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Fair carbon removal obligations under climate response uncertainty

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ABSTRACT

Deploying carbon dioxide removal (CDR) is considered unavoidable to meet global climate goals. However, current assessments of the potential role of CDR tend to overlook uncertainty in the Earth System response to our emissions. Here, we assess the level of 'preventive' CDR needed to draw warming down to 1.5°C in case of a stronger-than-median Earth System response. Using the '1.5°C with no or limited overshoot' ensemble of pathways assessed by the Intergovernmental Panel on Climate Change (IPCC), we estimate that around 323–787 Gt CO_2 (interquartile range) of additional CDR (beyond the 418–763 Gt CO_2 (interquartile range) already deployed in these pathways) may be required after net zero CO_2 for a *very likely* (> = 90%) chance of reaching 1.5°C in 2100. We cannot know now whether a net zero society will need to utilize the preventive capacity, but the option must be available to them. Feasibility and sustainability concerns associated with large-scale CDR deployment raise fundamental questions over reducing potential future CDR reliance in light of Earth System uncertainty. Our analysis shows that reducing residual emissions from long-lived (e.g. CO_2 and N_2O) and short-lived climate forcers (e.g. CH_4) can significantly reduce the scale of preventive CDR required. We also explore an illustrative approach to equitably allocate global preventive CDR needs. North America is allocated a per-capita removal responsibility of 13 t CO_2/capita annually between 2020 and 2100 in a pathway with limited residual emission cuts, which is more than halved in another with deeper residual emission cuts. Our results underscore the importance of limiting so-called 'hard-to-abate' emissions in addition to rapid near-term cuts in emissions as preventive measures to avoid over-reliance on unsustainable levels of preventive CDR.

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Carbon dioxide removal; Harm prevention; Equity; Mitigation pathways

Policy insights

- A 'preventive' capacity of several hundred gigatonnes of carbon dioxide removal may be needed as a hedging strategy against a stronger-than-median Earth System response to our emissions.
- Given potential sustainability limits of large-scale CDR deployment, mitigation strategies should reserve CDR for a preventive role as far as possible, instead of utilising it to balance emissions that can be avoided.

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- Mitigating residual emissions in so-called 'hard-to-abate' sectors is also critical to reduce the chance of high-end warming outcomes and the need for preventive CDR.

Introduction

Carbon dioxide removal (CDR) refers to the process of removing carbon dioxide (CO_2) from the atmosphere and storing it durably in geological or biological reservoirs (Babiker et al., 2022). CDR, while initially considered a potential 'game changer' for climate change mitigation (Kriegler et al., 2013), is now considered an 'unavoidable' component of a portfolio of solutions to meet global climate objectives due to ongoing failure to cut global emissions (IPCC, 2022b). The potential deployment of CDR at scale is associated with many potential drawbacks and challenges – considering these, several scientists from different disciplines have argued in favour of reducing the potential future deployment of CDR. A group of these arguments is motivated by concerns over 'mitigation deterrence', i.e. delayed near-term action to reduce emissions based on the expectation of future CDR deployment (Brad & Schneider, 2023; Carton et al., 2023). Stuart-Smith et al. (2023) build on these to suggest that national policies based on mitigation scenarios (or pathways) that depend heavily on CDR may violate key provisions of international law. They argue that: (1) pathways heavily reliant on CDR typically overshoot the 1.5°C goal of the Paris Agreement by a wide margin, (2) large-scale reliance on CDR raises technical, economic, sustainability, and social feasibility concerns, and hence (3) mitigation strategies designed based on a high deployment of CDR are not consistent with international environmental law, sustainable development, and ecological diversity. The range of concerns over CDR deployment has been documented in several papers that explore them and investigate associated uncertainties in detail (Andreoni et al., 2024; Creutzig et al., 2021; Deprez et al., 2024; Fuss et al., 2018). Deprez et al. (2024) suggest that an alternative approach is needed to govern and limit the use of CDR – to estimate a socio-ecologically sustainable CDR budget, identify mitigation pathways that keep within this, and allocate the limited CDR supply to the 'most legitimate' uses.

These papers effectively argue that mitigation strategies should prioritize rapid cuts in emissions and strive to minimize the role of CDR in a portfolio of mitigation options to meet global climate goals. We agree with this but argue there may be grounds to consider a third element guided by a pivotal background source of uncertainty – the uncertainty in the earth system response to our emissions and removals. This third element, which we term 'preventive CDR capacity' aims to account for the principle of 'harm prevention' applied in an intergenerational context. Harm prevention is a customary principle of international law that obliges states to ensure that activities within their jurisdiction or control do not cause damages to other states and areas beyond national boundaries (Rajamani, 2024). Relevant dimensions of uncertainty in the response of the earth system include the Transient Climate Response to Cumulative Emissions (TCRE), the Zero Emissions Commitment (ZEC), and the potential asymmetry in the response of the climate system pre- and post-net-zero CO_2 (Koven et al., 2023; MacDougall et al., 2020; Zickfeld et al., 2023). Roughly speaking, the TCRE governs our expected magnitude of peak warming around the time of net zero CO_2, ZEC governs the expected long-term warming or cooling without net-negative CO_2 emissions, and the potential asymmetry in the response governs the effective reduction in warming per unit of net-negative emissions. These dimensions of uncertainty imply that even if a stringent emission reduction pathway is followed (Figure 1(b)), a high peak-warming future may occur (Figure 1(a)) in case of a stronger-than-median earth system response to our emissions. Other relevant dimensions of uncertainty are related to the earth system response to removals and depend on the CDR option, including carbon cycle feedbacks (Asaadi et al., 2024), efficiency and timing of the removal, the permanence of the carbon stored, the impact of the emissions scenario on carbon sinks and CDR efficacy (Babiker et al., 2022; Boysen et al., 2016; Chiquier et al., 2022), as well as possible competing effects of the option on the climate (Matthews et al., 2022).

Here, we suggest that an approach sensitive to climate response uncertainty and grounded in fundamental principles of international environmental law (harm prevention and intergenerational equity) may require us to consider approaches that prioritize rapid emission cuts alongside the development of a relatively high CDR capacity (which may or may not be deployed). This builds on the early risk-management framing of the role of BECCS (Obersteiner et al., 2001) and complements recent work that has explored the implications of uncertain CDR deployment on optimal mitigation strategies (Schaber et al., 2024). To demonstrate this, we quantify

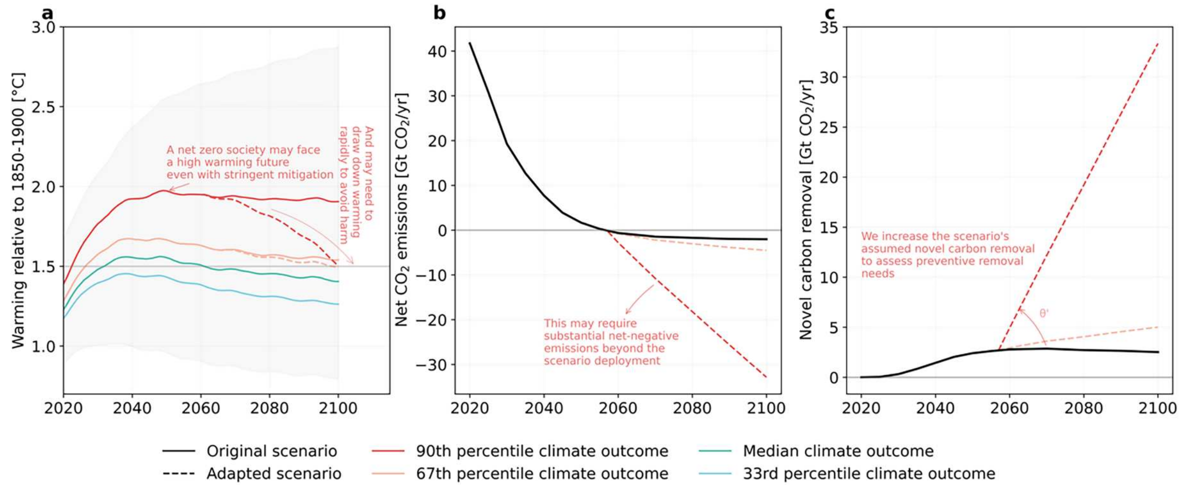

Figure 1. Conceptual overview of our approach to estimate preventive CDR deployment. Our objective in this paper is to evaluate the magnitude of additional CDR (panel c) and resulting net-negative CO_2 emissions (panel b) necessary to draw down warming to 1.5°C in 2100 in case of higher-than-median warming (panel a). The grey shaded range in panel a indicates the minimum and maximum range across the ensemble members.

the additional CDR deployment beyond CDR trajectories assessed in the IPCC AR6 WG3 scenarios (Ganti et al., 2024; Riahi et al., 2022) that may be required to draw warming down to 1.5°C with a high chance (termed 'preventive CDR' in line with Schleussner et al., 2024). Both the assessed CDR trajectories and the responsibility to develop preventive CDR capacity is then allocated to different regions, guided by the principles of equity and common but differentiated responsibilities. Exploring fair CDR deployment is increasingly relevant since it is becoming likely that we will exceed the 1.5°C limit of the Paris Agreement and enter a period of overshoot – drawing down warming (and related climate impacts) will require the deployment of CDR (IPCC, 2022b; Prütz et al., 2023; Schleussner et al., 2024). Our work goes beyond previous contributions to the literature (e.g. Fyson et al., 2020; Lee et al., 2021; Yuwono et al., 2023) by introducing the idea that two linked quantities (or global efforts) should be equitably distributed to collectively minimize harm due to climate overshoot. The first is the scenario-based CDR quantity shared across all regions in proportion to their gross cumulative emissions, and the second is an additional preventive CDR quantity allocated to those regions that consume more than their fair share of the remaining carbon budget (and are thus responsible for global overshoot).

The following section outlines the methods applied to evaluate the scale of preventive CDR and allocate it between regions, followed by a section highlighting key quantitative results. We conclude with reflections on the implications of a preventive framing for the existing policy architecture.

Methods

Figure 1 provides a brief conceptual overview of our approach. We assume a society would always want to meet a global temperature goal by 2100 but might face different peak warming futures depending on the earth system response to emissions (Figure 1(a)). To achieve this objective, they would need to have the capability to deploy net-negative emissions at a higher scale than assumed for a median temperature response (Figure 1(b)). Current mitigation pathways developed using IAMs, which map out the solution space for global climate policy, have tended to focus on median outcomes, and hence omit a comprehensive consideration of climate uncertainty (Schleussner et al., 2024). In this paper, the additional CDR (Figure 1(c)) that may be necessary to enable this is calculated across a range of emission pathways. Our approach is described in further detail below.

Accounting for scenario and climate uncertainty

There are two broad sources of uncertainty underlying the additional CDR deployment necessary to meet a global climate target across a range of carbon cycle and climate responses. First, there is uncertainty in the composition of a future multi-gas emissions pathway (i.e. scenario uncertainty), and second, there is uncertainty in the climate system's response to these emissions (i.e. climate uncertainty). The former is accounted for by performing the assessment across the 'C1' (limit warming to 1.5°C (>50%) with no or limited overshoot) category of pathways assessed by the IPCC that report sufficient information on CDR (see next section). These pathways keep warming below 1.5°C with at least a 33% chance and limit warming below 1.5°C in 2100 with at least a 50% chance, representing different mitigation strategies, including a range of CO_2, CH_4 and other greenhouse gas reductions to meet broadly similar warming outcomes (Riahi et al., 2022).

We account for climate uncertainty by estimating the additional CDR across the warming outcomes for each scenario using the probabilistic distribution for the simple carbon cycle and climate model MAGICC v7.5.3 (Meinshausen et al., 2009, 2011, 2020). The model is run 600 times with different parameters to represent uncertainty in critical metrics from the IPCC AR6 assessment, including, among others, equilibrium climate sensitivity (ECS), historical global average surface temperature, and the transient climate response to emissions (TCRE) to within +/−5% of the central estimate and +/−10% of the *likely* and *very likely* ranges (Forster et al., 2021). We perform our calculations across 57,000 realizations (95 emission reduction pathways with sufficient CDR information × 600 warming outcomes[1]).

Adapting novel CDR in the assessed pathways

The following CDR options are aggregated to represent total novel CDR: bioenergy with carbon capture and storage (BECCS), direct air carbon capture and storage (DACCS) and enhanced weathering (Smith et al., 2023). These are the novel CDR methods currently represented in most IAMs, with efforts ongoing to represent a more diverse novel CDR portfolio in a new generation of IAM scenarios (Fuhrman et al., 2023; Gidden, Brutschin, et al., 2023; Strefler et al., 2021). For each assessed emission pathway (p) and each ensemble member for MAGICC v7.5.3 (ens), we estimate the deviation ($\delta_{p,ens,b}$) between the warming outcome for that emission scenario – ensemble member combination ($T^{2100}_{p,ens,b}$) and the desired warming outcome (1.5°C in 2100 in this paper) (Equation (1)).

$$\delta_{p,ens,b} = T^{2100}_{p,ens,b} - 1.5 \tag{1}$$

We perturb (or rotate) the novel CDR in the original pathway (per ensemble member) by an angle θ'_{ens} to get a new emission pathway, where the new cumulative CDR is represented by $C(\theta'_{ens})$ (Equation (2)). The new CDR pathway is subtracted from the CO_2 emissions from energy and industrial processes in the original pathway with no changes made to any other emission species.

$$C(\theta'_{ens}) = \sum_{t=t_{nz}}^{2100} c_{p,t} + \{(t - t_{nz}) * \tan(\theta')\} \tag{2}$$

Where, $c_{p,t}$ is the original novel CDR in the pathway p at timestep t, and t_{nz} is the year of net zero CO_2 in the original pathway. θ'_{ens} is bounded between 0 (when $\delta_{p,ens,b} \Leftarrow 0$) and 90°. We then try to search for θ'_{ens} that minimizes the deviation $\delta_{p,ens}$ in an iterative manner (Equation (3)). $T^{2100}_{p,ens}$ is a function of θ'_{ens} and is estimated using MAGICC v7.5.3.

$$\delta_{p,ens} = T^{2100}_{p,ens} - 1.5 \tag{3}$$

Allocating long-term removal effort consistent with harm prevention

How could the responsibility for providing this preventive CDR capacity be distributed between countries (or regions)? We propose a two-stage approach, distinguishing between the responsibility for deploying CDR in

[1]The scenarios omitted are: EN_NPi2020_500 and EN_NPi2020_600_COV from the GEM-E3_V2021 modelling framework.

line with scenarios (in line with existing literature, for instance, Fyson et al., 2020; Lee et al. 2021) and the responsibility for deploying additional preventive CDR (our contribution in this work), using the regional scenario information at the aggregate ten-region ('R10') level adopted by the IPCC (IPCC, 2022a) across a selection of pathways (see previous section).

Separating gross and net budgets in fair share assessments: Gross emission reductions are separated from CDR deployment in our fair shares assessment, as opposed to using net emission budgets. There are valid applications of approaches that consider net emissions or budgets, for instance the use of 'net zero carbon budgets' to track overshoot responsibilities, and each approach should be carefully selected based on the scope of the question it seeks to answer (Pelz et al., 2024, 2025). A clear separation between gross emission reductions and CDR deployment is important for mitigation target setting (Carton et al., 2021; Lamb et al., 2024; McLaren et al., 2019). Lamb et al. (2024) further argue that this separation facilitates a reflection on fairness considerations, a view that underlies recent contributions to the literature that have assessed fair shares of CDR effort (Fyson et al., 2020; Pozo et al., 2020; Yuwono et al., 2023), and which is taken forward in our work.

Determining groups for assigning responsibility: We propose the formation of two groups of regions (per scenario) to assign responsibilities for scenario-based novel CDR (Group I) and to assign additional responsibility to deploy preventive CDR (Group II). The first group contains all world regions, i.e. all regions carry some responsibility to deploy novel CDR assumed in each scenario in proportion to their relative responsibility for gross emissions over the course of the century, following earlier literature (Pozo et al., 2020). Regions are subsequently assigned to Group II – (i.e. take responsibility for preventive CDR) based on whether they emit more than their 'fair' allocation by 2100 and thus accrue 'carbon debt', or not, indicating that this overconsumption implies an additional responsibility to address climate response uncertainties that may arise despite a proportional contribution by all regions to scenario-based mitigation efforts. Carbon debt refers to the emissions for a region that exceed (or are below) a counterfactual fair allocation of emissions consistent with global climate goals – in most cases, a fair counterfactual 'equal cumulative per capita' emissions pathway that stays within an estimated global remaining carbon budget (Ganti et al., 2023; Gignac & Matthews, 2015; Pelz et al., 2024; van den Berg et al., 2020). Summing up the cumulative difference between the regional gross emissions and the counterfactual pathway gives us 'debtor' (cumulative emissions exceed cumulative counterfactual equal per capita pathway) and 'creditor' (cumulative emissions are less than a cumulative counterfactual equal per capita pathway) regions. We propose that these so-called debtor regions should be assigned to Group II and be allocated additional responsibility to deploy preventive CDR (see SI).

Assigning responsibility for scenario-based CDR: For each of our illustrative pathways, we first calculate the gross CO_2 emissions from energy and industrial processes by adding the net CO_2 emissions from energy and industrial processes and the novel CDR deployment. Cumulative gross CO_2 emissions from energy and industrial processes is then summed up for each region, per scenario, between 1990 and 2100 and calculate the share of regional gross emissions in the global total. The scenario's global novel CDR is assigned to each region in proportion to this share. Our focus on CO_2 emissions from energy and industrial processes omits the effect of other emissions species and sectors – however, this choice is sufficient given the illustrative nature of this assessment (see section on 'Important caveats').

Assigning responsibility for additional preventive CDR: We group the regions into debtor and creditor categories. Global cumulative gross CO_2 emissions from energy and industrial processes between 1990 and 2022 are compared to the median estimate of the remaining carbon budget (RCB) for 1.5°C (Lamboll et al., 2023). For each region, an equal cumulative per capita share of this quantity (assuming SSP2 populations) is calculated and subtracted the region's historical emissions (from 1990) from this quantity, giving us the remaining regional allocation from 2023. Regional future gross CO_2 emissions from energy and industrial processes (per scenario) are subsequently subtracted from this remaining budget to get the cumulative regional gross debt or credit in the year 2100. For the debtor (Group II) regions, we calculate the regional share of the total debt added across all the debtor regions, and assign the scenario's additional global preventive CDR to each region in proportion to this share.

Important caveats: It is important to note that this analysis is purely illustrative, and we make quite a few value judgments that can (and should) invite critiques. For instance, we select the year 1990 as the first year for our assessment – the choice of this year is based on the argument that this was the year when the IPCC

Table 1. Illustrative mitigation pathways – selection and reasoning.

Model	Scenario	Label	Reason for selection
MESSAGEix-GLOBIOM 1.0	LowEnergyDemand_1.3_IPCC	IMP – LD	These three C1 pathways were highlighted as illustrative mitigation pathways (IMPs) in the AR6 WG3 report (IPCC, 2022b; Riahi et al., 2022). We do not perform the fair share assessment for IMP – LD and IMP – Ren; this is because the former does not report data at the R10 regional resolution and the latter has high DACCS deployment in the historical period for R10AFRICA.
REMIND-MAgPIE 2.1-4.2	SusDev_SDP-PkBudg1000	IMP – SP	
REMIND-MAgPIE 2.1-4.3	DeepElec_SSP2_HighRE_Budg900	IMP – Ren	
REMIND-MAgPIE 2.1-4.2	CEMICS_SSP1-1p5C-fullCDR	REMIND SSP1 Full CDR	These scenarios represent variations in socio-economic drivers (SSP1 and SSP2) as well as the availability of CDR options. These are two relevant factors to the deployment of preventive CDR. In addition, we compare these to the IMP – SP in the fair shares section given they span a range of residual emission outcomes.
	CEMICS_SSP2-1p5C-fullCDR	REMIND SSP2 Full CDR	
	CEMICS_SSP1-1p5C-minCDR	REMIND SSP1 Min CDR	
	CEMICS_SSP2-1p5C-minCDR	REMIND SSP2 Min CDR	
IMAGE 3.2	SSP1_SPA1_19I_D_LB	IMAGE SSP1 D	These scenarios also represent variations in socio-economic drivers and provide another line of evidence to assess their effect on preventive CDR.
	SSP2_SPA1_19I_D_LB	IMAGE SSP2 D	
	SSP1_SPA1_19I_LIRE_LB	IMAGE SSP1 LIRE	
	SSP2_SPA1_19I_LIRE_LB	IMAGE SSP2 LIRE	
	SSP1_SPA1_19I_RE_LB	IMAGE SSP1 RE	
	SSP2_SPA1_19I_RE_LB	IMAGE SSP2 RE	

published its first assessment report, aimed at informing policymakers about the impacts and response strategies to climate change (Beusch et al., 2022; Nauels et al., 2019). However, there are other valid starting years, an issue that has been discussed and debated over many years, because more than half of historical net CO_2 emissions have occurred before 1990 (IPCC, 2022b). Similarly, the allocation approach applied is only one of many potential approaches – this has also been discussed and debated over many years. The primary aim of our explorative analysis here is to shed light on *what* needs to be considered instead of *how exactly* to explore the potential solution space, which can be the focus of follow-up work.

Illustrative pathway approach

We apply an illustrative scenario approach to provide a descriptive assessment of the drivers underlying our estimates of preventive CDR and evaluate regional fair shares of the scenario and preventive novel CDR. Such an illustrative scenario approach was applied in the IPCC AR6 WG3 assessment and aimed to illustrate the storylines and quantitative results supporting the theme covered in the report (Riahi et al., 2022). This technique can be helpful when assessing an unstructured scenario ensemble (Guivarch et al., 2022) and also increases the transparency in underlying choices instead of a comparison with broad scenario ranges (Lamb et al., 2024). The selection of the scenarios and the underlying reasons for selection is documented in Table 1.

Results and discussion

Preventive CDR at the global level

We first evaluate the results across all the assessed pathways at the global level (Figure 2(a)). The total CDR deployed in the original pathways is calculated by including information on CDR through afforestation and reforestation (Gidden, Gasser, et al., 2023). This information is available for a subset ($n = 70$) of the scenarios assessed ($n = 95$), and we present results for these 70 scenarios in Figure 2(a). At the global level, around 532 Gt CO_2 of CDR (median, with [418, 763] interquartile range) is cumulatively deployed between global net zero CO_2 and 2100 in the assessed scenarios (i.e. the scenario uncertainty). Around 625 Gt CO_2 (median, with [323, 787] interquartile range) of additional preventive CDR deployment is consistent with a 90%

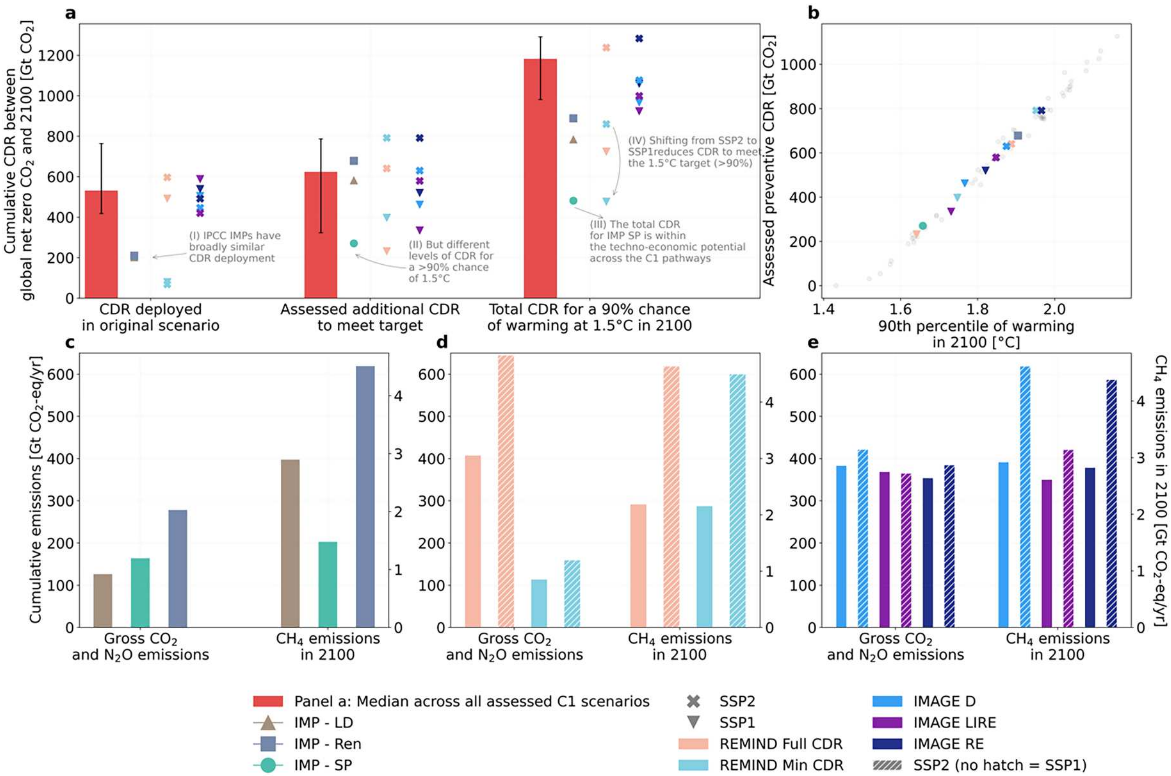

Figure 2. Evaluation of preventive CDR at the global level across scenarios. (a) Comparing the CDR deployed in the 1.5°C with no or limited overshoot scenarios with the potential additional preventive CDR, and also showing the total CDR. (b) Preventive CDR against the 90th percentile warming outcome of the original scenarios as assessed using the simple climate model MAGICC v7.5.3. (c–e) Gross CO_2 and N_2O emissions between global net zero CO_2 and 2100 and the level of CH_4 emissions in 2100 across illustrative pathways.

chance of bringing warming to 1.5°C in 2100 across the same scenarios (i.e. scenario and climate uncertainty). The additional CDR need increases almost linearly with the 90th percentile of warming from the original scenarios (Figure 2(b)). The total CDR (scenario and preventive) amounts to 1182 Gt CO_2 (median, with [981, 1291] interquartile range). We now apply an illustrative pathway selection approach to tease out how the scale of this preventive CDR can be informed by mitigation in other sectors (see Methods).

First, three IPCC 'Illustrative Mitigation Pathways' (IMPs) are evaluated from the broader set of 1.5°C with no or limited overshoot pathways (Figure 2(a,c)). These include the IMP Shifting Pathway (IMP – SP) (Soergel et al., 2021), IMP Renewable (IMP – Ren) (Luderer et al., 2022), and IMP Low Demand (IMP – LD) (Grubler et al., 2018). These pathways are also interesting for our inquiry because they have similar levels of CDR deployment in the original scenario but different levels of assessed preventive CDR (Figure 2(a)). We trace this back to the quantity and composition of 'residual' emissions – these are emissions considered either economically or technically unfeasible to eliminate (Buck et al., 2023; Luderer et al., 2018). We use the cumulative gross fossil fuel CO_2 and gross N_2O emissions between global net zero CO_2 and 2100 and the level of CH_4 emissions in 2100 as a measure of residual emissions (Figure 2(c)). IMP – Ren has the highest amount of cumulative total (i.e. scenario + preventive) CDR (888 Gt CO_2) among the three scenarios (Figure 2(a)) – this is driven by the high residual emissions after global net zero CO_2 (Figure 2(c)). IMP – LD (784 Gt CO_2) has over 1.5 times more total CDR than IMP – SP (482 Gt CO_2) despite having somewhat lower cumulative fossil CO_2 and N_2O emissions (126 Gt CO_2eq vs 164 Gt CO_2eq) (Figure 2(c)). This is because the scenario has nearly twice the level of CH_4 emissions in 2100 compared to the IMP – SP (Figure 2(c)). The IMP-SP focuses on achieving multiple sustainable development objectives and has a co-benefit of reducing the scale of assessed preventive CDR. Beyond the IMPs, we also investigate two additional sets of scenarios that, in principle, have similar scenario designs but different socioeconomic drivers (Figure 2(a)) (Strefler et al., 2021; van Vuuren et al., 2021). We find that scenarios that implement an 'SSP1' storyline (focused on sustainability, with low challenges to mitigation and adaptation) (O'Neill et al., 2017) tend to have lower levels of preventive CDR compared to their 'SSP2' counterparts (with social, economic, and technological development broadly in line with historical trends) (Figure 2(a,d,e)).

Fair shares of CDR in line with harm prevention – an illustrative assessment

We now evaluate the fair shares of scenario-consistent and preventive CDR (Figure 3). Across the five illustrative pathways we assess, the North America region is consistently allocated the highest share of preventive CDR followed by the Eastern Asia region (Figure 3(a)). The scenario-consistent cost-effective deployment of novel CDR is typically lower than the fair share of the same quantity for these regions (Figure 3(b–d)) and typically less than a third of the sum of the fair share of the scenario and preventive CDR. On the other hand, some

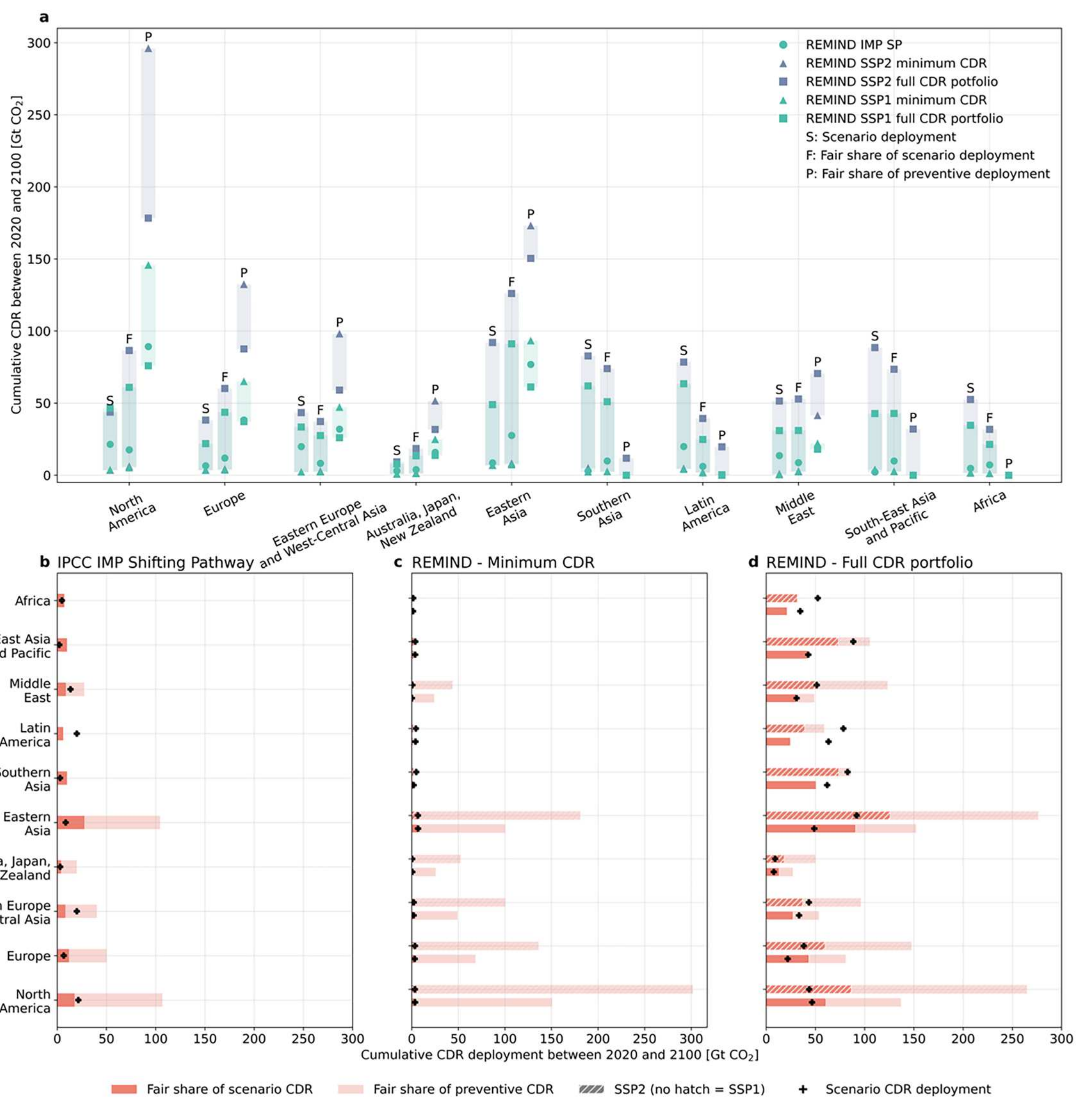

Figure 3. Fair shares of CDR in line with the principle of harm prevention. (a) Summary across the five illustrative pathways assessed. (b–d) Fair share assessment for illustrative mitigation pathways from the REMIND-MAgPIE framework.

regions, including Latin America, Africa, and Southern Asia are typically not allocated a share of preventive CDR (Figure 3(b-d)). This reflects that their assessed per-capita cost-effective mitigation pathways are typically lower than their fair share emission allocations. Interestingly, one of our assessed scenarios, with a relatively low focus on reducing residual emissions (REMIND SSP2 Full CDR – Figure 3(d)) has preventive CDR allocated to Latin America and Southern Asia. However, the scenario's cost-effective deployment of CDR in these regions exceeds the sum of their fair shares of scenario and preventive CDR. This not only reiterates previous findings on the importance of CDR in developing regions, but also suggests that under these scenarios, these regions would be contributing beyond their fair share to harm prevention in case of a stronger-than-median climate response to our emissions.

Finally, we compare the per-capita deployment of preventive CDR across a scenario with a strong focus on cutting residual emissions (REMIND IMP-SP) and a scenario with a relatively weaker focus on cutting residual emissions (REMIND SSP2 Full CDR). On a per-capita basis, the North America region is assigned a total preventive CDR responsibility of 13 tCO_2/capita/year between 2020 and 2100 in the latter scenario, which reduces to 5.3 tCO_2/capita/year over the same timeframe in the scenario with a stronger focus on cutting residual emissions. To place this in context, the per-capita emissions of USA was around 14 tCO_2 per capita emissions in 2022 (Friedlingstein et al., 2023). The Eastern Asia region is correspondingly allocated a total preventive CDR responsibility of 3.4 and 1.3 tCO_2/capita/year respectively over the same timeframe.

Conclusion

A net zero CO_2 society will inherit the legacy of our emissions, and should they experience a stronger-than-median Earth System response, experience high peak warming outcomes and associated impacts. These potential high warming outcomes raise questions of intergenerational equity – to what extent are we (current society) responsible for developing approaches that a future society could, yet may not, deploy to draw down warming and reduce the impacts they (and subsequent generations) will face? Here, we argue that this responsibility implies that we should invest in research and development and scale a selection of mitigation options beyond those currently assumed in deep mitigation pathways. Crucially, the responsibility to deploy these mitigation options should be recognized today, given the likely scale-up period required for different technologies (Bento & Wilson, 2016; Nemet et al., 2023).

The starting point for our assessment was that preventive mitigation could take the form of preventive novel CDR. The scale of such additional preventive CDR under a higher-than-expected Earth System response is of the order of magnitude of the CDR already deployed across existing scenarios. However, the existing level of CDR in scenarios is already criticized for potentially violating important sustainability considerations (Creutzig et al., 2021; Deprez et al., 2024; Fuss et al., 2018), with these concerns being significantly exacerbated in the face of additional preventive CDR requirements.

This observation leads to the first important conclusion of our paper – that delayed action to cut emissions has left us in a position where a given principled consideration (in this case, enabling 'sustainable development') does not have a unique directional relationship with a given quantity (say, CDR). We can invoke the same principle to argue in favour of reducing CDR (invoking harms to biodiversity, competition for land, etc.) as well as in favour of increasing our available CDR (as we argue here, to be consistent with harm prevention, and provide a future society with the tools it might need to reduce impacts). The lack of a unique directional relationship implies the need for a more comprehensive framework to evaluate competing considerations while preparing, scaling and deploying CDR. However, if limits for future CDR deployment continue to be a binding constraint, we argue that priority needs to be given to a preventive approach, rather than budgeting in the available CDR capacity in emission pathways to make up for insufficient near-term mitigation ambition.

Skepticism over the likelihood of realizing such quantities of preventive CDR, driven by concerns over feasibility, techno-economic potential, and sustainability, leads us to our second conclusion. Reducing the scale of total CDR (including the preventive component) requires rapid, deep, and sustained cuts in gross emissions and minimizing all residual emissions, including in so-called hard-to-abate sectors. Scenarios with lower preventive CDR needs are those that reduce both long-lived and, additionally, short-lived climate forcers such as methane in these sectors. We argue that a preventive mitigation lens allows us to have an open discussion about the deep trade-offs necessary for a climate-safe future – for instance, deciding how much to focus on a hard-to-abate sector versus a hard-to-deploy CDR portfolio consistent with a similar climate outcome and the principle of harm prevention. A new generation of scenarios that are consistent with the principle of harm prevention will thus require two broad characteristics: (1) reducing emissions in hard-to-abate sectors as far as possible, a solution space which recent IAM scenarios have begun to systematically explore (Edelenbosch et al., 2024; Fuhrman et al., 2024), and (2) the development of a preventive CDR capacity that can be deployed to hedge against a higher-than-expected warming future. Further considering method-specific climate-related risks to CDR deployment (for instance, sink strength and disturbances) is also important while designing such scenarios (Sanderson et al., 2023).

Finally, we argue that a more nuanced type of differentiation is necessary in the literature that evaluates fair shares of mitigation efforts across different regions (or countries). Most existing literature assumes that we face a given quantity (for instance, a remaining carbon budget) and then propose several ways to split this quantity. This approach ignores the significant uncertainty around this quantity and suggest an approach to differentiate between groups of regions (or countries) that take on some responsibility for this uncertainty. This is only one possible approach to incorporate responsibility for climate uncertainty in fairness assessments and is aimed at spurring critique and alternate suggestions from scientists, policy analysts, and policymakers.

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Author contributions

GG initiated the research. GG and ZN designed the analytical approach for the global scenario assessment. GG and SP designed the analytical approach for the regional assessment. GG, ZN, and SP performed the analysis and drafted the figures with input from C-FS. GG wrote the manuscript with input from ZN, C-FS, SP, UK, and MJG.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Code and data availability

The code necessary to replicate this analysis is openly available at: https://github.com/gaurav-ganti/cdr_climate_uncertainty. Please refer to the README file in the repository for instructions to install the necessary software and the recommended citations.

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