of emission reduction efforts across different sectors. Emerging evidence from national net zero strategies indicates that policymakers expect considerable quantities of residual emissions in 2050, averaging 21% of peak emissions (with a min/max range of 5–52%) in Annex I (developed) countries.<sup>143,351</sup> These levels have led some to question whether reduction proposals are ambitious enough and to examine the emerging politics of residual emissions.<sup>143,168,352,353</sup>

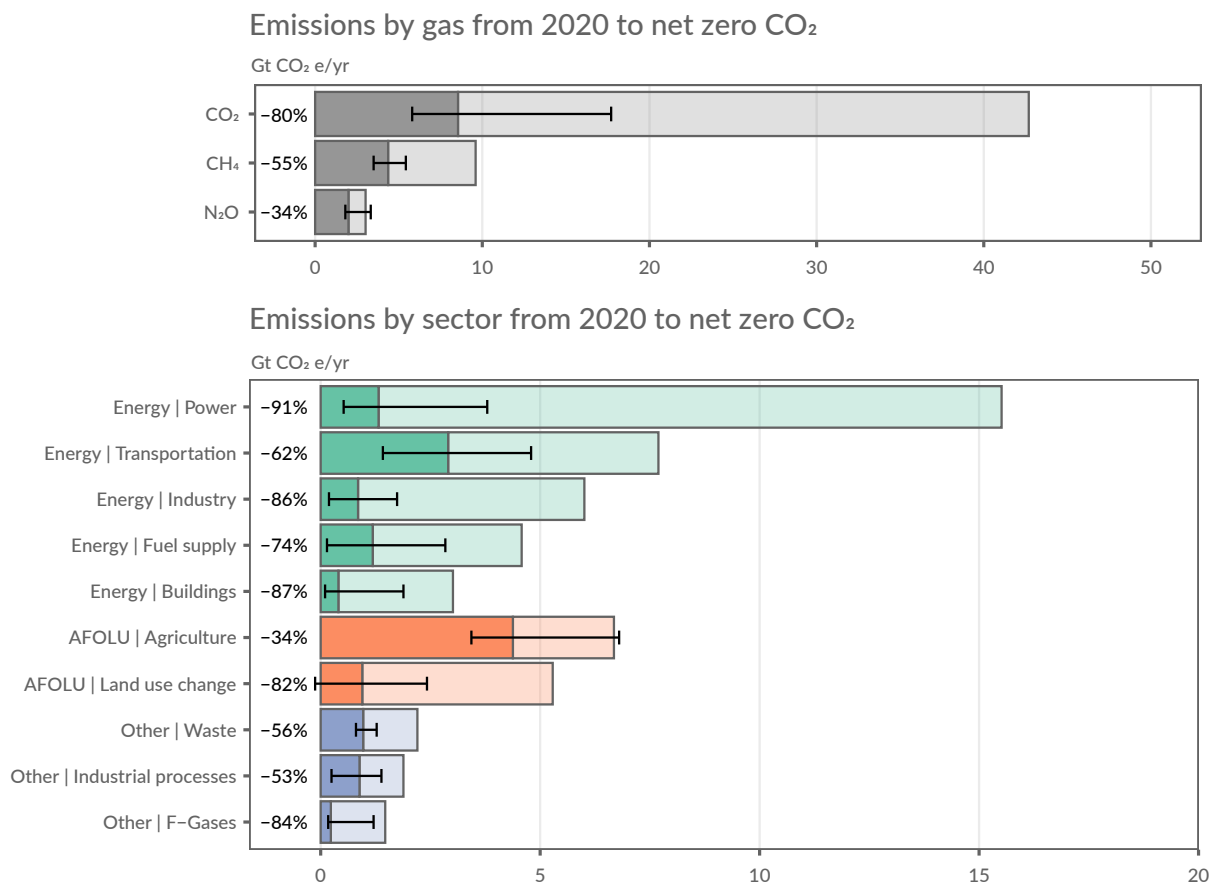
Residual emissions can be considered either the cumulative quantity of unabated emissions in the 21<sup>st</sup> century<sup>354</sup> or the annual gross emissions that are balanced by CDR once net zero CO<sub>2</sub> is reached. This report uses the latter definition, as it focuses attention on the specific sectors where emissions are considered hard to abate (i.e. sectors in which emission reductions level off after a transition period). This section draws from a study that examines residual emissions in the full range of IPCC AR6 C1–C3 (1.5–2°C) scenarios,<sup>355</sup> focusing on emission levels at the time that net zero CO<sub>2</sub> is reached (approximately the early 2050s for C1 scenarios, in the 2060s for C2 and in the 2070s for C3). This compilation of scenarios differs from those evaluated in Section 8.1, as it is not constrained by a set of sustainability criteria, nor does it include new scenarios since AR6.

The IPCC AR6 scenarios project considerable volumes of residual emissions, even after a period of deep reductions across sectors (see Figure 8.3). The AR6 scenarios have residual greenhouse gas emissions at the point of net zero CO<sub>2</sub> of 16 (13–22) GtCO<sub>2</sub>e. This represents gross emission reductions of 71 (62–77) % by a median net zero year of 2066. While some scenarios subsequently continue to reduce gross emissions, potentially reaching net zero greenhouse gas emissions in the 21<sup>st</sup> century, others scale up CDR to reach those goals. Residual emissions of 13 (7.6–20) GtCO<sub>2</sub>e still remain by 2100 across the IPCC AR6 scenario ensemble. These levels are less ambitious than benchmarks in corporate net zero standards such as the International Organization for Standardization and Science Based Targets initiative standards, which arrive at net zero CO<sub>2</sub> in 2050 to align with a 1.5°C pathway.<sup>355</sup>

Scenario evidence supports the notion that residual emissions are weighted towards non-CO<sub>2</sub> greenhouse gases in the agricultural and industrial process sectors (see Figure 8.3).<sup>356</sup> The largest sources of emissions at the point that net zero CO<sub>2</sub> is reached in scenarios are methane emissions from livestock, CO<sub>2</sub> emissions from transport (including international aviation), nitrous oxide emissions from agriculture, CO<sub>2</sub> emissions from industrial processes (e.g. from cement and steel manufacture), and methane emissions from

the waste sector. However, there is considerable variation across the scenarios, primarily driven by the type of model used and, presumably, by the underlying cost distribution of the models' mitigation options.

The precise quantity of non-CO<sub>2</sub> greenhouse gas emissions that would need to be compensated by CDR or removals of methane or nitrous oxide to ultimately stabilize temperatures remains uncertain.<sup>23</sup> The frontier of possible emission reductions is also far from explored in current scenarios, as there have been few systematic studies of low residual emission scenarios. However, scenarios at the lower end of residual emissions (e.g. less than 12 GtCO<sub>2</sub>e per year at net zero CO<sub>2</sub>) tend to involve demand-side changes, such as dietary shifts (lowering livestock emissions) and reduced aviation demand;<sup>339,356</sup> achieve a deep electrification of end-use sectors;<sup>357</sup> or purposefully constrain CDR availability in the model, thus implementing higher-cost gross emission reductions.<sup>358</sup> Although there may be trade-offs to achieving such deep reductions, these strategies intersect with sustainability-oriented pathways to net zero and thus deliver significant co-benefits for social well-being and the environment. As such, limiting residual emissions and thereby lowering dependence on CDR should be considered a key objective at all levels of climate policymaking.



**Figure 8.3** Gross emission reductions and residual emissions in IPCC Sixth Assessment Report scenarios by gas and sector. The specific compilation of scenarios differs to those presented in Figure 8.1 and is discussed in Lamb, 2024.<sup>355</sup> Faded bars represent median scenario gross emissions in 2020; solid bars represent median scenario gross emissions at the point of net zero carbon dioxide (CO<sub>2</sub>). Error bars indicate the 5th to 95th percentile of the scenario range at the point of net zero CO<sub>2</sub>. The timing of net zero CO<sub>2</sub> varies by scenario but is reached between 2050 and 2055 in the assessed C1 scenarios, in the 2060s in C2 scenarios and in the 2070s in C3 scenarios. AFOLU = agriculture, forestry and other land use; CH<sub>4</sub> = methane; F-gases = fluorinated greenhouse gases; N<sub>2</sub>O = nitrous oxide.

## 8.3 The role and potential risks, benefits and uncertainties of conventional and novel CDR

**All scenarios assessed deploy conventional CDR early on, then shift towards novel CDR later in the century. Different CDR approaches carry different potential risks and benefits, and it is highly uncertain how much CDR will be needed.**

Conventional CDR measures, such as afforestation/reforestation and soil carbon sequestration, tend to be deployed in the first half of this century in scenarios that limit warming to 1.5°C and 2°C, whereas novel CDR technologies, such as BECCS or DACCS, tend to be scaled up in the latter half of the century. Early deployment of conventional CDR in scenarios is due to the relative maturity, scalability and cost-effectiveness of these methods. For instance, mitigation costs are estimated to range from -\$45 to \$100/tCO<sub>2</sub> for soil carbon sequestration and from \$0 to \$240/tCO<sub>2</sub> for afforestation/reforestation, whereas BECCS costs are projected to range from \$15 to \$400/tCO<sub>2</sub> and DACCS costs from \$200 to \$1,000/tCO<sub>2</sub>.<sup>4,359</sup>

The potential risks and benefits of CDR approaches are also increasingly influencing their use and deployment in scenarios and in practice. Relying on CDR, especially large-scale CDR at the gigaton scale, poses social and environmental sustainability risks as well as climate change mitigation risks. However, if strategically planned and deployed, some CDR options can also provide benefits for people and nature beyond climate change mitigation.

This section discusses the role of conventional and novel CDR in scenarios, including their geographical deployment. It also outlines the potential risks and benefits of the various CDR approaches and highlights ways to avoid or reduce risks and maximize benefits.

### The role of conventional CDR in scenarios

In the Paris-consistent scenarios with sustainability limits assessed in this report, conventional CDR reaches 4.5 GtCO<sub>2</sub> per year in 2035 and 5.7 GtCO<sub>2</sub> per year in 2050, cumulatively amounting to 150 GtCO<sub>2</sub> at the point of net zero CO<sub>2</sub> (Table 8.2). Methods of conventional CDR include afforestation/reforestation, forest management, soil carbon sequestration in croplands and grasslands, agroforestry, restoration of peatland and coastal wetlands such as mangroves, and durable wood products (see Chapter 1 – Introduction). To date, most of these options – with the exception of afforestation/reforestation and forest management – are not included in the IAM scenarios assessed in this report, though the newest versions of land-model components are beginning to incorporate soil carbon sequestration and peatland restoration.<sup>340</sup> Therefore, a large majority of the conventional CDR estimates are from large-scale afforestation/reforestation. The lack of additional conventional CDR methods in the IAMs is mainly because those methods are associated with components (e.g. land and soil management) that are themselves not yet explicitly represented in the IAMs.

Multi-model assessment<sup>360</sup> indicates that forested areas significantly expand at lower carbon prices (<\$50/tCO<sub>2</sub>), while the cropland area for bioenergy crops increases at higher carbon prices (>\$100/tCO<sub>2</sub>), largely replacing pastureland. Trade-offs and competition

for land between conventional CDR and food production may be difficult to avoid without explicit consideration of sustainable food policies taken in tandem with national mitigation planning.<sup>361,362</sup>

The geographical deployment of conventional CDR depends on the specific method's technical potential in that location; for instance, afforestation/reforestation requires an area and climate suitable for forestation with high carbon density potential. Under mitigation pathways, afforestation/reforestation tends to be primarily implemented in Africa, Latin America, South Asia and certain developed countries.<sup>363</sup> Soil carbon sequestration tends to have higher potential in Africa, Asia, and some developed countries;<sup>364</sup> however, it is not a major CDR option deployed in assessed scenarios to date.

The scientific teams that produce scenarios are exploring ways to incorporate more conventional CDR methods, which will likely affect future assessments of CDR levels compatible with multiple sustainability goals due to their potential social and biodiversity co-benefits (see next section). For example, agroforestry and soil carbon sequestration are being considered by some models, which could potentially expand conventional CDR further. Studies show a mitigation potential of 1.1 GtCO<sub>2</sub> per year for agroforestry and of 1.8 GtCO<sub>2</sub> per year for soil carbon sequestration by 2050 at a carbon price of less than \$100/tCO<sub>2</sub>.<sup>364</sup>

### Potential risks and benefits of conventional CDR

The potential risks and benefits of conventional CDR approaches are relatively well researched in the literature on ecosystem-based approaches, such as nature-based solutions, natural climate solutions, ecosystem-based adaptation, and agroecology.

All land-based interventions (including relevant novel CDR approaches) have implications for climate change mitigation, adaptation and resilience, food security, biodiversity, water quality and supply, and livelihoods and poverty, where the scale of benefit or risk largely depends on (1) the type of activity undertaken (e.g. reforestation in forest biomes versus afforestation in non-forest biomes), (2) the deployment strategy (e.g. native species in habitat corridors versus large-scale monoculture plantations of non-native species), and (3) the regional and local context (e.g. soil type, biome type, climate, land ownership and beneficiaries, competing land uses).<sup>365</sup>

### Potential social and environmental benefits

There is increasing evidence that when well planned and deployed with explicit consideration of the local context and sustainable development outcomes, conventional CDR measures can deliver significant benefits for people and nature in addition to climate.<sup>4</sup> For example, community-led mangrove restoration not only sequesters carbon, it can also benefit local livelihoods, provide species habitat (including commercial fish habitat), buffer impacts from storm surge and floods, reduce pollution and improve water quality.<sup>366</sup> Agroforestry – or planting native fruit trees in croplands and pastures and improving soil carbon sequestration by selecting perennials and longer rooted cultivars and strategically applying compost – could improve soil health, water retention, productivity and farmer incomes, and increase resilience to heatwaves, floods and droughts.<sup>367-371</sup> Reforestation of

degraded land that previously supported forests through community-supported natural regeneration with rewilding of native seed dispersers enhances biodiversity and provides habitat, reduces erosion and improves soil health and, depending on scale, could increase water cycling, local cooling and the resilience of the region to extreme weather.<sup>372-374</sup> Potential benefits from these conventional CDR approaches are therefore well positioned to contribute to the SDGs, the Global Biodiversity Framework and other global and national policy goals.<sup>365</sup>

### **Potential social and environmental risks**

Conversely, poorly planned and implemented land interventions that do not adequately consider local contexts and outcomes beyond climate could have adverse effects on climate, nature and people. Potential risks include implementation of large-scale interventions (e.g. afforestation/reforestation) that compete with croplands and reduce incomes and food security;<sup>360,375</sup> afforestation of non-forest ecosystems, like native grasslands, to exotic monoculture plantations, reducing biodiversity and resilience to climate change, and straining water resources;<sup>376-379</sup> marginalization of local communities due to land grabbing and benefit capture;<sup>380</sup> and reduced mitigation effectiveness due to biophysical impacts from adding forests in high latitudes (e.g. albedo).<sup>381,382</sup>

### **Climate change mitigation risks**

All land-based CDR approaches (conventional and novel) are vulnerable to climate impacts and reversals, which could reduce their mitigation efficacy. The capacity of land to sequester carbon over time is subject to various uncertainties, including biogeochemical, biophysical, anthropogenic and carbon accounting uncertainties, further challenging CDR estimation (see Box 8.3).

### **Risk mitigation strategies**

To mitigate negative consequences, sustainable land-use planning and management can balance the use of land for CDR with other aspects of land-based sustainability. Through various approaches (e.g. managing scale, focusing on sustainable deployment strategies catered to local context), the benefits of CDR techniques can be optimized to achieve multiple goals, including carbon sequestration and enhancement of biodiversity, ecosystem services and livelihoods.<sup>373</sup> Other land-based measures, including sustainable agricultural intensification, reduced food waste, and dietary changes, can lessen the land required for food production and thus facilitate carbon sequestration through CDR, all while safeguarding food security and land sustainability.<sup>365,383</sup>

### **The role of novel CDR in scenarios**

Across most of the scenarios assessed in this report, novel CDR increases to megaton scale by 2030, then to gigaton scale around mid-century and beyond. The scenarios mostly include BECCS and DACCS, with some scenarios also including enhanced rock weathering and biochar (see Table 8.1). When and how fast these technologies can be scaled up depends mainly on costs but also on technological readiness and policy.

Most of the models include large-scale deployment of BECCS in C1–C3 scenarios as it is

comparatively cheap<sup>8</sup> and able to supply low-carbon energy, especially liquid fuels,<sup>384</sup> which is one part of the energy sector that is difficult and expensive to decarbonize otherwise. However, BECCS is limited by the supply of sustainable bioenergy.<sup>8,385-388</sup> Enhanced rock weathering is more expensive due to the extensive mining and related operations needed to produce crushed basalt rock, but little additional technological development and no carbon storage infrastructure is required. In the limited number of scenarios available, enhanced rock weathering scales up to megaton and gigaton scale around mid-century. DACCS has the highest costs and energy requirements, but also the largest potential to scale.<sup>8</sup> Therefore, the models invest in early upscaling to the megaton scale by about 2035, to be able to reach the gigaton scale in the second half of the century.

After mid-century, most novel CDR scales up higher than conventional CDR in the scenarios assessed (Figure 8.1). The extent of total deployment depends to a large degree on the climate policy logic<sup>389</sup> used to drive the scenario, for example either using a full century carbon budget, which can first be exceeded and then drawn down, or not exceeding a peak temperature, which can result in lower overall system costs and lower levels of CDR deployment.<sup>338,390</sup> The deployment levels of the different options then depend on each option's total potential and the options' relative competitiveness.

Enhanced rock weathering performs more efficiently in warm and humid climates and has the highest potential in Asia and Latin America.<sup>358</sup> BECCS needs biomass supply, thus has higher technical potential in Asia and Latin America (similar to conventional CDR), with regional distribution dependent on the modelling framework used.<sup>384,391</sup> However, for BECCS to be considered a CDR method, its carbon emissions must be captured and ultimately stored, requiring extensive carbon capture and storage infrastructure, which may be more prevalent elsewhere. Also, the bioenergy could potentially be traded, as is the case currently between the UK and the US, which itself can raise sustainability concerns if the biomass is sourced, for example, from existing primary forests, as has been alleged in the UK context.<sup>392</sup> This means biomass could be grown elsewhere but ultimately used as BECCS in a different location. However, given the low energy density of biomass, the cost and energy penalty for transportation would be higher than for fossil fuels.

DACCS shows a different geographic profile, with high deployment in regions that have high renewable energy potential in combination with high carbon storage potential. Regions with the highest DACCS deployment in currently assessed scenarios are developed countries, Asia, and the Middle East and North Africa. If DACCS is built further away from these areas, it would require extensive carbon capture and storage infrastructure, similar to BECCS.

The well-known questions and potential risks related to the sustainability (see next section) and monitoring, reporting and verification of BECCS have led the scenario literature to focus more on DACCS as a novel CDR option. However, DACCS is still expected to be one of the most expensive CDR options. Scenario evidence shows DACCS exceed the 1 GtCO<sub>2</sub> per year scale only at carbon prices above \$350/tCO<sub>2</sub>, and sometimes far higher. DACCS also requires substantial energy inputs, which must come from carbon-free energy to maximize carbon capture efficiency and avoid environmental degradation,<sup>393</sup> in addition to the carbon-free energy required to support the transition of other sectors. Furthermore,

carbon storage needs to be provided in potential competition with other sectors – for example, for process emissions in the cement industry – and with other CDR methods.

### Potential risks and benefits of novel CDR

The IPCC provided a recent assessment of the risks and benefits of various novel CDR methods including biochar, BECCS, DACCS, enhanced rock weathering, ocean fertilization, ocean alkalinity enhancement and biomass sinking (e.g. macroalgae, seaweed).<sup>4</sup> Although scientific studies are continuing to emerge, large knowledge gaps remain about the effectiveness and risks of large-scale deployment of most novel CDR methods.

#### Potential social and environmental benefits

Novel CDR methods that store carbon geologically have the benefit of greater storage durability than conventional land-based CDR, locking in removals for as much as hundreds to thousands of years.<sup>4</sup> Similar to conventional CDR, some novel CDR methods also have the potential to yield social and environmental co-benefits depending on the type of activity deployed, its scale, and the local or regional context in which it is used. For example, strategically deployed biochar and enhanced rock weathering could help improve soil health and crop yields and reduce drought effects,<sup>367,394,395</sup> seaweed production and BECCS could contribute to market opportunities,<sup>8</sup> and regional ocean alkalinity enhancement could help protect coral reefs and shellfisheries from ocean acidification.<sup>396,397</sup> However, it is very difficult to determine the scale at which the benefits of various novel CDR technologies outweigh their potential negative impacts (outlined in the following subsections).<sup>365</sup>

#### Potential social and environmental risks

The sustainability risks of BECCS – such as increased land use and conversion, water use and fertilizer use, and their related adverse effects on food security, biodiversity and greenhouse gas emissions – have been relatively well explored and are similar to those of large-scale afforestation/reforestation covered in the section on the potential risks of conventional CDR.<sup>349,385,387,398–403</sup> Large-scale DACCS deployment requires volumes of sorbent bulk materials orders of magnitude larger than are produced today as well as significant energy requirements, on the order of a quarter to a third of today's global energy production.<sup>393,404</sup> Deploying enhanced rock weathering at scale would have a significant mining footprint, and the required rock grinding would have a significant energy and water footprint, with related potential negative impacts on biodiversity, on local water availability and quality, and on air quality.<sup>394,405</sup> In the scientific literature, ocean-based approaches including ocean fertilization and ocean alkalinity enhancement currently have a high risk profile due to large uncertainties related to ecosystem destabilization, feedback effects, and impacts on biodiversity.<sup>4</sup> Ocean alkalinity enhancement also has similar risks from mining (e.g. silicate materials) as are associated with enhanced rock weathering.<sup>397,406</sup>

#### Climate change mitigation risks

A key risk of large-scale novel CDR is scalability: that the technical, economic and political requirements and social acceptance for such levels of deployment may not be feasible or materialize in time, jeopardizing mitigation goals.<sup>8,407,408</sup> In particular, assumptions related

to the mitigation efficiency of novel CDR methods have been challenged, in particular for BECCS (biomass yield and CDR conversion assumptions)<sup>398,399,409,410</sup> and DACCS and enhanced rock weathering (renewable energy use and availability assumptions).<sup>393,404,405</sup> In addition, models tend to assume very large capture efficiencies, on the order of 90–95%, and would overestimate the effectiveness of carbon capture and storage should these efficiencies fail to materialize in practice.

### Risk mitigation strategies

The choice of feedstock (e.g. agricultural residues instead of dedicated bioenergy crops), coupled with reduced energy demand and a limited scale of deployment, can help mitigate the negative consequences of many novel CDR approaches. More research is needed to reduce the uncertainties, better understand the magnitude of risks compared with benefits, and develop strategies to mitigate the risks and maximize the benefits associated with most novel CDR.

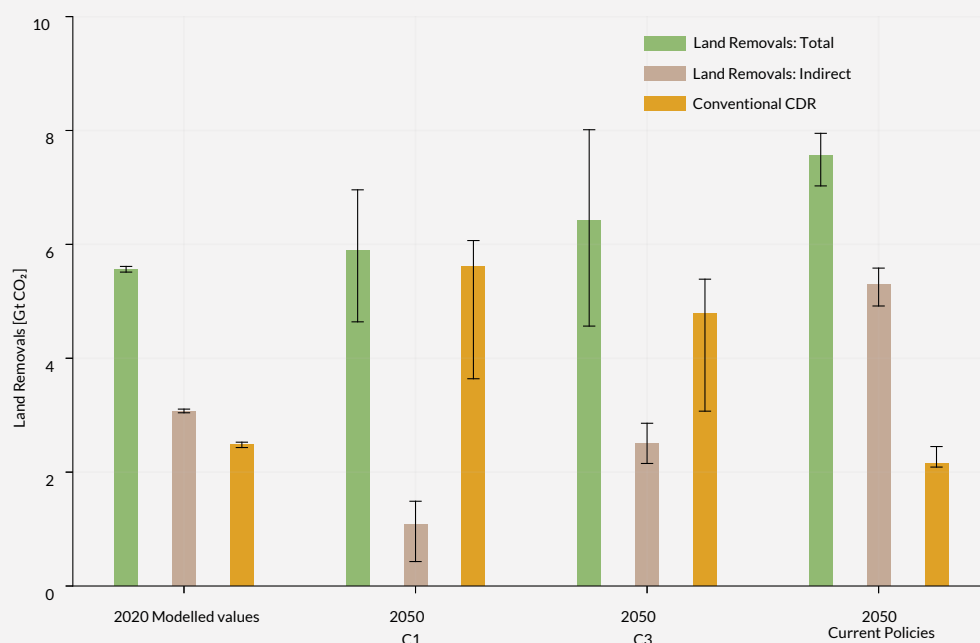
#### Box 8.3 Uncertainties related to land-based CDR (conventional and novel)

The ability for land-based ecosystems to effectively remove CO<sub>2</sub> from the atmosphere is subject to multiple uncertainties, including physical uncertainties and accounting uncertainties. These uncertainties further emphasize that the most reliable strategy to keep temperatures within liveable limits is to reduce sources of emissions rather than depend on uncertain future sinks.

Both conventional and novel methods of land-based CDR are subject to physical uncertainties (in this case, biogeochemical and biogeophysical uncertainties) caused by imperfect understanding of how the land biosphere and its cycling of carbon and other greenhouse gases will respond to future climate change. The uncertainties are dominated by poorly constrained carbon densities (notably in soils), biospheric regrowth curves, and the fate of dead biomass. In addition, under a changing climate, disturbances such as pests, wildfires and windthrow will see changes in frequency and intensity, which in turn may reduce the durability of land carbon storage and the overall efficiency of land-based CDR. Finally, it is not clear that land-based CDR will be as effective after net zero CO<sub>2</sub> as it is when CO<sub>2</sub> emissions are net positive.<sup>411</sup> The estimates of future land-based CDR in this report do not account for these additional risks.

Accounting uncertainties affect current and future estimates of CDR as well as net emissions on land. As discussed in Chapter 7 (Current levels of CDR), countries and parties to the UNFCCC account for emissions and removals (together called *carbon fluxes*) in a different way in their national greenhouse gas inventories than is considered by scientific models (including the bookkeeping models assessed in Chapter 7 and the IAMs assessed in this chapter).<sup>326</sup> The different approaches mean that model-based results cannot be compared one-to-one with country-based accounting, presenting another layer of uncertainty. The divergent accounting practices have important ramifications for mitigation benchmarks<sup>337</sup> as well as for how CDR

is measured, both today and in the future. Because the strength of future indirect removals is directly linked to mitigation action (strong mitigation action likely means weaker indirect removals; weak mitigation action likely means stronger indirect removals), exactly what level of future CDR is estimated depends critically on which accounting approach is used. By 2050, under current policy pathways, for example, total land-based removals increase relative to today even more so than in 1.5°C and 2°C scenarios (see Figure 8.4), whereas CDR as defined by the IPCC and in this report shows opposite trends.



**Figure 8.4** Future levels of carbon removal differ according to which land accounting practice is used. Land-based removals (green) are those from national greenhouse gas inventories, conventional carbon dioxide removal (CDR; yellow) is from integrated assessment models, and indirect land-based removals (brown) is the difference between the two in a given scenario. Median and interquartile ranges are shown across all scenarios (the summation of conventional CDR and indirect removals does not hold for distributional values).

## 8.4 Towards sustainable development pathways

**CDR pathways and deployment strategies need to be aligned with the SDGs and other global goals *in addition to significantly reducing emissions to meet the Paris temperature goal.***

Countries have set ambitious global goals under the three Rio Conventions (UNFCCC, the Convention on Biological Diversity, and the United Nations Convention to Combat Desertification) and the SDGs, committing to address multiple intertwined challenges, including climate change, biodiversity, desertification, poverty, hunger and equity. These global goals provide a picture of a collective desire, which is increasingly informing private sector (e.g. Science Based Targets initiative, International Organization for Standardization, Science Based Targets Network, Task Force on Climate-Related Financial Disclosures) and subnational goals. However, scenarios, road maps and policies are frequently developed and implemented through a siloed approach, focusing on one issue (e.g. climate change).

Truly holistic perspectives are rare. Effectively meeting the global goals will require more-integrated planning and deployment that achieves multiple outcomes simultaneously and minimizes trade-offs.

As outlined in Chapter 7 (Current levels of CDR), most countries currently deploy or include plans to deploy conventional CDR. Often, those actions are prioritized as policymakers and practitioners seek other benefits beyond climate change mitigation, including to stop land degradation, enhance adaptation and resilience, and improve biodiversity outcomes (e.g. land degradation neutrality targets, SDG 13, Global Biodiversity Framework, United Nations Decade on Ecosystem Restoration). However, these country priorities are still not adequately reflected in model scenarios, including those assessed in this report.

Most scenarios continue to optimize solely for climate change mitigation and cost, too often producing unsustainable futures including very high levels of CDR that may jeopardize the attainment of other global goals. This report uses scenarios as a key line of evidence to explore more-sustainable CDR deployment, but the analysis is limited by the kind and quality of information available in scenario databases. A key future improvement in the scenario community would be to standardize variable information critical to understanding impacts across multiple SDGs, in particular in the land sector. For example, distinguishing between primary ecosystems (e.g. old-growth forests), secondary ecosystems (e.g. regrowth), and plantations could provide helpful information on risks to biodiversity and ecosystem services from land conversion associated with CDR options. Separating the extent of land area used for afforestation versus reforestation would also significantly enhance understanding of the biodiversity and water implications associated with conventional CDR. Ultimately, progress towards a larger set of scenarios that go beyond optimizing for mitigation and cost towards optimizing the delivery of globally agreed goals on biodiversity, land degradation and sustainable development would be helpful and highly relevant for policy development.

Approximately 7–9 GtCO<sub>2</sub> per year of CDR will likely be needed by 2050 to limit global temperature change consistent with the Paris Agreement. However, the most important near- and long-term action remains reducing sources of emissions to the largest extent possible. The assessment in this report shows that deploying CDR at a multi-gigaton scale could be consistent with sustainability objectives if it is paired with ambitious gross emission reductions. Scenarios that are more aligned with sustainable development tend to deploy less cumulative CDR and much less novel CDR than scenarios that are not likely to be sustainable. However, sustainability outcomes can only be attained through strategic planning and deployment of CDR that explicitly caters to regional, landscape and local contexts and is designed for multiple benefits. It is vital that CDR policy and strategy be considered in the context of sustainable development to balance benefits and trade-offs and explicitly address the associated risks.

### **Box 8.4 Limitations and knowledge gaps**

This report has identified areas on which future assessments can build, including:

- The development of a larger set of sustainability scenarios that go beyond optimizing for climate change mitigation and cost and incorporate other globally agreed goals on biodiversity, land degradation and sustainable development
- Standardization of variable information in scenarios critical to understanding impacts across multiple SDGs
- Environmental, social and economic trade-offs, including the effectiveness and risks of deploying different CDR methods across regions



THE STATE OF  
**Carbon  
Dioxide  
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