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Prudent carbon dioxide removal strategies hedge against high climate sensitivity

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Uncertainty in climate sensitivity has been shown to warrant early-on mitigation to limit global warming while anticipating future carbon dioxide removal creates mitigation deterrence. Here we use an integrated assessment model to quantify the impacts of under- or overestimating the cost and availability (feasibility) of carbon dioxide removal when limiting warming to 1.5 °C by 2100 under uncertain climate sensitivity. If climate sensitivity uncertainty is disregarded, initial assumptions on the feasibility have only minor effects on mitigation costs. However, the climate sensitivity risk compounds the impact of prior assumptions. Wrong assumptions on carbon dioxide removal feasibility can lead to lower costs under extreme realizations of climate sensitivity. Moreover, scenarios considering uncertainty in climate sensitivity rely less on carbon dioxide removal. A prudential strategy assuming low feasibility for carbon dioxide removal reduces the "double whammy" risk of overestimating carbon dioxide removal in combination with a realization of high climate sensitivity.

The main goal of the Paris Agreement is to keep global warming well below 2 °C, pursuing 1.5 °C. Limiting temperature increase to these levels requires rapid and deep reductions of greenhouse gas (GHG) emissions; and likely, additional large-scale deployment of carbon dioxide removal (CDR)[1,2]. Most climate change mitigation scenarios developed using integrated assessment models (IAMs) imply net-zero CO_2 emissions by mid-century to reach the Paris Agreement targets[1,2]. IPCC AR6[1] portrays CDR as an indispensable mitigation measure to compensate for hard-to-abate emissions and to reach net-zero GHG emissions. Similarly, CDR is a critical element in many national mitigation strategies and net zero emission pledges[3–6]. Proposed CDR methods include both engineered technologies (e.g., direct air carbon capture and storage, DACCS) and enhancement of natural carbon sinks (e.g., soil carbon sequestration) to store CO_2 in reservoirs or products.

However, substantial uncertainty exists about the feasibility (costs, carbon removal potential, and availability) of CDR, leading to a serious gap between the expectations of future deployment and the existing knowledge on CDR[7–11]. The most prevalent CDR techniques in IAM scenarios are the highly land-intensive options of afforestation and bioenergy with carbon capture and storage (BECCS)[9,12,13]. Particularly BECCS has raised concerns about its feasibility, negative impacts on biodiversity and land carbon stocks, and potential conflicts with other sustainable development goals[14–16]. Another problem is that scenarios often employ promising and favorable assumptions on CDR feasibility, thereby possibly overstating the role of large-scale CDR in mitigation strategies[7,8,10,17]. Considering a wider range of CDR feasibility is crucial for estimating the realistic future mitigation contribution, and is one way of addressing the "moral hazard" risk of high near-term emissions justified with the uncertain promise of reaching highly negative net emissions with CDR later[1,7,18–25]. Hedging against the risk of CDR deployment failure would require even stronger emission reductions in the 2020s[26].

A prevalent uncertainty also exists around Earth's climate sensitivity (CS), the equilibrium temperature increase that follows from doubling CO_2 concentration in the atmosphere[27–29]. The value of CS determines the mitigation required to reach the Paris Agreement targets[30–34], and hence the need for CDR. Additionally, a cost-effective strategy to limit temperature increase under uncertain CS requires ambitious, early-on mitigation to hedge the CS risk[35,36], as well as the risk of CDR deployment failure[26], which conflicts with the mitigation deterrence effect of CDR[37]. This necessitates that the uncertainties in CDR and CS are analyzed jointly.

We investigate how uncertainty in CS and differing—and possibly false—assumptions today regarding future CDR feasibility affect long-term strategies for limiting warming to 1.5 °C by 2100. We study separately three levels of CDR feasibility (quantified by their costs and potentials) denoted as pessimistic, average, or optimistic, and calculate cost-effective emission pathways with SCORE, a lightweight IAM performing stochastic optimization over a learning process on CS (Fig. 1b)[35,36]. Five CDR options are considered: afforestation and reforestation, biochar, DACCS, enhanced weathering, and soil carbon sequestration. BECCS is not explicitly modeled

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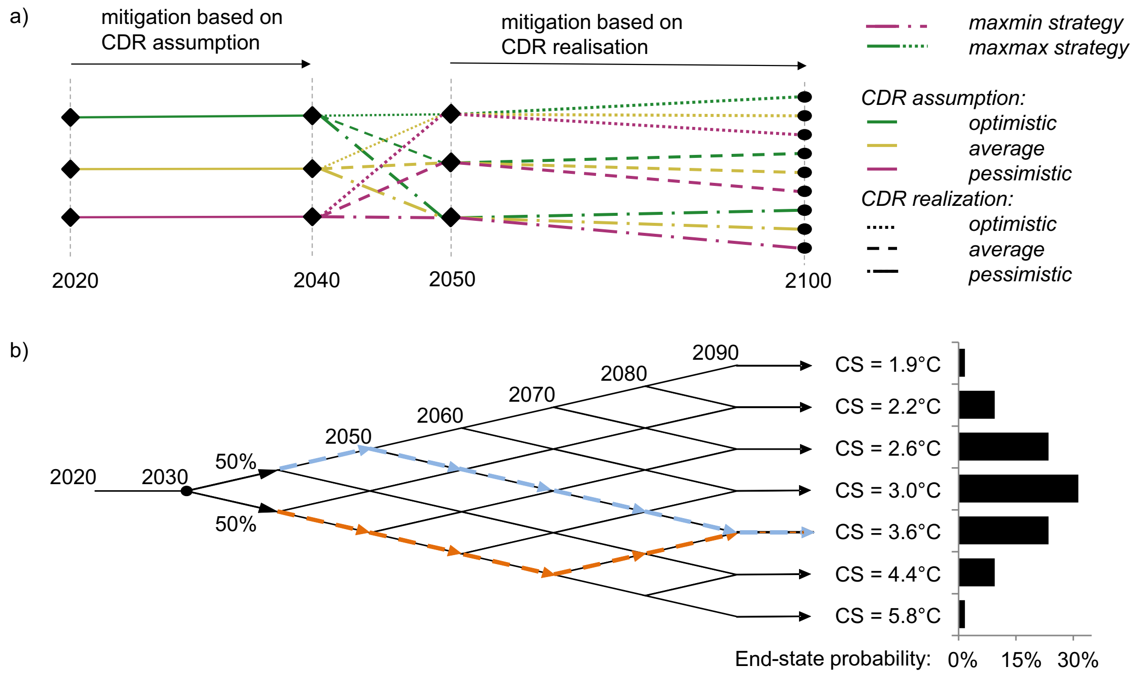

Fig. 1 | Overall CDR scenario setup and learning process on climate sensitivity. **a** The scenario setup with three possible assumptions and three realizations each for CDR feasibility, mapping nine possible scenarios in total. The true CDR feasibility is observed after 2040, leading to the adaptation of the mitigation strategy between 2040-2050 in all scenarios. Scenarios with pessimistic or optimistic assumptions correspond respectively to the maxmin or maxmax strategy. **b** The learning processes and binomial probability distributions assumed for climate sensitivity in SCORE[36]. The uncertainty in CS is considered through a binomial probability distribution and is assumed to gradually decrease over time through exogenous, epistemic learning on CS. A predefined, perfect learning process maps a scenario tree resulting in 64 pathways by the end of the century. The scenario tree branches every ten years with 50% branching probabilities from 2040 onwards, ruling out either the lowest or highest possible CS until reaching a discretized, non-symmetric end-state probability distribution[57] by 2090. That is, by 2090 the uncertainty in CS is resolved and all 64 pathways follow a deterministic CS based on their end-state in the learning process. Two possible pathways that end in a climate sensitivity of 3.6 °C are illustrated with arrows.

since it is implicitly considered in the marginal abatement cost curves of the IAM (Supplementary Fig. 1). To limit the year-2100 warming to 1.5 °C the model chooses between reducing emissions from a baseline level using marginal abatement costs fitted to a large ensemble of past scenario studies; or the five CDR options, based on their costs associated with each assumption (see the Methods for details), allowing for unlimited overshooting before 2100. To avoid end-of-horizon effects, we assume post-2100 a temperature limit that decreases linearly to 1 °C by 2200 (see Methods).

We consider the uncertainty in CDR and CS in three steps: first by assuming perfect foresight for CDR feasibility and no uncertainty in CS; second, by taking into account the uncertainty in CDR feasibility; and last, by jointly considering the uncertainty in CDR feasibility and CS. The uncertainty regarding CDR is studied by assigning a fixed, singular prior assumption for CDR feasibility in 2020, which can turn out either as correct, overly optimistic, or overly pessimistic in 2050 (Fig. 1a). Thus, the considered mitigation strategy is "betting on negative emissions"[7] in 2020 with the bet being resolved between 2040 and 2050, and consequently following the true realization of CDR feasibility. Last, we add uncertainty in CS to the betting framework, with the requirement of remaining below 1.5 °C by 2100 under all realizations of CS. The uncertainty on CS is assumed to be epistemic and resolves gradually through learning (Fig. 1b)[36].

The fixed CDR assumptions represent possible overconfidence[23] about current knowledge about future CDR feasibility, but also have a dual interpretation. We show in the supplementary information that the optimal strategies implied by maxmin and maxmax, two well-known decision rules to deal with ambiguity, correspond respectively to having a singular prior assumption of pessimistic and optimistic CDR. In particular, the maxmin strategy has been proposed as a prudential, uncertainty averse or pessimistic strategy to deal with ambiguity, as it maximizes payoffs in the worst-case[38,39]. The maxmax strategy instead maximizes the maximum available payoff and can be characterized as a risk-seeking and optimistic strategy.

Our results indicate that CDR might have an important role in reaching 1.5 °C by 2100, but that early emission reductions are needed to hedge against both the risk of high CS[35] and the possibility of CDR deployment failure[26]. Discarding uncertainty in CS results in postponed mitigation efforts and a greater reliance on CDR in the future, and suggests that an initial, and possibly wrong assumption on CDR feasibility has minor impacts on mitigation costs. However, considering the CS risk compounds the impacts of prior CDR assumptions, especially if 1.5 °C by 2100 is to be met with a high CS. We find that a prudential strategy on CDR reduces the "double whammy" risk of overestimating CDR in combination with a realization of high CS and can even lower mitigation costs in scenarios of high CS due to stronger precautionary action.

Results

A world with perfect foresight on CDR

Under perfect foresight regarding CDR feasibility and with a deterministic CS of 3 °C, limiting global warming below 1.5 °C by 2100 is possible with every considered level of CDR, however with noteworthy differences in the timing and costs of mitigation efforts. Net emissions can be lower than the explicitly modeled CDR deployment due to the implicit negative emissions (BECCS) in the marginal abatement cost curves of SCORE (Supplementary Fig. 1). Pessimistic CDR levels entail early and steep mitigation, which slows down by 2050 and reaches net zero GHG emissions by 2070 (Fig. 2a). The optimistic CDR scenario postpones the strongest mitigation efforts to future decades when cheap and effective CDR becomes available, leading to high levels of net negative emissions after 2070. However, this postponing leads to overshooting 1.5 °C already around 2060 (Fig. 2c). The slight warming after reaching net-zero CO_2 emissions (~0.1 °C between 2050 and 2080) is primarily due to the high inertia in the atmosphere-ocean heat transfer in SCORE. By contrast, the pessimistic scenario overshoots 1.5 °C by only 0.013 °C in 2080. Yet, this

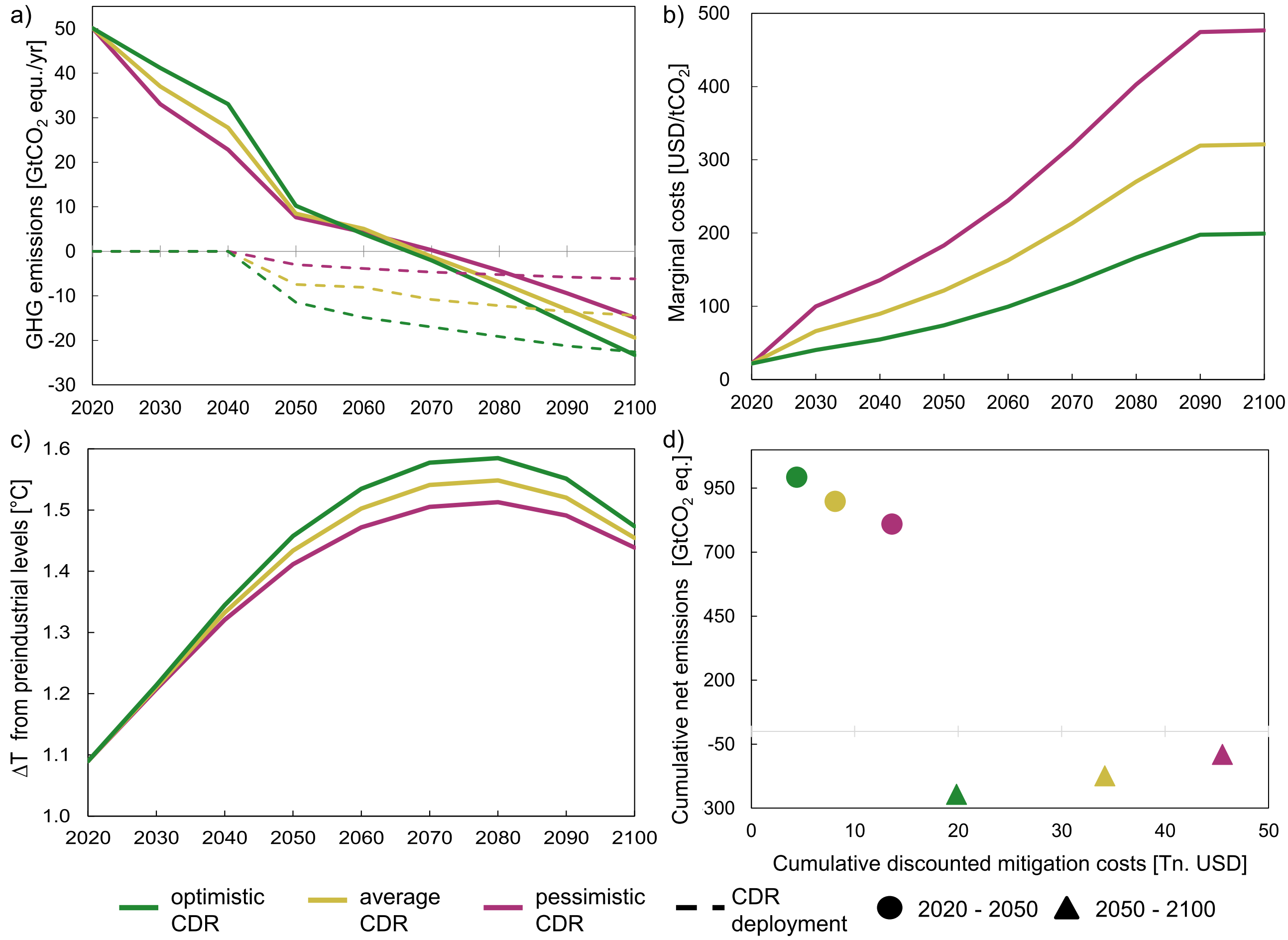

Fig. 2 | Scenarios with perfect foresight regarding future CDR feasibility and a deterministic CS of 3 °C with a global temperature increase limit of 1.5 °C for the year 2100. **a** Net global GHG emissions aggregated with 100-year global warming potentials. **b** Marginal abatement costs. **c** Global mean temperature change relative to preindustrial levels. **d** Cumulative discounted mitigation costs in periods of 2020–2050 and 2050–2100 against cumulative net GHG emissions for respective periods.

comes at higher marginal and cumulative mitigation costs, which are here discounted with a 3% discount rate (Fig. 2b, d).

The marginal costs of the pessimistic CDR are more than twice as high as in the optimistic scenario throughout the century (Fig. 2b). Similarly, the cumulative mitigation costs are higher in the pessimistic CDR scenario, both pre-and post-2050, caused by early and expensive emission reductions as well as costly CDR measures later in the century (Fig. 2d). For all three levels of CDR, the bulk of the cumulative mitigation costs incur post-2050. Nonetheless, emissions will be reduced substantially before 2050 (Fig. 2a) for the 1.5 °C temperature limit to be reached; but due to cost-discounting, declining marginal abatement cost curves throughout the century, and the availability of CDR, the majority of mitigation actions take place in the second half of the century. Higher cumulative net GHG emissions between 2020 and 2050 in the optimistic scenario are compensated by more net negative emissions between 2050-2100 (more than double in magnitude compared to the pessimistic scenario).

Taking a wrong bet on CDR

To investigate the impact of over- or underestimating future CDR feasibility, we analyze nine scenarios combining the three levels of CDR as assumptions until 2050 and three realizations from 2050 onwards (Fig. 1a). That is, the scenarios follow either the optimistic, average, or pessimistic pathway from Fig. 2 until 2050, and a cost-optimal pathway is sought from 2050 according to the realized CDR feasibility.

Cumulative mitigation costs until 2100 are mainly driven by the CDR realization and not the initial assumptions, indicating that taking a wrong bet has only minor effect on costs (Fig. 3a). By definition, a correct bet always reaches the lowest cumulative costs, corresponding with Fig. 2d. Given that the pre-2050 mitigation comprises only a minor part of total mitigation costs (Fig. 2d), the additional costs from a prudential strategy with pessimistic CDR assumptions (i.e., the maxmin strategy) before the true CDR feasibility become known is comparably small. The benefit of this strategy is lower total costs with the pessimistic realization, scenarios in which costs are high in any case, but higher total costs with the optimistic realization, due to the underestimation of CDR feasibility. The disadvantage, however, is a short-term cost increase, potentially having strong distributional impacts. Optimistic CDR assumption (i.e., the maxmax strategy) has the highest cumulative costs with the pessimistic CDR realization, a result of overestimating CDR, but—by definition—the lowest costs with the optimistic realization.

While the realization-driven results indicate little benefit from considering separate assumptions and realization on CDR compared to perfect foresight, the scenario set-up does influence the marginal costs' development notably (Fig. 3b). An overestimation of CDR increases marginal costs drastically and rapidly between 2040 and 2050. In the worst overestimation scenario—an optimistic assumption and a pessimistic realization—marginal costs almost quintuple within that decade. Conversely, underestimation leads to a considerable decrease in marginal costs after 2040 if high-potential, low-cost CDR options unexpectedly become available, allowing for cheaper mitigation than previously assumed. These rapid changes in marginal costs are partly driven by the scenario design which assumes CDR strategy adaptation within one decade (Fig. 1a). A slower

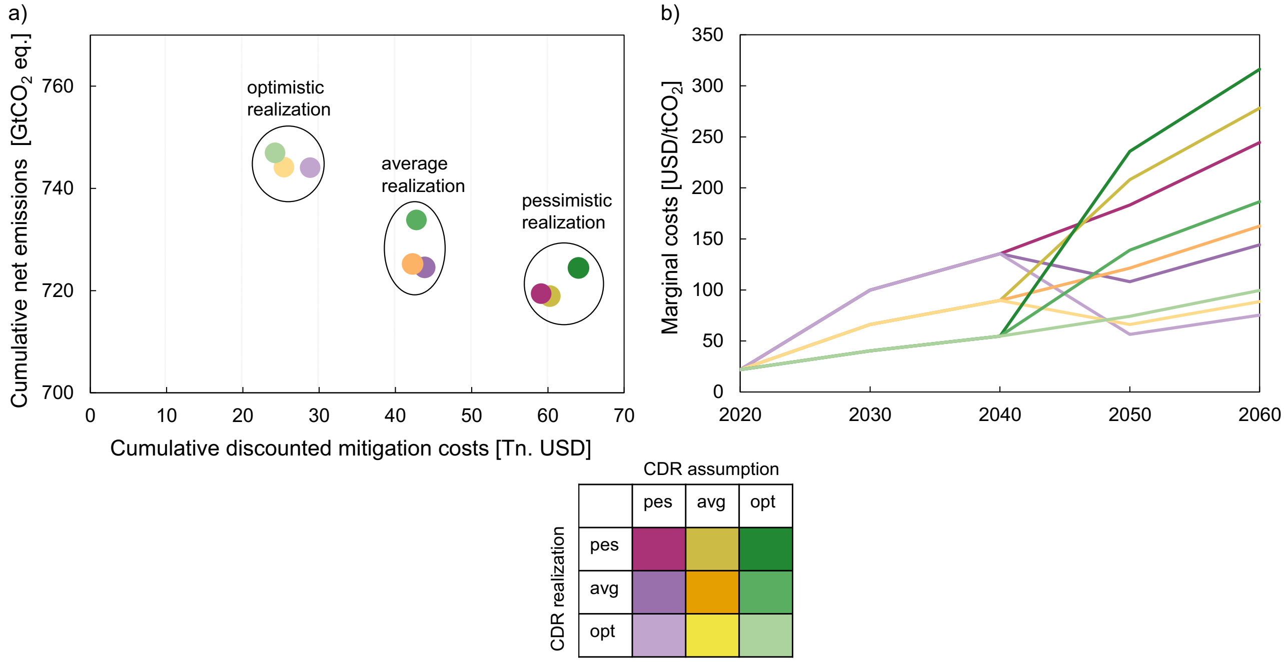

Fig. 3 | Results of the nine constructed scenarios with non-perfect foresight regarding future CDR feasibility and a deterministic CS of 3 °C with a global temperature increase limit of 1.5 °C for the year 2100. Each scenario consists of an assumption-realization pair on CDR feasibility with true feasibility realized in 2050. **a** Net cumulative GHG emissions and cumulative discounted mitigation costs in 2100. **b** The evolution of marginal abatement costs until 2060.

adaption would be more realistic as previous studies have indicated considerable challenges in quickly ramping up the mitigation investments[40–43].

Uncertainty in climate sensitivity and betting on CDR

Last, we consider jointly the non-probabilistic betting setup for CDR and probabilistic uncertainty regarding CS. For reference, we also run all nine scenarios with a deterministic CS using the best-guess climate sensitivity of 3 °C, with other parameters of the problem setup remaining the same. Hedging against the CS uncertainty under a temperature limit entails earlier and steeper emission reductions than with a deterministic CS. We assume that the uncertainty in CS starts to reduce gradually in 2040 (Fig. 1b), with the diverging scenario pathways either raising the required mitigation efforts (with higher values of CS) or gradually scaling down mitigation (with lower values of CS) (Fig. 4a). The pathways with high CS overshoot 1.5 °C already before 2050, peaking at almost 1.7 °C in 2070 (Fig. 4b). Due to the precautionary mitigation, however, the overshoot remains relatively contained even with a high CS compared to the deterministic CS scenario with a considerably lower CS. Moreover, the mean of the stochastic CS pathways involves barely any overshoot compared to the deterministic CS scenario, again due to the early-on mitigation (Fig. 4b). Most pathways end up below 1.5 °C by 2100 due to the assumed, linearly decreasing post-2100 temperature limit and the anticipation for the possibility of a high climate sensitivity by strong, up-front mitigation efforts.

The median of cumulative CDR by 2100 is 597 $GtCO_2$ (ranging from 90 to 1076 $GtCO_2$) across the nine stochastic scenarios with 64 pathways each, and 665 $GtCO_2$ (from 288 to 1063 $GtCO_2$) for the nine deterministic scenarios. This magnitude is similar to estimates in the IPCC AR6[1], where the median of scenarios aligned with the 1.5 °C target (with high overshoot) involved 687 $GtCO_2$ (from 0 to 1282 $GtCO_2$) of cumulative CDR by 2100. Figure 4c shows the CDR deployment, which is constrained by the scenario design of this study and the CDR ramp-up assumptions. Especially from 2070 onwards, the deterministic CS scenario deploys more CDR potentials than almost all the stochastic CS pathways with the same assumption and realization for CDR feasibility from 2070 onwards and therefore relies more heavily on CDR. The reason for this difference is the early-on mitigation in the stochastic scenarios to hedge the risk in CS, whereas scenarios omitting the uncertainty in CS rather rely on maxing out CDR potentials in the second half of the century since near-term mitigation is more expensive due to cost discounting.

The different realizations for CS (ranging from 1.9 °C to 5.8 °C) lead to vast differences in marginal abatement costs under a correct bet with average CDR realization, reaching over 2000 $/$tCO_2$ in 2080 with the highest realization of 5.8 °C (Fig. 4d). Moreover, it is notable that the deterministic CS scenario has lower marginal costs than the mean of the stochastic CS scenarios until 2090, indicating again that mitigation efforts are further postponed when omitting the uncertainty in CS. Note that the mean of the stochastic scenarios also reaches a lower temperature in 2100 compared to the deterministic scenario (Fig. 4b). Due to the cost-effective model set-up, any benefits from lower temperatures and potential damages of overshooting are not accounted for.

While the marginal costs for scenarios with a deterministic CS were primarily driven by the CDR realization from 2050 onwards (Fig. 3a), the impact from the initial CDR assumption is amplified when accounting for uncertainty in CS (Fig. 5). With a too-optimistic assumption on CDR, mitigation is postponed to future decades, leading to marginal costs that are the highest throughout all studied scenarios (Fig. 5a (dark grey colored cells), Supplementary Fig. 3). This highlights how "betting on CDR" to reach the Paris Agreement targets is much more problematic given the uncertainty over CS, as these two risks compound each other. If CDR is underestimated, the uncertainty also affects the marginal costs, however, far less in absolute terms than with an overestimation (Fig. 5a (light grey colored cells), Supplementary Fig. 3).

Analyzing cumulative mitigation costs separately for the stochastic paths with specific realization of CS reveals another noteworthy interaction between the uncertainties regarding CDR and CS. While a correct bet always yields the lowest cumulative costs with a deterministic CS (Fig. 3a), this is not true with uncertain CS. Compared to the correct bet, underestimating CDR lowers the cumulative costs for levels of CS ≥ 3.6 °C, while overestimation leads to slightly lower costs for lower levels of CS (Fig. 5b). That is, a wrong CDR assumption can lead to a better outcome with the tail-end realizations of CS. This occurs because the ambitious early-on mitigation under a pessimistic CDR assumption (Fig. 2a) also contributes to the strong

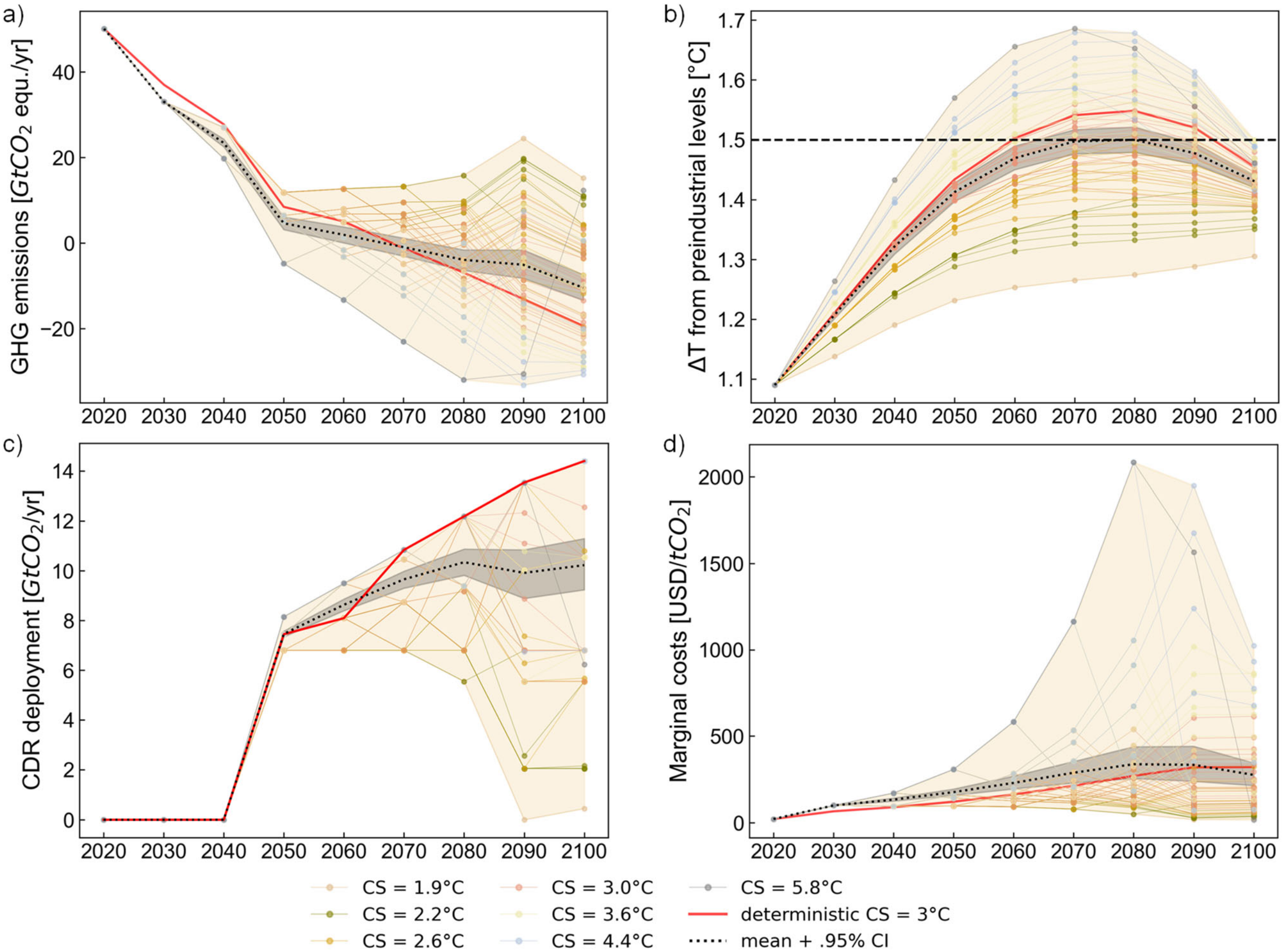

Fig. 4 | Stochastic scenarios with a global temperature increase limit of 1.5 °C for the year 2100 and uncertainty and learning on CS. All plots show scenarios with an average CDR feasibility for both the assumption and the realization. **a** Net global GHG emissions aggregated with 100-year global warming potentials. **b** Global mean temperature increase relative to preindustrial levels. **c** CDR deployment. **d** Marginal abatement costs. The line color indicates the true value of CS for a given stochastic pathway. The stochastic CS scenarios branch every ten years from 2040 on with a 50% probability, creating 64 scenarios at the end of the century. The solid red line represents a deterministic scenario run with a CS of 3 °C and the dotted black line represents the mean over all stochastic pathways with a 95% confidence interval shaded in grey.

mitigation required to reach 1.5 °C with high CS, and thereby underestimating CDR lowers mitigation costs if CS is found to be high. Conversely, the lax pre-2050 mitigation under an optimistic CDR assumption is aligned with the low mitigation needs under a low CS.

The strongest effect occurs for the highest level of CS, where an underestimation lowers cumulative mitigation costs by 13.6 tn. USD compared to the correct bet (average CDR assumption). In comparison, overestimation (optimistic CDR assumption for average realization) is beneficial for CS < 3 °C, because postponing mitigation to future decades ends up being unproblematic if CS is found to be low (Fig. 5b). However, in this case, the monetary savings compared to a correct bet are small, 2.4 tn. USD with the lowest level of CS.

The uncertainties in CS and CDR also affect the temporal distribution of mitigation costs (Fig. 5c). With high CS, a pessimistic assumption of CDR distributes mitigation costs (relative to the GDP) more evenly between the pre-2050 and post-2050 periods (Fig. 5c), independently of the CDR realization (Supplementary Material, Fig. 2). With an optimistic CDR assumption, the share of near-term mitigation (2020–2050) is comparably high for low CS of <3.6 °C but the shares of the mitigation costs relative to GDP are still closer to each other than in cases of high CS. Thus, from an intergenerational equity perspective, a pessimistic CDR assumption mitigates the risk of placing vastly higher costs to future generations under high CS, allowing for more leeway for mitigation decisions and pathways throughout the second half of the century, but entails increased costs to the current generation, especially if CS is low.

Discussion

Our scenarios indicate that CDR might have an important role in cost-effective mitigation strategies for staying within the 1.5 °C limit by 2100. Simultaneously, reliance on too optimistic future CDR feasibility creates mitigation deterrence[37]. Early emission reductions are needed to hedge against both the risk of high CS[35] and the possibility of CDR deployment failure[26]. For this reason, the risk of 'betting on negative emissions'[7,26] and the CS risk[27,28,44] need to be considered jointly.

Scenarios considering a deterministic CS result in a greater reliance on CDR, because omitting the risk in CS allows for delayed mitigation efforts, which are consequently balanced by CDR in the future. Moreover, we show that the initial assumption on CDR feasibility has only a minor impact on subsequent mitigation trajectories if the uncertainty in CS is disregarded. However, if the 1.5 °C target is to be met also with higher values of CS, the increased mitigation challenge compounds with the problem of possibly overestimating the CDR feasibility. This renders the joint consideration of uncertainties about future CDR and CS more critical.

Then, how should the CDR uncertainty be dealt with in long-term mitigation pathways? The deep nature of this uncertainty, we think, excludes the use of similar probabilistic methods as applied for CS here. The

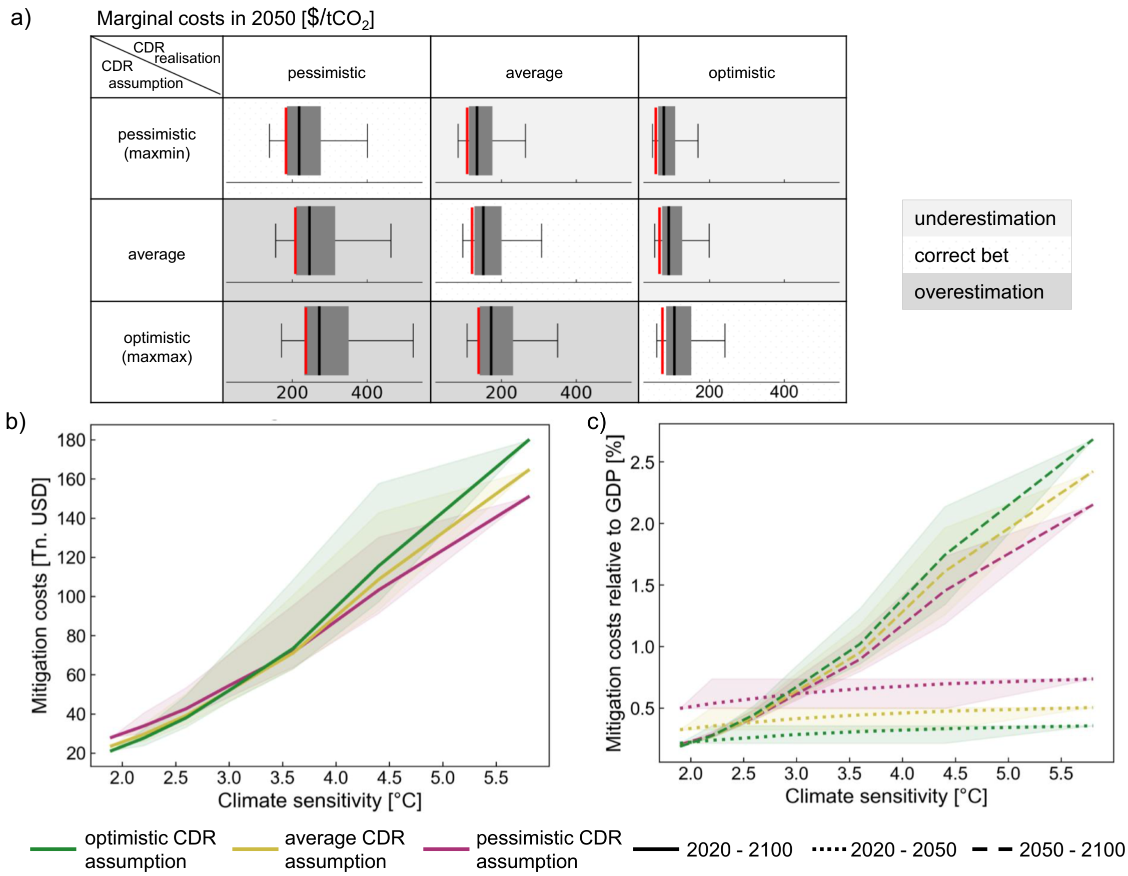

Fig. 5 | Marginal and mitigation costs in stochastic scenarios with a global temperature increase limit of 1.5 °C for the year 2100 and uncertainty and learning on CS. a Marginal costs in 2050 for all nine stochastic (box plot denoting the full range, quartiles, and median) and deterministic CS scenarios (red line), color-coded to show over/underestimations scenarios and correct bet scenarios. **b** Cumulative, discounted mitigation costs in 2020–2100 under an average CDR realization and the three CDR assumptions **c** Cumulative mitigation costs relative to GDP under an average CDR realization and the three CDR assumptions divided into near-term (2020–2050) and long-term (2050–2100) costs. The lines in (**b**) and (**c**) represent means over the 64 stochastic pathways and the shading shows the total range of the pathways.

probabilities for future CDR potential cannot be solidly justified. Instead, we relied on two common decision rules for non-probabilistic uncertainty. Maxmin is more often suggested for its prudence, and this equates with taking a pessimistic view of future CDR. Maxmax aligns with the optimistic CDR assumption, but it exposes to the 'double whammy' risk of overestimating CDR feasibility and a high CS. Future research could use other methods for dealing with ambiguity[45,46] to enrich this perspective.

There are several aspects our scenarios did not consider explicitly. Overestimating CDR assumption can also become problematic due to the rapid ramp-up for mitigation required if CS turns out to be higher than currently assumed. Although the achievable rate of mitigation ramp-up is dependent on e.g., capital turnover rates, availability of financial resources, and other inertia in transforming society[40–43], we did not consider any constraint relating thereto. Additionally, the assumption of global, perfect carbon markets and uniform carbon pricing omits locational factors such as physical, technological, financial, and socio-economic barriers[47]. Overestimating CDR potentials can thus lead to overshoot from which we are not able to return to 1.5 °C by 2100 if mitigation cannot be ramped up sufficiently as suggested by IAM scenarios[33]. This additionally supports the prompt action needed to hedge the risk in CS and decreases the severity of high CS realizations, again highlighting the importance of considering uncertainties both in CDR and CS jointly. However, to avoid mitigation deterrence and the 'moral hazard' risk, mitigation scenarios could also be challenged in terms of their implementation of long-term temperature limits aligned with the Paris Agreement[25] as well as their carbon price trajectory[24], both typically leading to a peak-and-decline behavior in global temperature, which can also be observed in our results.

While our analysis focused explicitly on the uncertainty in the CDR potential and cost, CDR might have wide-ranging, unintended side-effects on biogeochemical cycles and climate with unclear trade-offs that potentially either weaken or strengthen their carbon removal potential[1,48]. Our study design did not either account for risks and co-benefits associated with CDR deployment e.g., on biodiversity, ecosystems, food production, water availability, local livelihoods[15,49–51] nor for competition with other CCS applications, between different CDRs, and their dependency on a fast, and low-cost renewable energy transition[9–11,52].

Despite these caveats, all our scenario results unquestionably show that aggressive near-term mitigation is required to limit the year-2100 warming to 1.5 °C even in an optimistic CDR scenario, but that some level of CDR is likely required in the future even if CS turns out to be extremely low. This need for immediate, deep emissions reduction is in line with mitigation scenarios depicted in the IPCC AR6 report[1]. To hedge against prevalent uncertainties in CS, and overconfidence in future CDR, our results show that precautionary action in terms of deep, near-term mitigation is particularly important and needs to be focused. However, current mitigation efforts are insufficient with required mitigation trajectories complying with the Paris Agreement targets[53]. Relying solely on an optimistic view of CDR feasibility creates a false sense of predictability about easy and economical future CDR deployment, thus, further deterring current mitigation efforts. CDR potentially plays a crucial role in future mitigation but omitting the joint risks and

Table 1 | CDR input parameters

CDR	Cumulative Potential 2020–2100 [$GtCO_2$][56]			Peak potential [$GtCO_2$/yr][8]			Costs [US$/$tCO_2$][8]		
	pes	avg	opt	pes	avg	opt	pes	avg	opt
Afforestation and reforestation	100	200	300	0.5	2.05	3.6	50	27.5	5
Biochar	100	150	200	0.5	1.25	2	120	75	30
DACCS	200	350	500	0.7	3.85	7	300	200	100
Enhanced Weathering	100	100	100	2.5	3.75	5	200	125	50
Soil Carbon Sequestration	20	60	100	2	3.5	5	100	50	0

Parameters are based on refs. 56,8 with pessimistic feasibility (pes) representing the lowest values of their potential estimates and highest of the cost estimates, optimistic feasibility (opt) conversely the highest values of their potential estimates and lowest of the cost estimates. The average feasibility (avg) is the mean of pessimistic and optimistic cases.

uncertainties of CDR and CS could lead to irreversible and high-temperature overshoot and risk a livable future.

Materials and methods

Model description

Scenarios are calculated with SCORE[35,36], a lightweight IAM with stochastic capabilities (see Model description, Supplementary information). The objective of the model is to minimize the expected value of discounted (with a discount rate of 3%) mitigation costs in long-term scenarios. The model includes baseline emissions of CO_2, CH_4, and N_2O based on multi-model mean and marginal abatement cost (MAC) curves corresponding to high-cost and low-cost envelopes of the Shared Socioeconomic Pathways[54]. Here, we use only the low-cost MAC curves. SCORE includes a simplified climate module to calculate the global mean temperature change. Warming from CO_2, CH_4, and N_2O is calculated explicitly by using their atmospheric stock, lifetime, decay between periods, and radiative efficiency according to AR5[55]. For analysis and plots their emissions are aggregated together with CO_2 using their Global Warming Potentials (feedback not included) from AR5 with a 100-year time frame[55]. The uncertainty in CS is considered through a discrete, non-symmetric probability distribution[29]. This uncertainty is assumed to gradually decrease over time. A predefined, perfect learning process maps a scenario tree that branches every 10 years from 2030 onwards with a 50% branching probability, resulting in 64 pathways by the end of the century (Fig. 1b), and allowing for temporary negative learning. Before branching, the pathways have the same information regarding CS, and thereby the emission reductions are required to be equal through non-anticaptivity constraints. In the deterministic scenarios, CS is set to the most probable value of 3 °C[1], which is also most commonly used in IAMs. In a cost-effective scenario the 1.5 °C target according to the Paris Agreement is set to be reached in 2100, however, allowing for unconstrained overshooting of the 1.5 °C target before the end of the century. To avoid end-of-horizon effects (e.g., rapid scale-down of CDR once the temperature constraint is reached) the temperature target decreases linearly to 1.0 °C in 2200. This slow decline in the constraint (0.05 °C per decade) corresponds approximately to the required decline from the temperature overshoot to meet the 1.5 °C constraint by 2100.

CDR implementation

The technologies implemented are afforestation and reforestation, biochar, DACCS, enhanced weathering, and soil carbon sequestration. They are chosen based on their level of investigation in the scientific literature[8,9]. CDR characteristics include yearly and cumulative carbon removal potential, and carbon removal costs (Table 1). The five CDR options are implemented into SCORE with deterministic characteristics[8,56] in three different CDR scenarios: pessimistic, average, and optimistic. The choice of implementing three scenarios with different levels of CDR feasibility is based on the uncertainty in the scientific literature on CDR's performance of key aspects[8,9,56]. However, Rueda et al.[56] conclude that the "(…) consensus around the relative performance level of CDR's critical aspects is evident enough to already get valuable insights from their joint evaluation." The optimistic scenario considers high potential and low costs for CDR, while the pessimistic scenario setting assumes the opposite. The average case uses the average values of these two extremes. For instance, the range of the cumulative removal potential of AR is given as 100–300 $GtCO_2$, and therefore the average scenario uses a value of 200 $GtCO_2$. To maintain consistency with the scenario design all CDR technologies are set to start in 2050, although this is not necessarily consistent with CDR literature[8], as most CDRs can be available earlier. However, most literature expects CDRs to reach their peak potential only by 2050[8], therefore assuming a delayed start year is less critical. For CDRs that are expected to reach their peak potential after 2050 (DACCS and enhanced weathering[56]), we set a linear ramp-up from zero in 2050 to the peak potential in 2105 for DACCS and 2108 for enhanced weathering[56]. Other CDR technologies can be started with full potential immediately from 2050 onwards.

Data availability

The data that supports the findings of this study are available from https://doi.org/10.5281/zenodo.11230655.

Code availability

The code of the SCORE IAM is publicly available at https://doi.org/10.5281/zenodo.11230816.

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The authors declare no competing interests.

Additional information

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