

<https://doi.org/10.1038/s43247-024-01527-z>

Evaluating the near- and long-term role of carbon dioxide removal in meeting global climate objectives

Check for updates

Gaurav Ganti ^{1,2,3} ✉, Thomas Gasser ³, Mai Bui ^{4,5}, Oliver Geden ⁶, William F. Lamb ^{7,8}, Jan C. Minx ^{7,8}, Carl-Friedrich Schleussner ^{1,2,3} & Matthew J. Gidden ^{2,3} ✉

The 6th Assessment Report from the Intergovernmental Panel on Climate Change lacked sufficient land-sector scenario information to estimate total carbon dioxide removal deployment. Here, using a dataset of land-based carbon dioxide removal based on the scenarios assessed by the Intergovernmental Panel on Climate Change, we show that removals via afforestation and reforestation play a critical near-term role in mitigation, accounting for around 10% (median) of the net greenhouse gas emission reductions between 2020 and 2030 in scenarios that limit warming to 1.5 °C with limited overshoot. Novel carbon dioxide removal technologies such as direct air carbon capture and storage scale to multi-gigatonne levels by 2050 and beyond to balance residual emissions and draw down warming. We show that reducing fossil fuel and deforestation emissions (gross emissions) accounts for over 80% of net greenhouse gas reductions until global net zero carbon dioxide (CO₂) independent of climate objective stringency. We explore the regional distributions of gross emissions and total carbon dioxide removal in cost-effective mitigation pathways and highlight the importance of incorporating fairness and broader sustainability considerations in future assessments of mitigation pathways with carbon dioxide removal.

The Intergovernmental Panel on Climate Change (IPCC) assesses Integrated Assessment Model (IAM) scenarios to explore different ways to meet global climate targets and inform international and national climate policy processes¹. Climate change mitigation is achieved through deep cuts in gross carbon dioxide (CO₂) and non-CO₂ emissions as well as different methods of carbon dioxide removal (CDR) depending on assumptions of the availability, cost, and feasibility of different mitigation options^{2,3}. However, the IPCC's 6th Assessment Report (AR6) did not provide a complete assessment of total CDR deployment, and consequently, residual CO₂ and greenhouse gas (GHG) emissions in the assessed scenarios. This was because the underlying modelling frameworks either used different reporting methodologies for land CDR (removals via afforestation and reforestation) or did not separate gross emissions and removals in the land sector⁴. Scientific publications that analyse removals based on the AR6 scenarios either omit scenarios that do not report land removals⁵ (without accounting for differences in reporting methodologies) or use net-negative CO₂ emissions from the agriculture, forestry, and land-use (AFOLU) sector

as a proxy for land-based removals⁶ (ignoring current removals and near-term land sector dynamics). This creates a fundamental data and knowledge gap, as a comprehensive understanding of the mitigation solution space requires information on both gross emissions reductions and total removals to evaluate the relevant contributions and trade-offs of different mitigation options.

Here, we close this gap by providing a comprehensive global and regional assessment of total CDR in mitigation scenarios using a novel dataset of land-based carbon fluxes⁷ derived from the AR6 scenario database⁸. We evaluate the roles of gross emission cuts and resulting residual emissions as well as total CDR across three categories of pathways assessed by the IPCC - C1 (limit warming to 1.5 °C (>50%) with limited overshoot), C2 (return warming to 1.5 °C (>50%) after a high overshoot) and C3 (limit warming to 2 °C (>67%)) pathways (see Methods for definitions). We further evaluate the components of total CDR across two categories - conventional CDR on land (methods that provide CDR at scale today, capturing and storing carbon in the land biosphere – currently estimated to

¹Geography Department and IRI THESys, Humboldt-Universität zu Berlin, Berlin, Germany. ²Climate Analytics, Berlin, Germany. ³International Institute for Applied Systems Analysis, Laxenburg, Austria. ⁴Centre for Environmental Policy, Imperial College London, London, UK. ⁵Centre for Process Systems Engineering, Imperial College London, London, UK. ⁶German Institute for International and Security Affairs, Berlin, Germany. ⁷Mercator Research Institute on Global Commons and Climate Change, Berlin, Germany. ⁸Priestley Centre for Climate Futures, University of Leeds, Leeds, UK. ✉e-mail: gaurav.ganti@climateanalytics.org; gidden@iiasa.ac.at

contribute around 2 Gt CO₂ of removals per year⁷) and novel CDR (proposed methods not used at scale today that store captured carbon in geological formations, the ocean, or products – the methods include bioenergy with carbon capture and storage, or BECCS, direct air carbon capture and storage, or DACCS, and enhanced weathering – currently estimated to contribute around 2 Mt CO₂ of removals per year^{9,10}).

Results and discussion

Global mitigation assessment

We assess the difference in GHG emission reduction rates over different time frames across the three IPCC categories of pathways (Table 1). In 1.5 °C pathways with limited overshoot (C1), most of the mitigation between 2020 and 2030 (Fig. 1a) is achieved by reducing gross CO₂ emissions (70% [64, 77 interquartile range]) and cutting non-CO₂ emissions (20% [16, 24]). This is accompanied by a smaller, yet important, contribution from pursuing sustainable land-use strategies through halting deforestation and expanding conventional CDR on land (accounting for 10% [5, 14] of net GHG reductions), nearly doubling the volume of CDR in this decade (Table 1). Across most C1 scenarios, novel CDR methods scale up by mid-century to support the achievement of net zero CO₂, increasing to levels of around 4 Gt CO₂ [2, 6] by 2050. Between 2020 and global net zero CO₂, gross CO₂ reductions account for 71% [66, 74] of the net GHG reductions in C1

pathways with CDR contributing a much smaller amount (15% [12, 21]). These patterns (dominant reductions in gross CO₂ emissions and alternating importance of non-CO₂ reductions and CDR) are similar in C2 and C3 pathways (Supplementary Fig. 1 and Supplementary Table 1) but with slower near-term net GHG reductions (Table 1). Across all the scenarios, at the year of global net zero CO₂, we estimate a gross greenhouse gas emission level of 18 [16, 21] Gt CO₂eq/yr (Fig. 1c), which is largely consistent with an alternate estimation approach adopted by ref. 11, who estimate a residual emission level of 16 [12, 26] Gt CO₂eq/yr across these three categories of pathways.

Across all the categories of pathways, over 80% of the net GHG reductions between 2020 and global net zero CO₂ are achieved by cuts in gross CO₂ and non-CO₂ emissions (Fig. 1c). This indicates that less stringent climate objectives do not imply a fundamental change in the scale of gross CO₂ reductions necessary, but merely shift this over time, raising questions of intergenerational fairness. In other words, overall mitigation effort is similar across different temperature categories, while climate impacts and related adaptation needs increase in line with additional warming.

Delaying mitigation action impacts the volume and composition of CDR until global net zero CO₂ (Fig. 1d, e). We conceptualise delay across two dimensions - the time to halve net CO₂ emissions and the number of years until global net zero CO₂ is achieved. We find that the amount of

Table 1 | Key global benchmarks in assessed mitigation pathways

IPCC category	Variable	Level [Gt CO ₂ e/yr]				
		2020	2030	2035	2050	2100
C1 (n = 70)	Net GHG (direct)	53.4 [55.2, 52.6]	28.9 [32.4, 26.0]	21.1 [24.2, 18.5]	7.2 [8.7, 5.3]	1.7 [7.6, -5.9]
	Gross CO ₂ (direct)	41.8 [43.7, 40.0]	24.5 [26.2, 21.1]	18.1 [20.6, 16.1]	8.3 [10.1, 7.5]	5.5 [11.7, 3.9]
	Non-CO ₂	14.8 [15.2, 14.0]	9.8 [10.8, 9.3]	9.0 [9.9, 8.4]	7.6 [8.9, 6.7]	6.6 [7.6, 5.3]
	CDR (direct)	2.5 [2.5, 2.5]	5.1 [5.7, 3.9]	6.1 [7.1, 4.9]	9.3 [11.5, 7.6]	11.8 [17.1, 9.5]
	Novel CDR	0 [0, 0]	0.3 [0.6, 0.1]	1 [1.7, 0.3]	3.8 [5.7, 1.8]	7.7 [12.6, 5.7]
	Conventional CDR on land	2.5 [2.5, 2.5]	4 [5.1, 3.4]	4.8 [5.6, 3.9]	5.4 [6.3, 3.6]	3.6 [4.6, 2.2]
C2 (n = 102)	Net GHG (direct)	55.2 [55.7, 53.4]	41.5 [49.0, 36.0]	31.4 [36.4, 27.9]	12.8 [15.5, 9.0]	-5.5 [-2.7, -8.0]
	Gross CO ₂ (direct)	43.3 [43.9, 41.5]	33.5 [39.2, 28.4]	26.2 [29.3, 22.5]	12.6 [16.1, 10.7]	5.3 [7.9, 4.0]
	Non-CO ₂	14.3 [15.2, 13.8]	11.8 [13.4, 10.6]	10.0 [11.0, 9.4]	8.2 [9.1, 7.7]	6.0 [7.1, 4.9]
	CDR (direct)	2.5 [2.5, 2.5]	3.2 [4.1, 2.8]	4.5 [5.6, 3.5]	8.1 [10.5, 6.5]	17.6 [19.9, 13.9]
	Novel CDR	0 [0, 0]	0.1 [0.2, 0]	0.3 [0.6, 0.1]	3.5 [5.8, 1.2]	13 [15.8, 10.3]
	Conventional CDR on land	2.5 [2.5, 2.5]	3.1 [3.8, 2.7]	4 [4.5, 3.1]	5.2 [5.7, 3.7]	3.5 [5.1, 2.4]
C3 (n = 229)	Net GHG (direct)	53.5 [55.5, 52.5]	43.1 [49.1, 37.9]	34.5 [37.6, 29.5]	18.5 [21.1, 14.1]	3.8 [8.1, -2.1]
	Gross CO ₂ (direct)	42.1 [43.7, 40.0]	34.0 [39.3, 30.8]	28.1 [30.3, 24.8]	16.2 [18.3, 13.8]	8.7 [12.7, 6.8]
	Non-CO ₂	14.8 [15.3, 14.0]	12.2 [13.2, 11.0]	10.5 [11.4, 9.3]	8.6 [9.1, 7.2]	6.8 [7.7, 5.4]
	CDR (direct)	2.5 [2.5, 2.5]	3.2 [4.7, 2.7]	4.1 [5.5, 3.2]	6.3 [9.4, 5.5]	13.5 [17.4, 10.1]
	Novel CDR	0 [0, 0]	0 [0.2, 0]	0.2 [0.6, 0.1]	2 [3.6, 0.8]	9.7 [13.9, 6.3]
	Conventional CDR on land	2.5 [2.5, 2.5]	3.2 [4.5, 2.5]	3.6 [5, 2.5]	4 [5.5, 2.7]	3.4 [4.7, 2.2]

Note that we use the modelled 2020 values from the scenarios. We report the median and the interquartile range across the scenarios.

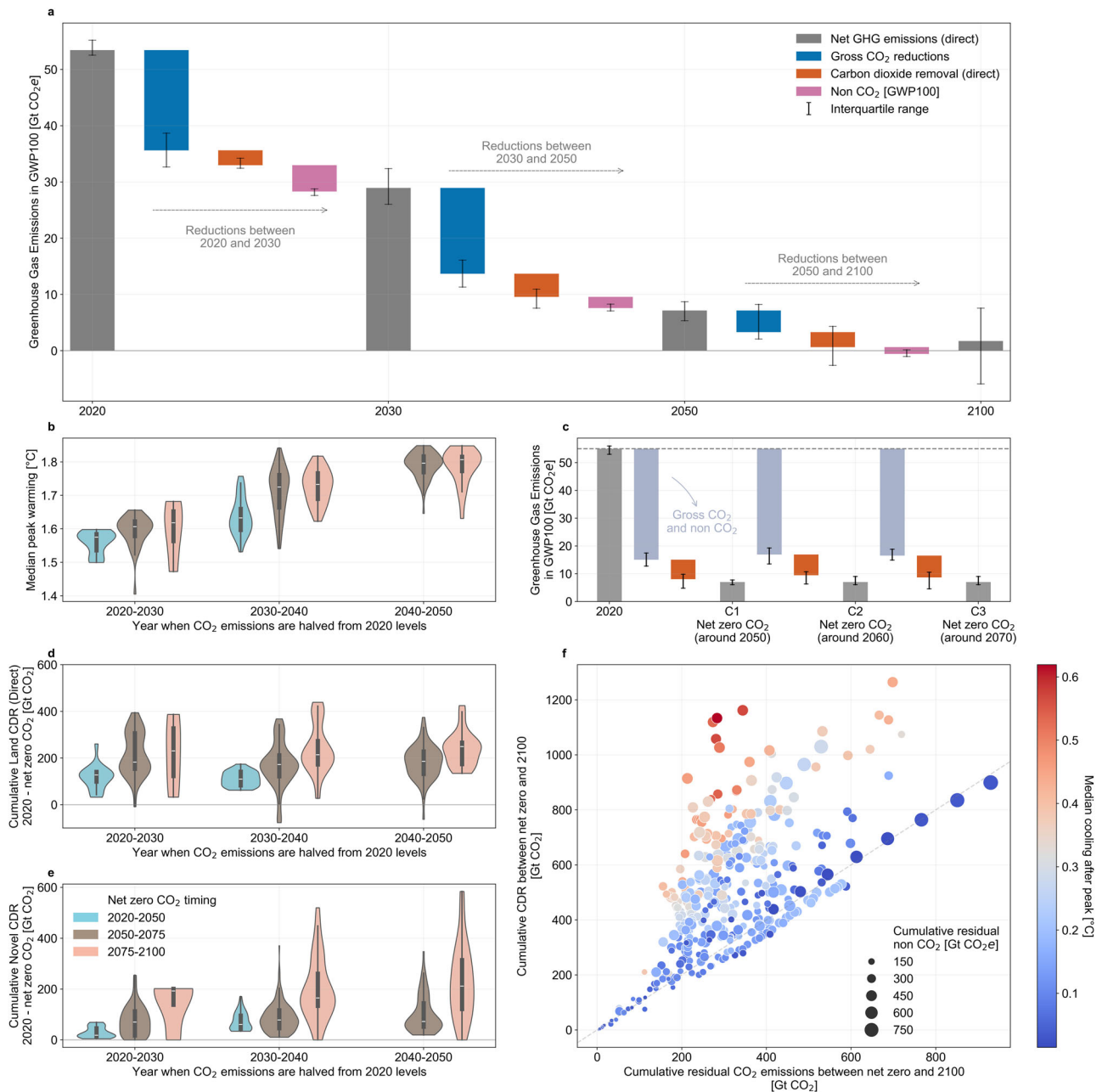


Fig. 1 | Global characteristics of gross emission reductions and total carbon dioxide removal (CDR) in deep mitigation pathways. a Contributions of gross CO₂ reductions, total CDR (direct – see Methods for definition) and non-CO₂ reductions to overall kyoto greenhouse gas emission reductions in C1 (limited overshoot 1.5 °C) pathways. **b** Distribution of median warming outcomes according to different dimensions of delayed mitigation. Scenarios are binned according to the number of years until global net zero CO₂ starting from 2020, as

well as the year when net CO₂ emissions (direct) are halved from 2020 levels. **c** Contributions to net GHG reductions until the year of net zero CO₂ across the C1, C2, and C3 categories of pathways. **d** Cumulative land (direct) and **(e)** novel CDR between 2020 and net zero CO₂. **f** Cumulative CDR between net zero CO₂ and 2100 versus cumulative residual CO₂ emissions over the same period. In panel **b**, **d**, **e**, the box represents the interquartile range (25–75th percentile) and the whiskers represent the range.

conventional CDR on land is largely consistent across different timings of delayed emissions reductions, implying that scenarios utilise land-based CDR regardless of the delay of emissions reductions elsewhere. Conversely, we observe a strong signal both in the median and extreme values in the amount of novel CDR utilised in scenarios which have longer net emission halving times, showing scenarios’ dependence on future, unproven CDR technologies when net emissions reductions are delayed. Delaying the time of net zero CO₂ results in an increase in the total CDR deployed till this year; for scenarios with a net zero timing by mid-century, the total volume of CDR deployed is 166 Gt CO₂ [149, 193], increasing to 251 Gt CO₂ [203, 320]

and 445 Gt CO₂ [345, 524] respectively for scenarios with a net zero timings between 2050 and 2075, and later than 2075. Conventional CDR on land tends to increase faster in scenarios with net zero CO₂ timing between 2050 and 2075 (Fig. 1d) while novel CDR increases faster in scenarios with net zero CO₂ timing between 2075 and 2100 (Fig. 1e). This reflects the lead time necessary to scale up novel removals, which are still at a nascent stage of development¹². These options are expected to require both time and investment to ramp up deployment and become a cost-effective part of a mitigation portfolio¹³. The contributing factors to high costs vary across the novel carbon removal options represented in IAMs, e.g., due to capital and

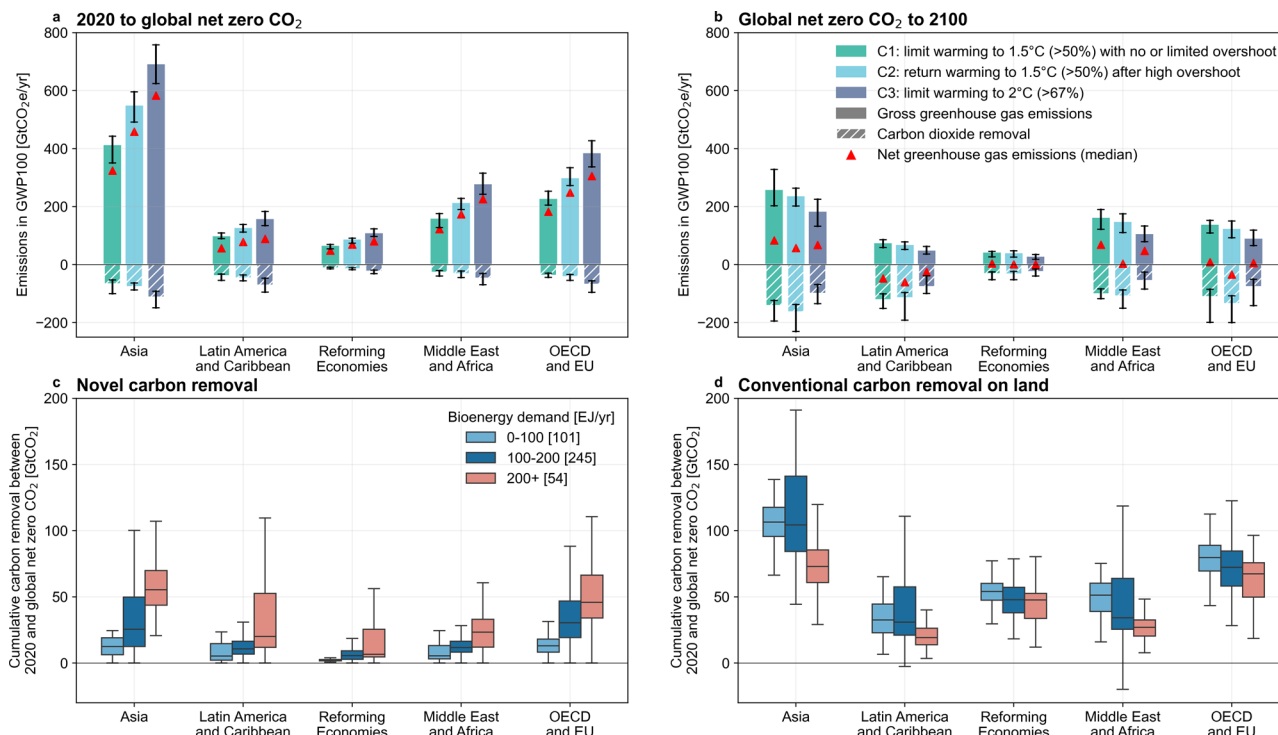


Fig. 2 | Regional assessment of gross emissions and carbon dioxide removal (CDR). **a** Cumulative gross emissions (CO₂ and non-CO₂) and carbon dioxide removal between 2020 and global net zero CO₂, **b** As in panel a, between global net zero CO₂ and 2100, **c** Cumulative regional novel CDR deployment across different levels of global bioenergy demand at the year of global net zero CO₂, **d** As in panel c, for conventional CDR on land. A level of 100 EJ/yr has been discussed in the

literature as a limit beyond which there are high sustainability concerns¹³. The number of scenarios in each group are indicated in square brackets in the legend. In panels **a** and **b**, the error bar represents the interquartile range (25–75th percentile). In panels **c** and **d**, the box represents the interquartile range (25–75th percentile) and the whiskers represent the range.

operating expenditures for DACCS or mining and transportation costs for enhanced weathering. Conventional removals on land, on the other hand, are currently deployed at scale and have a higher a near-term cost-effective mitigation potential when compared to novel carbon removal options, with a likely lower potential in the future given land competition and storage permanence risks caused by future climate change. Novel removal options may provide more cost-effective CDR in the longer term with lower permanence concerns compared to conventional removals on land⁴.

Beyond global net zero CO₂, CDR is the dominant mitigation option used in scenarios. CDR volumes are over 3 times higher than the 2020 levels in C1 pathways and over 6 and 4 times higher in C2 and C3 pathways by 2100 (Table 1). We tease out the effect of two factors influencing the volume of deployed CDR, drawing on previous research^{5,6} - the cumulative residual CO₂ emissions that need to be balanced to stabilise warming (see identity line in Fig. 1f) and the desired post-peak cooling. The latter is influenced by the residual non-CO₂ emissions. In the assessed C1 scenarios, 55% [44, 91] (in volume terms, 342 Gt CO₂ [245, 426]) of the total CDR deployed over this timeframe is to balance residual gross CO₂ emissions. The corresponding values for C2 scenarios are somewhat lower at 50% [40, 60] (in volume terms, 298 Gt CO₂ [236, 384]) linked to a greater demand for CDR to reverse temperature overshoot in C2 pathways when compared to C1 pathways - higher volumes of CDR are deployed in C2 pathways to reverse warming (309 Gt CO₂ [221, 424]) when compared to the C1 pathways (184 Gt CO₂ [26, 418]). In terms of composition, novel CDR accounts for around two thirds of total CDR between net zero CO₂ and 2100 (66% [58, 79]) across all pathways with similar ranges for each category of pathway.

Regional mitigation assessment

The composition of CDR and gross emission reductions vary across world regions depending on the cost-effective allocations in each scenario we assess, and we find some consistent regional observations and trends across

scenarios (Supplementary Table 2). We first focus on the regional gross GHG and CDR characteristics pre- and post-net-zero-CO₂ (Fig. 2a, b). Between 2020 and global net zero CO₂, the Asia region has the highest cumulative gross GHG emissions (410 [351, 443] Gt CO₂eq across the C1 pathways) as well as cumulative CDR (66 [53, 100] Gt CO₂ across the C1 pathways) across all three categories of the pathways we assess (Fig. 2a). The OECD and EU region (see Methods) consistently has the second highest contribution across the three pathway categories (225 [205, 253] Gt CO₂eq across the C1 pathways). However, the relative composition of cumulative gross GHG emissions shows pronounced variation across the regions, especially for the Latin America and the Middle East and Africa regions. While the Asia, OECD and EU, and Reforming Economies regions typically have a 70/30% (median) split between gross CO₂ and non-CO₂ emissions, the Latin America and Middle East and Africa regions have a split closer to 60/40% (median) across the C1 pathways. This is driven by the relatively low gross CO₂ emissions and the relatively high (and growing) shares of methane (CH₄) and nitrous oxide (N₂O) in the emissions profile of these regions (Supplementary Fig. 3a, b). For the Latin America region, this is largely driven by CH₄ and N₂O emissions in the AFOLU sector, while the Middle East and Africa region also has CH₄ contributions from the energy sector, reflecting the diverse energy systems within this macro region (Supplementary Fig. 3c, d).

Beyond global net zero CO₂, we observe that the Middle East and Africa region replaces the OECD and EU regions as the second highest source of gross emissions (160 [121, 190] Gt CO₂e across the C1 pathways), which is marginally higher than the region’s corresponding gross emissions between 2020 and net zero CO₂ (156 [128, 176] Gt CO₂e across the C1 pathways). The Asia region contributes the highest quantity of gross emissions (255 [203, 328] across the C1 pathways). These are the two regions typically have positive net emissions across the three categories of pathways (Fig. 2b), while the Latin America region is the only region which

typically contributes net negative GHG emissions (median). For the Latin America region, the cumulative CDR after net zero CO₂ is typically a roughly even split between conventional and novel CDR (the share of conventional CDR is 49% [38, 56], 41% [29, 49], 45% [32, 57] in C1, C2, and C3 pathways respectively). Cost-effective allocations reflect approaches which find the lowest cost deployment of mitigation options across regions which often differ markedly from the responsibility for deploying the resources to support this mitigation accounting for foundational principles of the Paris Agreement, including the principle of equity and common but differentiated responsibilities and respective capabilities^{14,15}.

We now turn our focus to the time varying role of different mitigation levers across the assessed regions. For the Asia region, we note a dominant contribution (median of around 80%) from gross CO₂ emission reductions across all three time periods in the C1 pathways with the rest largely coming from non-CO₂ reductions followed by CDR. However, in C2 and C3 pathways where there is slower global near-term action, CDR plays a larger role beyond 2050, accounting for over 20% (median) of the regional net GHG reductions. For the OECD and EU region we find similar patterns between 2020 and 2030 and onwards to 2050; however, after this 2050 removals play a much larger role in net GHG reductions across each category of pathways accounting for a median of around 43%, 48%, 35% respectively across the C1, C2 and C3 pathways. For the Latin America region, our analysis indicates that relatively high shares of GHG reduction (compared to other regions) are met through CDR between 2020 and 2030, with this role growing in each time frame thereafter. In C1 pathways, CDR accounts for 18% [14, 28.5] of regional GHG cuts between 2020 and 2030, and 32% [22, 42] and 79.5% [49, 136] between 2030 and 2050, and 2050 and 2100 respectively. A value greater than 100% for the 75th percentile in the latter estimate indicates that one (or both) of the other two components (gross CO₂ or non-CO₂ emissions) are growing in this period and hence have a negative contribution.

Broader sustainability concerns will play a role in constraining the role of CDR beyond the influence of regional costs and potentials. We provide an illustrative example using the case of the novel carbon removal option, bioenergy with carbon capture and storage (BECCS), where some of the sustainability concerns include competition for land, impact on food prices, and impacts on biodiversity, among others¹². Scenarios with lower levels of global bioenergy demand at net zero CO₂ (see Methods) tend to show a slight increase in deployment of conventional CDR on land across all world regions, with a marked decrease in the deployment of novel CDR between 2020 and global net zero CO₂ (Fig. 2c, d). However, there is a relatively weak correlation between the global bioenergy demand at net zero CO₂ and the cumulative total CDR deployed (Supplementary Fig. 2a) especially for bioenergy demand beyond 100 EJ (which we use as a sustainable threshold – see methods), consistent with the wide range of regional outcomes in Fig. 2c, d. One reason for this observation is because IAMs assume increasing crop yields for second-generation biofuel crops, which reduces the necessary agricultural area for their production per unit of CO₂ captured¹⁶. In principle, this means a given quantity of removals via BECCS can be consistent with different levels of bioenergy demand.

Large-scale deployment of conventional CDR on land is associated with a different set of concerns, including the impact on local livelihoods¹³ and the potential effects of climate-related feedbacks on the integrity of the sinks. Novel carbon removal options like DACCS raise concerns over their energy demand (and potential emissions associated with this), and enhanced weathering raises concerns over potential habitat destruction and water consumption, in addition to concerns over energy demand¹⁷. Different options are also at varying levels of technological readiness and associated with different co-benefits^{17,18}. This points to the need for a balanced portfolio approach to CDR deployment in mitigation pathways. As a new generation of mitigation pathways incorporate more novel CDR options^{3,19–22}, future scenario-based assessments should aim for a more comprehensive sweep of regional equity and sustainability implications of large-scale CDR deployment²³.

Conclusion

In this paper, we have provided the first comprehensive assessment of gross reductions and CDR in the AR6 mitigation scenarios using a dataset that separates net emissions in the land-use sector into its components. We show that over 80% of the net GHG cuts between 2020 and global net zero CO₂ are achieved via deep cuts in current sources of emissions. Conventional CDR on land plays an important near-term role, scaling up quickly from present levels in future pathways, largely in Latin America and Asia. Our results are aligned with model-based land-use, land-use change and forestry accounting conventions, and results may differ when using accounting conventions by parties to the UNFCCC, highlighting the importance of translating between both conventions⁷. A limitation of the current scenario literature is the lack of a comprehensive representation of climate-related feedbacks and risks (sink strength, droughts and wildfires) which could strongly reduce land-based CDR potentials²⁴. In the medium- and long-term, novel CDR plays a more important role in future mitigation pathways.

These novel CDR options, which include bioenergy with CCS, direct air capture with CCS, and enhanced weathering, among others, are currently at a nascent stage of development, expensive, and not deployed at scale⁹. These methods tend to be deployed across regions very differently than conventional CDR on land, but still result in large shares of CDR being deployed in currently developing regions. These relatively high contributions from developing regions raises questions around fairness given uneven distribution of responsibility for causing climate change²⁵. Addressing these challenges will require rapid scaling up of mitigation investments, and one solution that has been suggested to address this problem is to assess fair shares of mitigation investment in these pathways¹⁴, which should also take into account principles underlying the Paris Agreement, including sustainable development and equity²⁶.

Methods

Datasets assessed

The Working Group III contribution to the IPCC's 6th Assessment Report (AR6) relied on a large database of climate change mitigation scenarios which span a wide range of climate outcomes^{4,8,27}. However, there were two key policy relevant components that were not assessed comprehensively in the report – the contribution of carbon dioxide removal on land and hence the total carbon dioxide removal deployed. In this analysis, we use a combination of two datasets: the AR6 scenarios database and a new reanalysis dataset that estimates gross carbon dioxide removal in the land-sector⁷. This reanalysis dataset uses a subset of the reported variables across the scenarios in the AR6 scenario database as an input to the compact Earth system model OSCAR v3.2²⁸. These variables include information on the reported CO₂ emissions from the AFOLU sector (Emissions|CO₂|AFOLU), land cover data (Land Cover|Cropland, Land Cover|Forest, Land Cover|Pasture) and information from the climate assessment from the simple climate model MAGICC v7.5.3^{29–31}. This reanalysis dataset is available only at the R5 region level assessed by the IPCC due to land-cover data availability in the original scenarios:

- R5OECD90 + EU: North America, Europe, Australia, Japan and New Zealand (referred to as OECD and EU in the main text)
- R5REF: Eastern Europe and West-Central Asia
- R5ASIA: Eastern Asia, Southern Asia, South-East Asia and Pacific (referred to as Asia in the main text)
- R5MAF: Middle East and Africa
- R5LAM: Latin America and Caribbean

While the IPCC regional definitions (outlined below) are relatively coarse, they still allow us to tease out broad regional differences³². Nonetheless, they should be interpreted with caution if they are applied to component countries of these regions.

Scenario categories assessed

We assess three groups (or categories) of scenarios in this paper; this categorisation is based on an assessment of the climate outcomes of the scenarios.

Two of these categories of scenarios (C1: limit warming to 1.5 °C (>50%) with limited overshoot, and C3: limit warming to 2 °C (>67%) were highlighted by the IPCC in its Summary for Policymakers. The C1 scenarios are scenarios which simultaneously limit peak warming below 1.5 °C with at least a 33% chance and 2100 warming below 1.5 °C with at least a 50% chance. This category is arguably closest to operationalising Article 2.1(a) of the Paris Agreement, which includes a commitment to “[h]old the increase in global average temperature to well below 2 °C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels [...]”³³. In addition to the C1 and C3 scenarios, we also evaluate the C2 scenarios (return warming below 1.5 °C (>50%) after a high overshoot). For the assessment of sustainability, we adopt a different grouping strategy by grouping the scenarios on their levels of global bioenergy demand at global net zero CO₂ (variable: Primary Energy|Biomass). The first group (0–100 EJ/yr) includes scenarios with global bioenergy demand within sustainability limits previously discussed in the literature^{13,34}, with the other two groups (100–200 and 200 + EJ/yr) reflecting much higher levels of global bioenergy demand.

Additional data processing

In this section, we document the additional processing steps to generate the variables we analyse in this paper. We first calculate the total CDR deployed for each scenario, both at the global and the R5 region level as the sum of the novel CDR (variable label: AR6 Reanalysis|OSCARv3.2|Carbon Removal|Non-Land) and the direct conventional CDR on land (variable label: AR6 Reanalysis|OSCARv3.2|Carbon Removal|Land|Direct). The “Direct” effect that we refer to here includes direct anthropogenic land fluxes, including human-driven changes in land-use. Novel CDR includes: bioenergy with carbon capture and storage (Carbon Sequestration|CCS|Biomass), direct air carbon capture and storage (Carbon Sequestration|Direct Air Capture) and enhanced weathering (Carbon Sequestration|Enhanced Weathering). From this estimate of total CDR, we can estimate the gross CO₂ emissions (which we also refer to as residual CO₂ emissions), by adding the derived total CDR to the direct net CO₂ emissions (variable label: AR6 Reanalysis|OSCARv3.2|Emissions|CO2|Direct Only). We check whether the value for the World region is positive in all years and omit 6 scenarios where this is not the case. We assess the non-CO₂ contribution by subtracting the direct net CO₂ emissions from the assessed direct Kyoto greenhouse gas emissions (AR6 Reanalysis|OSCARv3.2|Emissions|Kyoto Gases|Direct Only). The constituent greenhouse gases are aggregated by converting them into CO₂-equivalent units using 100-year global warming potentials (GWP100) from the Working Group 1 contribution to the IPCC’s 6th Assessment Report³⁵. Where we refer to the global net zero CO₂ year in this analysis, we are referring to the harmonised global net zero CO₂ year reported in the metadata that accompanies the AR6 scenario database (column name: ‘Year of netzero CO2 emissions (Harm-Infilled) table’). The net zero CO₂ years in the reanalysed dataset are very close to the reported harmonised global net zero CO₂ year, with a median difference of 1 year [−1, 5]. To compute the components of mitigation effort for a given period, we first calculate the change in the desired variable relative to the starting year and divide the corresponding values from the component regional results or component variables to derive the percentage compositions. For instance, suppose we want to evaluate the contribution of gross CO₂ emission reductions to net GHG emission reductions in the Asia region between 2020 and 2030. We first calculate the change in 2030 for gross CO₂ emissions and net GHG emissions for this region across all the scenarios and then proceed to divide the change in gross CO₂ emissions by the change in net GHG emissions.

Data availability

The reanalysis dataset from ref. 7 is available at: <https://data.ece.iiasa.ac.at/genie>. The AR6 scenario data from refs. 4,8 is available at: <https://data.ene.iiasa.ac.at/ar6>.

Code availability

The code underlying this study is openly available at: https://github.com/gaurav-ganti/2023_ganti_ar6_cdr_assessment

Received: 23 January 2024; Accepted: 24 June 2024;

Published online: 15 July 2024

References

1. Pedersen, J. T. S. et al. IPCC emission scenarios: How did critiques affect their quality and relevance 1990–2022? *Glob. Environ. Change* **75**, 102538 (2022).
2. Strefler, J. et al. Between Scylla and Charybdis: Delayed mitigation narrows the passage between large-scale CDR and high costs. *Environ. Res. Lett.* **13**, 044015 (2018).
3. Gidden, M. J. et al. Fairness and feasibility in deep mitigation pathways with novel carbon dioxide removal considering institutional capacity to mitigate. *Environ. Res. Lett.* **18**, 074006 (2023).
4. Riahi, K. et al. Mitigation pathways compatible with long-term goals. In *IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (eds. Shukla, P. R. et al.) (Cambridge University Press, 2022). <https://doi.org/10.1017/9781009157926.005>.
5. Prütz, R., Strefler, J., Rogelj, J. & Fuss, S. Understanding the carbon dioxide removal range in 1.5 °C compatible and high overshoot pathways. *Environ. Res. Commun.* **5**, 041005 (2023).
6. Schleussner, C.-F., Ganti, G., Rogelj, J. & Gidden, M. J. An emission pathway classification reflecting the Paris Agreement climate objectives. *Commun. Earth Environ.* **3**, 1–11 (2022).
7. Gidden, M. J. et al. Aligning climate scenarios to emissions inventories shifts global benchmarks. *Nature* 1–7, <https://doi.org/10.1038/s41586-023-06724-y> (2023).
8. Byers, E. et al. AR6 Scenarios Database. Zenodo <https://doi.org/10.5281/ZENODO.5886911> (2022).
9. Powis, C. M., Smith, S. M., Minx, J. C. & Gasser, T. Quantifying global carbon dioxide removal deployment. *Environ. Res. Lett.* **18**, 024022 (2023).
10. Smith, S. M. et al. *The State of Carbon Dioxide Removal*, 1st ed. <https://doi.org/10.17605/OSF.IO/W3B4Z> (2023).
11. Lamb, W. F. The size and composition of residual emissions in integrated assessment scenarios at net-zero CO₂. *Environ. Res. Lett.* **19**, 044029 (2024).
12. Nemet, G. F. et al. Near-term deployment of novel carbon removal to facilitate longer-term deployment. *Joule* **7**, 2653–2659 (2023).
13. Fuss, S. et al. Negative emissions—Part 2: Costs, potentials and side effects. *Environ. Res. Lett.* **13**, 063002 (2018).
14. Pachauri, S. et al. Fairness considerations in global mitigation investments. *Science* **378**, 1057–1059 (2022).
15. Fyson, C. L., Baur, S., Gidden, M. & Schleussner, C.-F. Fair-share carbon dioxide removal increases major emitter responsibility. *Nat. Clim. Change* **10**, 836–841 (2020).
16. Popp, A. et al. Land-use futures in the shared socio-economic pathways. *Glob. Environ. Change* **42**, 331–345 (2017).
17. Babiker, M. et al. Cross-sectoral perspectives. In *Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, <https://doi.org/10.1017/9781009157926.005> (2022).
18. UNEP. *Emissions Gap Report 2023*. <http://www.unep.org/resources/emissions-gap-report-2023> (2023).
19. Fuhrman, J. et al. Diverse carbon dioxide removal approaches could reduce impacts on the energy–water–land system. *Nat. Clim. Change* **13**, 341–350 (2023).
20. Strefler, J. et al. Carbon dioxide removal technologies are not born equal. *Environ. Res. Lett.* **16**, 074021 (2021).
21. Ampah, J. D. et al. Prioritizing Non-Carbon Dioxide Removal Mitigation Strategies Could Reduce the Negative Impacts Associated with Large-Scale Reliance on Negative Emissions. *Environ. Sci. Technol.* **58**, 3755–3765 (2024).

22. Adun, H., Ampah, J. D., Bamisile, O. & Hu, Y. The synergistic role of carbon dioxide removal and emission reductions in achieving the Paris Agreement goal. *Sustain. Prod. Consum.* **45**, 386–407 (2024).
23. Deprez, A. et al. Sustainability limits needed for CO₂ removal. *Science* **383**, 484–486 (2024).
24. Sanderson, B. M. et al. The need for carbon emissions-driven climate projections in CMIP7. *EGUsphere* 1–51, <https://doi.org/10.5194/egusphere-2023-2127> (2023).
25. Skeie, R. B. et al. Perspective has a strong effect on the calculation of historical contributions to global warming. *Environ. Res. Lett.* **12**, 024022 (2017).
26. Rajamani, L. et al. National ‘fair shares’ in reducing greenhouse gas emissions within the principled framework of international environmental law. *Clim. Policy* **21**, 983–1004 (2021).
27. Kikstra, J. S. et al. The IPCC Sixth Assessment Report WGIII climate assessment of mitigation pathways: from emissions to global temperatures. *Geosci. Model Dev.* **15**, 9075–9109 (2022).
28. Quilcaille, Y., Gasser, T., Ciais, P. & Boucher, O. CMIP6 simulations with the compact Earth system model OSCAR v3.1. *Geosci. Model Dev.* **16**, 1129–1161 (2023).
29. Meinshausen, M. et al. The shared socio-economic pathway (SSP) greenhouse gas concentrations and their extensions to 2500. *Geosci. Model Dev.* **13**, 3571–3605 (2020).
30. Meinshausen, M., Raper, S. C. B. & Wigley, T. M. L. Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 – Part 1: Model description and calibration. *Atmospheric Chem. Phys.* **11**, 1417–1456 (2011).
31. Nicholls, Z. et al. Changes in IPCC Scenario Assessment Emulators Between SR1.5 and AR6 Unraveled. *Geophys. Res. Lett.* **49**, e2022GL099788 (2022).
32. Al Khourdajie, A., van Diemen, R., Lamb, W.F., Pathak, M., Reisinger, A., de la Rue du Can, S., Skea, J., Slade, R., Some, S., Steg, L. IPCC. Annex II: Definitions, Units and Conventions. In *IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (eds. Shukla, P. R. et al.) (Cambridge University Press, 2022). <https://doi.org/10.1017/9781009157926.021>.
33. UNFCCC. *Decision 1/CP.21 Adoption of the Paris Agreement* (UNFCCC, 2015).
34. Luderer, G. et al. Economic mitigation challenges: how further delay closes the door for achieving climate targets. *Environ. Res. Lett.* **8**, 034033 (2013).
35. Forster, P. et al. The Earth’s Energy Budget, Climate Feedbacks, and Climate Sensitivity. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (IPCC, 2021).

Acknowledgements

GG acknowledges support from the Bundesministerium für Bildung und Forschung (BMBF) under grant no. 01LS2108D (CDR PoEt). M.J.G., J.C.M. and W.F.L. acknowledge support by the European Research Council (ERC) under the European Union’s Horizon 2020 Framework Programme as part of the project “GeoEngineering and Negative Emissions pathways in Europe”

(GENIE) [grant agreement No. 951542]. O.G. acknowledges support from the Bundesministerium für Bildung und Forschung (BMBF) under grant nos. 01LS2101A (CDRSynTra) and 03F0898E (ASMASYS). T.G. was also supported by the European Union’s Horizon Europe research and innovation program under grant agreement no. 101056939 (RESCUE project). C.F.S. acknowledges funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement no. 101003687 (PROVIDE). We acknowledge support by the Open Access Publication Fund of Humboldt-Universität zu Berlin.

Author contributions

M.J.G. and G.G. conceived the research. G.G. and M.J.G. performed the research and wrote the manuscript with input from T.G., M.B., O.G., W.L., J.M. and C.-F.S.

Funding

Open Access funding enabled and organized by Projekt DEAL.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1038/s43247-024-01527-z>.

Correspondence and requests for materials should be addressed to Gaurav Ganti or Matthew J. Gidden.

Peer review information *Communications Earth & Environment* thanks Jeffrey Ampah and HUMPHREY ADUN for their contribution to the peer review of this work. Primary Handling Editors: Martina Grecequet, Heike Langenberg. A peer review file is available.

Reprints and permissions information is available at <http://www.nature.com/reprints>

Publisher’s note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article’s Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article’s Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

© The Author(s) 2024