The climate implications of failing to manage carbon

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In scenarios that limit the increase in global mean temperature (GMT) this century to 1.5 or 2°C, large quantities of carbon are managed by both carbon capture and storage (CCS) at point sources and atmospheric carbon dioxide removal (CDR). Such carbon management may be used to offset ongoing ("residual") emissions from hard-to-abate sectors and to decrease the concentration of carbon dioxide in the atmosphere if various feasibility and sustainability challenges are overcome. Here, in over 16 million simulations of the simple climate model MAGICC, we systematically analyze the climate implications of failing to manage carbon to the degree called for in 407 different climate mitigation scenarios. We find that entirely failing to manage carbon relates to ~0.5°C higher GMT in 2100, making it impossible to meet the 1.5°C target, but leaving 2°C in reach this century–assuming the projected decreases in emissions still occur. Our results also show that peak temperatures are especially sensitive to land-based CDR (afforestation and reforestation) that often ramps up quickly in the scenarios, whereas end-of-century temperatures depend more on levels of engineered CDR (bioenergy with carbon capture and storage, direct air capture with storage). What is clear, though, is that the quantity of carbon in avoided emissions is vastly larger than carbon managed in every climate mitigation scenario.

Limiting the increase in global mean temperature to 1.5 or 2°C (the Paris Agreement goal) requires decreases in net carbon dioxide (CO_2) emissions of roughly 83% and 78% between 2020 and the net-zero CO_2 year, respectively (reaching net-zero emissions by 2060 and 2077, respectively)[1]. In scenarios generated by integrated assessment models (IAMs), such decreases are dominated by absolute reductions in emissions as global energy services transition away from fossil fuels[2]. For example, in the most ambitious climate scenarios (i.e. 1.5°C with no or low temperature overshoot), global coal, oil, and natural gas total energy supply from all uses decrease on average by 95%, 62%, and 42%, respectively, between 2020 and 2050[3]. However, over time, climate mitigation scenarios also increasingly project the deployment of carbon management technologies[4] that allow for continued use of fossil energy and industrial processes by capturing related emissions from point sources (carbon capture and storage, CCS), as well as capturing and storing CO_2 directly from the atmosphere (carbon dioxide removal, CDR) to either offset emissions from hard-to-abate sectors[5,6] or to reduce the atmospheric concentration of CO_2 (and thus global mean temperature)[7]. Although there are a wide range of CDR approaches being explored[8–10], IAMs typically include only land-based methods like afforestation and reforestation and engineered (sometimes called "novel") methods like bioenergy with carbon capture and storage (BECCS) and direct air capture with storage (DACS)[8].

The reason ambitious mitigation scenarios increasingly rely on carbon management is because without it, the required growth rate of non-fossil energy (and/or decrease in energy demand)[11,12] is unprecedented and thus difficult to materialize in the near-term[13]. Indeed, before IAMs fully incorporated CDR technologies in the early 2000s, many could not produce feasible solutions for 2°C in their modeling frameworks[14]. Now, the argument that engineered CDR is essential for meeting climate goals is widely accepted in industry, academic, and policy circles[15–18]. But the models may have only traded implausible changes in energy systems for implausible changes in carbon management: Paris-compliant scenarios included in the Intergovernmental Panel on Climate

Change (IPCC) Sixth Assessment Report (AR6) project global median values of 8.9 $GtCO_2$/yr from BECCS and 1 $GtCO_2$/yr from DACS by 2100[19], and reanalysis data for these scenarios project median values of 2.2 $GtCO_2$/yr from afforestation/reforestation by the same year[20], which altogether is almost an order of magnitude more than global CDR today (~2 $GtCO_2$/yr, >99.9% of which is land-based with contested effectiveness)[21]. Such rapid projected growth raises concerns of socioeconomic and political feasibility[22–28], sustainability and resource constraints[29–38], deficient monitoring, reporting and verification mechanisms[39], lack of governance[40,41], and inequities[42,43].

But despite the incongruity of claims that large-scale carbon management is both essential and implausible, there has not been a systematic analysis of the climate implications if we fall short of the levels of carbon management called for in ambitious climate mitigation scenarios. Here we present the results of such an analysis with details of our approach in the Methods section. In summary, we first quantify the use of carbon management technologies in 407 AR6 scenarios (Supplementary Table 1), including those that have >67% probability of limiting warming to 2°C (n=231), and those that have >50% probability of limiting warming to 1.5°C by the end-of-century either with no or low overshoot (n=70) or after a high overshoot (n=106). We then use the simple climate model MAGICC to evaluate global mean temperatures in 16,117,200 simulations: 600 ensembles of 407 different IAM scenarios[44], and each with 66 different levels of assumed fractional shortfall, or "underdelivery", of the called-for carbon management (i.e. failure to scale carbon management due to feasibility and sustainability challenges and/or failing to measure carbon sequestration accurately).

Carbon management in IPCC scenarios

Among carbon management technologies, fossil combustion CCS and industrial processes CCS (e.g. cement calcination) has been included in IAMs the longest. In AR6 scenarios, both the annual rate and cumulative quantities of fossil combustion CCS and industrial processes CCS (hereafter fossil CCS) vary substantially, but tend to be greatest in 2°C scenarios (median values of 5.1 $GtCO_2$ in 2100 and 254 $GtCO_2$ 2020–2100), and decrease progressively in 1.5°C scenarios with low-overshoot (median 3.8 $GtCO_2$ in 2100 and 261 $GtCO_2$ 2020–2100) and high-overshoot (median 1.4 $GtCO_2$ in 2100 and 210 $GtCO_2$ 2020–2100; Figs. 1a–c). In contrast, although still quite variable, the annual rate and cumulative quantities of CDR tend to be greater in 1.5°C scenarios, especially those with high-overshoot (median values of 17.7 $GtCO_2$ in 2100 and 860 $GtCO_2$ 2020–2100) than 2°C scenarios (median values of 13.3 $GtCO_2$ in 2100 and 638 $GtCO_2$ 2020–2100; Figs 1d–f).

Over the course of the century in these scenarios, the type of carbon management shifts from almost entirely land-based CDR today (afforestation and reforestation) to a mix of land CDR, fossil CCS (e.g., post-combustion at a natural gas power plant or CCS for cement production), and engineered CDR (e.g., BECCS, DACS, enhanced weathering). By 2100 in 2°C scenarios, mean shares of engineered CDR and fossil CCS grow to 52% and 29% of carbon managed, respectively, and land CDR decreases to only 19% (Fig. 1g–h). Similar shares of carbon management types are used by 2100 in 1.5°C scenarios with low-overshoot (Fig. 1h), but in 1.5°C high-overshoot scenarios the mean of engineered CDR reaches 63% in 2100, with proportionally lower shares of land CDR and fossil CCS (17% and 20%, respectively; Fig. 1h). Cumulatively 2020–2100, the median quantity of carbon removed by engineered CDR is somewhat greater than that removed by land CDR in all mitigation scenarios: median land CDR is 304, 365, and 355 $GtCO_2$ in 2°C, 1.5°C low-overshoot, and 1.5°C high-overshoot scenarios, respectively, while median engineered CDR in the same scenarios is 389, 397, and 520 $GtCO_2$, respectively (Fig. 1i).

It is also worthwhile to consider the different functions being served by carbon management in these scenarios. Fossil CCS directly reduces emissions from point sources of industrial processes, industrial fuel combustion, fuel production (i.e. hydrogen, liquid fuel, and non-hydrogen gas), and electricity generation, whereas CDR is deployed either to offset residual emissions that cannot be cost-effectively avoided in IAMs, or—after net-zero global emissions are reached—to restore (reduce) atmospheric CO_2 concentrations with global net-negative emissions. Today nearly all carbon management is used to offset emissions (CCS accounted for <1% or 4 $MtCO_2$[45]), but that function dwindles over the century and by 2100 in 2°C scenarios the mean share of fossil CCS is roughly 30% (12% related to electricity, 9% for hydrogen and liquid fuels, 5% related to industry combustion, and 4% for industrial processes), and the mean level of restoring CDR reaches 24% (Figs. 1j-k). Shares of both offsetting CDR and fossil CCS further decrease as restoring CDR increases in 1.5°C scenarios, with the mean share of restoring CDR in high-overshoot scenarios reaching 53% by 2100 (Fig. 1k). Meanwhile, median cumulative quantities of offsetting CDR decrease modestly from 2°C scenarios to 1.5°C low-overshoot scenarios to 1.5°C high-overshoot scenarios (567, 562, and 484 $GtCO_2$, respectively), while median cumulative quantities of restoring CDR in the same scenarios increase dramatically (55, 213, and 317 $GtCO_2$, respectively; Fig. 1l, see Supplementary Fig. 1 for 1.5°C scenarios).

Temperature implications of underdelivering carbon management

Assuming some share of carbon management in a mitigation scenario is underdelivered implies a new emissions trajectory (because net emissions to the atmosphere are greater). We calculate a range of such trajectories for each scenario by varying the assumed underdelivery from 0% (i.e. all the carbon management projected by a scenario is delivered) to 100% (i.e. none of what is projected by a scenario is delivered) at increments of 10%. When all types of carbon management are underdelivered at once and in proportion, global GHG emissions decrease less, especially in the latter half of the century (for type-specific underdeliveries, see Supplementary Figs. 2–7). For example, whereas median annual GHG emissions in 2°C scenarios reach 3.9 $GtCO_2e$ by 2100 (p5-p95 range: -7.2–10.9), 50% and 100% underdelivery of carbon management leads to 2100 emissions of 12.8 (3.7–22.9) $GtCO_2e$ and 22.1 (11.4–35.2) $GtCO_2e$, respectively (Fig. 2a). Cumulative 2020–2100 median GHG emissions increase from 1,508 $GtCO_2e$ (no underdelivery, p5-p95 range: 985–1,809) to 1,971 (1,564–2,485) $GtCO_2e$ and 2,404 (2,077–3,318) $GtCO_2e$ in 50% and 100% underdelivery scenarios, respectively (Fig. 2b). Differences in annual emissions when underdelivering carbon management are similar in 1.5°C scenarios, remaining as high as 18.6 (8.2–28.4) $GtCO_2e$ and 14.5 (9.4–33.1) $GtCO_2e$ in 2100 when assuming 100% underdelivery in low- and high-overshoot scenarios, respectively, with cumulative 2020–2100 median GHG emissions for the same underdelivery cases reaching 1,965 (1,423–2,827) $GtCO_2e$ and 2,150 (1,841–3,006) $GtCO_2e$ (Figs. 2d, 2e, 2g, and 2h).

In turn, as carbon management is increasingly underdelivered, higher emissions result in higher GMT increases. Whereas the median increase in GMT by 2100 in 2°C scenarios with no underdelivery is 1.61°C, underdelivering carbon management by 50% or 100% is associated with comparable increases of 1.85°C and 2.06°C, respectively (Fig. 2c). Looking across all the 2°C scenarios and ensemble members, underdelivering carbon management by 50% or 100% increases the probability of exceeding the 2°C threshold in 2100 from just 18% (no underdelivery) to 36% and 54%, respectively (inset in Fig. 2c, Supplementary Fig. 8).

Underdelivering carbon management has similar implications for GMT in 1.5°C scenarios: in low-overshoot scenarios the increase in GMT by 2100 rises from 1.33°C (no underdelivery), to 1.61°C and 1.81°C when underdelivering 50% and 100%, respectively, while the probability of exceeding the 1.5°C threshold in 2100 increases from 30% (no underdelivery), to 61% and 80% when underdelivering half and all carbon management, respectively (Fig. 2f, Supplementary Fig. 9). Finally, in high-overshoot scenarios the increase in GMT by 2100 rises from 1.44°C (no underdelivery), to 1.67°C and 1.90°C when underdelivering 50% and 100%, respectively, while the probability of exceeding the 1.5°C threshold in 2100 increases from 43% (no underdelivery), to 67% and 85% when underdelivering half and all carbon management, respectively (Fig. 2i, Supplementary Fig. 10).

Thus, the climatic consequence of entirely failing to manage carbon in both 2°C and 1.5°C scenarios is consistently a median difference of 16-20 $GtCO_2e$/yr and 0.44-0.48°C in GMT by 2100 (cumulative 2020–2100 difference of 955–1,059 $GtCO_2e$), while the end-of-century implications of delivering only half of the called-for carbon management is a median difference of 8-10 $GtCO_2e$/yr and 0.23-0.28°C in GMT by 2100 (477–531 $GtCO_2e$ cumulatively) (Figs. 2j, 2k, and 2l).

Underdelivering different types of CDR

Focusing on CDR alone, underdelivery affects end-of-century temperature more than peak temperature in all mitigation scenarios (Figs. 3a, 3c, and 3e, Supplementary Figs. 11–12). However, peak temperatures are more sensitive to delivery of land-based CDR and 2100 temperatures are more sensitive to engineered CDR, especially in 1.5°C scenarios. For example, in 1.5°C high-overshoot scenarios, underdelivering 100% of engineered CDR increases the median 2100 temperature by 0.27°C, but peak temperature by only 0.03°C, whereas underdelivering 100% of land CDR increases median 2100 temperature by half as much (0.14°C) but peak temperature by nearly twice as much (0.05°C; Fig. 3e). This is because land CDR represents most of carbon managed before mid-century, while engineered CDR is deployed later in the century after peak temperature has been reached[46] (see Supplementary Figs. 13–18 for density distributions for 2100 and peak temperature).

We also explore the relative effects of underdelivering land and engineered CDR on the probabilities of staying below temperature targets. For example, the probability of staying below 2°C this century remains >67% even when underdelivering 80% of engineered CDR in 2°C scenarios as long as no more than 20% of land CDR is also underdelivered (and also assuming no underdelivery of CCS; Fig. 3b). Similarly, the probability of staying below 1.5°C in 2100 remains

>50% when underdelivering 60% of engineered CDR in 1.5°C scenarios with low-overshoot as long as no more than 40% of land CDR is also underdelivered (Fig. 3d). However, CDR is more critical in 1.5°C scenarios with high-overshoot: no more than 40% of engineered CDR can be underdelivered to maintain a 50% probability of staying below 1.5°C in 2100, and this falls to no more than 20% if 40% of land CDR is also underdelivered (Fig. 3f).

Discussion and conclusions

In IPCC scenarios compatible with the 1.5 and 2°C goals, humans actively manage almost a trillion tons of CO_2 this century (with median quantities of 210–254 $GtCO_2$ of fossil combustion and industrial processes CCS, and 638–860 $GtCO_2$ of CDR; Fig. 1). For comparison, this is more than the total cumulative emissions from burning fossil fuels in the latter half of the 20th century (~821 $GtCO_2$)[47]. Moreover, the scale-up of such management is fast, growing from historical 2 and 4 $MtCO_2$ of engineered CDR[48] and fossil CCS[45], respectively, in 2022, to projected median ranges of 39–321 and 115–699 $MtCO_2$ in 2030, to 2051–3835 and 2792–2921 $MtCO_2$ in 2050, respectively (i.e. growing by ~30% and ~26% per year until mid-century, respectively; Supplementary Table 2). Such growth rates are comparable to those of global nuclear power in the 1970s[49] or U.S. shale gas between 2007–2017[50], but sustained for 28 years (Supplementary Fig. 19).

Given the ambitious climate policies and investments entailed[22,51] and the current lack of social and political support[24,48,49], the prospect of managing such scales of carbon so fast has led some researchers to dismiss CDR as an "energetically and financially costly distraction"[33]. This characterization points to the critical consideration that, while failing to manage any carbon at all would leave little chance of meeting the 1.5°C target by the end of the century (Supplementary Figs. 9–10), failing to rapidly reduce fossil CO_2 emissions risks a much larger effect on global mean temperature. Across scenarios, emission reductions are core to successful climate mitigation and even the large scales of carbon management in scenarios pale in comparison (see Supplementary Tables 3 and 4 for mitigation rates). For example, in the median 2°C scenarios, gross emissions decrease by 4% per year from 2015–2050, whereas maintaining the same trajectory of net emissions in the absence of any carbon management (100% underdelivery) would require emissions to fall much faster, by 16% per year over the same time period.

Thus, although failing to manage carbon could jeopardize the most ambitious Paris goals, the greater risk may be such management distracting from—or delaying[52,53]—efforts to directly reduce emissions from energy and food systems[54]. Especially since carbon management to date has not focused on hard-to-abate sources of emissions[55–57]; those sources are excluded in most countries' emissions trading systems[57]; and roughly half of carbon credits that have been sold in voluntary carbon markets were bought by fossil fuel companies[58]. Moreover, because monitoring, reporting, and verification of carbon removals remain inconsistent and are not always scientifically rigorous, the validity and durability of market-based carbon removals are routinely questioned[59–65], with researchers finding 87% of company-bought carbon credits to be low-quality[66].

Several important limitations and caveats apply to our analysis. First, the simplified climate model we use (MAGICC) does not explicitly represent nonlinear feedbacks and tipping points in the Earth system[67–69], which could lead us to underestimate increases in global mean temperatures.

The potential for such underestimated warming is well known and not unique to our study, though, and such nonlinear responses are at least partially captured by the range of global temperature trajectories generated by our MAGICC ensembles: e.g. at the 95th percentile the increase in GMT of 100% underdelivery is 3.1°C (compared to 2.1°C at the median percentile; Supplementary Fig. 20). Secondly, although entirely failing to manage carbon may still limit the increase in global mean temperature this century to 2°C —assuming that all emission reductions are met—, warming in many cases would continue after 2100 in scenarios that underdeliver carbon management, as achieving net-zero CO_2 emissions is essential for temperature stabilization and is not achieved in any of the 407 scenarios that underdeliver all carbon management (Supplementary Figs. 21–22, Supplementary Table 5). Even more so, crossing the 1.5°C threshold is expected to cause substantial damages[70,71] (e.g., agricultural yield reductions in the tropics, increased heatwaves, and sea level rise, etc.[72–74]), impacting over a billion more people compared to a 2°C world, 19% of them living with <10$ a day[75]. Third, our underdelivery scenarios assume no change in mitigation efforts (i.e., we assume emission reductions embedded in each scenario are met, but not increased due to failures of carbon management), nor do we analyze economic damages of additional warming[76] or any implications for intergenerational[43,77] and international equity[78,79]. Finally, our scenarios assume a constant level of underdelivery; we do not explore the climate consequences of varying the degree of underdelivery over time.

Despite these limitations, our systematic analysis highlights more clearly than before the stakes of carbon management: falling short in scenarios by half would mean 0.28°C of extra warming in 2100, and entirely failing to manage carbon would mean ~0.5°C (or 0.18–0.27 °C if only engineered CDR were underdelivered, depending on the scenario category). This extra warming makes the 1.5°C target almost impossible but leaves the 2°C target in reach this century—assuming emissions rapidly decline. Such numbers are critical context for future discussions and research on the marginal costs and benefits of climate mitigation. And importantly, our results underscore the priority of direct emission reductions[80], not least because lower residual emissions will reduce both the need for carbon management and the risks of failing to deliver it[55,81,82].

Methods

Here, we first analyze data from the IPCC AR6[83] for CO_2 emissions and CO_2 capture from energy from existing scenarios and combined them with reanalysis data for CO_2 emissions and CO_2 capture from land[20]. Second, we create new emission trajectories for CO_2 based on assumptions for underdelivering carbon management technologies (from 10–100%, every 10% increments, and permutations from 20–100%, every 20% increments). Finally, we run MAGICC[84,85] v7.5 to estimate temperature outputs following the climate-assessment workflow from Working Group III from AR6[44] for a total of 16,117,200 emulator runs. We analyze 407 scenarios, including those that have >67% probability of limiting warming to 2°C (n=231 in category C3), and those that have >50% probability of limiting warming to 1.5°C throughout the 21st century with no or limited overshoot (n=70 in C1) and after a high overshoot (n=106 in C2). Note we only modify CO_2

emissions from energy/industrial processes and from land and we do not modify any emissions for non-CO_2 gases.

1. Analyzing AR6 scenarios

From AR6 data[83], we analyze the following variables for carbon management: "Carbon Sequestration | Direct Air Capture", "Carbon Sequestration | Enhanced Weathering", "Carbon Sequestration | Other", "Carbon Sequestration | CCS | Biomass", "Carbon Sequestration | CCS | Industrial Processes", "Carbon Sequestration | CCS | Fossil". For emissions we analyze: "Emissions | CO_2 | Energy and Industrial Processes", "Emissions | CO_2 | Other", "Emissions | CO_2 | Waste".

From Gidden et al.[20] reanalysis land data we analyze the following variables: "AR6 Reanalysis | OSCARv3.2 | Carbon Removal | Land | Direct" and ""AR6 Reanalysis | OSCARv3.2 | Emissions | CO_2 | AFOLU | Direct".

For Figure 1, fossil carbon capture and storage refers to: "Carbon Sequestration | CCS | Industrial Processes", "Carbon Sequestration | CCS | Fossil". Carbon dioxide removals include the engineered options of: "Carbon Sequestration | Direct Air Capture", "Carbon Sequestration | Enhanced Weathering", "Carbon Sequestration | Other", and "Carbon Sequestration | CCS | Biomass", and for land "AR6 Reanalysis | OSCARv3.2 | Carbon Removal | Land | Direct". Offsetting CDR refers to those removals used to get to net-zero CO_2 emissions, whereas restoring CDR refers to those removals used to go below zero CO_2 emissions.

Cumulative emissions and management are calculated following the trapezoidal rule:

$$C = \sum_{i=1}^{n-1} \frac{E_i + E_{i+1}}{2} \times \Delta t$$

Where C is the cumulative emissions or carbon managed from 2020 to 2100 in $GtCO_2$, Ei refers to CO_2 emissions or carbon managed in year i (from 2020 to 2100, every 5-year time steps), Δt is the difference between time steps (5 years), n is the number of years.

2. Adjusting emission trajectories

We have a total of 66 underdelivery emission trajectory sets (36 in the main text and 30 in Supplementary Figs. 2–7), each with 407 scenarios, where we adjust CO_2 emissions from 2020 to 2100 in each model period. The assumed carbon that was not managed (i.e., that was underdelivered) remains in the atmosphere resulting in higher CO_2 emissions in either land or energy (or both), leading to higher GHG emissions (as seen in Figure 2). The 66 underdelivery emissions trajectories sets include: one for the original emission trajectories, 10 for underdelivering all carbon management together (fossil CCS, engineered CDR, and land CDR, from 10–100% every 10% increments), 10 for underdelivering fossil CCS only, 10 for underdelivering engineered CDR only, 10 for underdelivering land CDR only. We then run 25 additional sets for underdelivering a combination of engineered CDR and land CDR simultaneously from 20–100%, every 20%, to assess the impact on temperature of underdelivering one CDR category compared to the other (and without modifying fossil CCS). Refer to Supplementary Fig. 23 for carbon management technologies in our scenarios and literature estimates.

3. Estimating temperature implications

We use MAGICC[84,85] v7.5 and run the 407 scenarios with a probabilistic ensemble of 600 each following the climate-assessment of Working Group III of AR6[44] for the 66 underdelivery sets, thus generating 16,117,200 emulator runs (600 ensembles for 407 IAM scenarios, 66 times). In this workflow emission trajectories are harmonized following historical GHG emissions and then infilled for missing emissions, consistent with the climate-assessment of Working Group III[44]. Each of the 600 ensemble members has a set of input climate assumptions that drive a probabilistic bell curve of temperature outcomes.

We report global mean temperature increase relative to the 1850–1900 period. For results in Figure 2, we calculate the median temperature across 600 ensembles for each scenario and year and then report the median across scenarios for each category (2°C or C3, 1.5°C low-overshoot or C1, 1.5°C high-overshoot or C2). For the probability of exceeding the 2°C and 1.5°C target/thresholds we estimate how many ensembles of the 600 ever cross the target/threshold, and for calculating the timeseries we estimate the percent of ensembles for each scenario at any given year that is above the threshold. For peak temperature we calculate the highest temperature from 2020–2100 for each of the 600 ensembles and report the median across the ensembles for each scenario.

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Funding: C.B. acknowledges the financial support of the Link Foundation Energy Fellowship, the National Academy of Sciences and International Institute for Applied Systems Analysis, and UCI's Dean Dissertation Fellowship. MJG and EB acknowledge funds received from the ERC-2020-SyG GENIE grant of the European Union, grant no. 951542. MJG is also affiliated with Pacific Northwest National Laboratory, which did not provide specific support for this paper.

Author contributions: Conceptualization: CB, EB, MJG, ZN, EG, SJD; Methodology: CB, EB, MJG, ZN, SJD; Investigation: CB; Visualization: CB, SJD; Funding acquisition: CB, EB, MJG, ZN, SJD; Project administration: SJD; Supervision: SJD, EB, MJG, ZN; Writing – original draft: CB, SJD; Writing – review & editing: CB, EB, MJG, ZN, EG, SJD.

Competing interests: the authors declare no competing interests.

Data and materials availability: We used data from the Sixth Assessment Report[83], as well as reanalysis data from Gidden et al.[20]. Code used for the figures is publicly available at GitHub (https://github.com/CandeBergero/underdelivering_CDR). All data needed to replicate the figures is publicly available at Zenodo (https://zenodo.org/records/15539829).

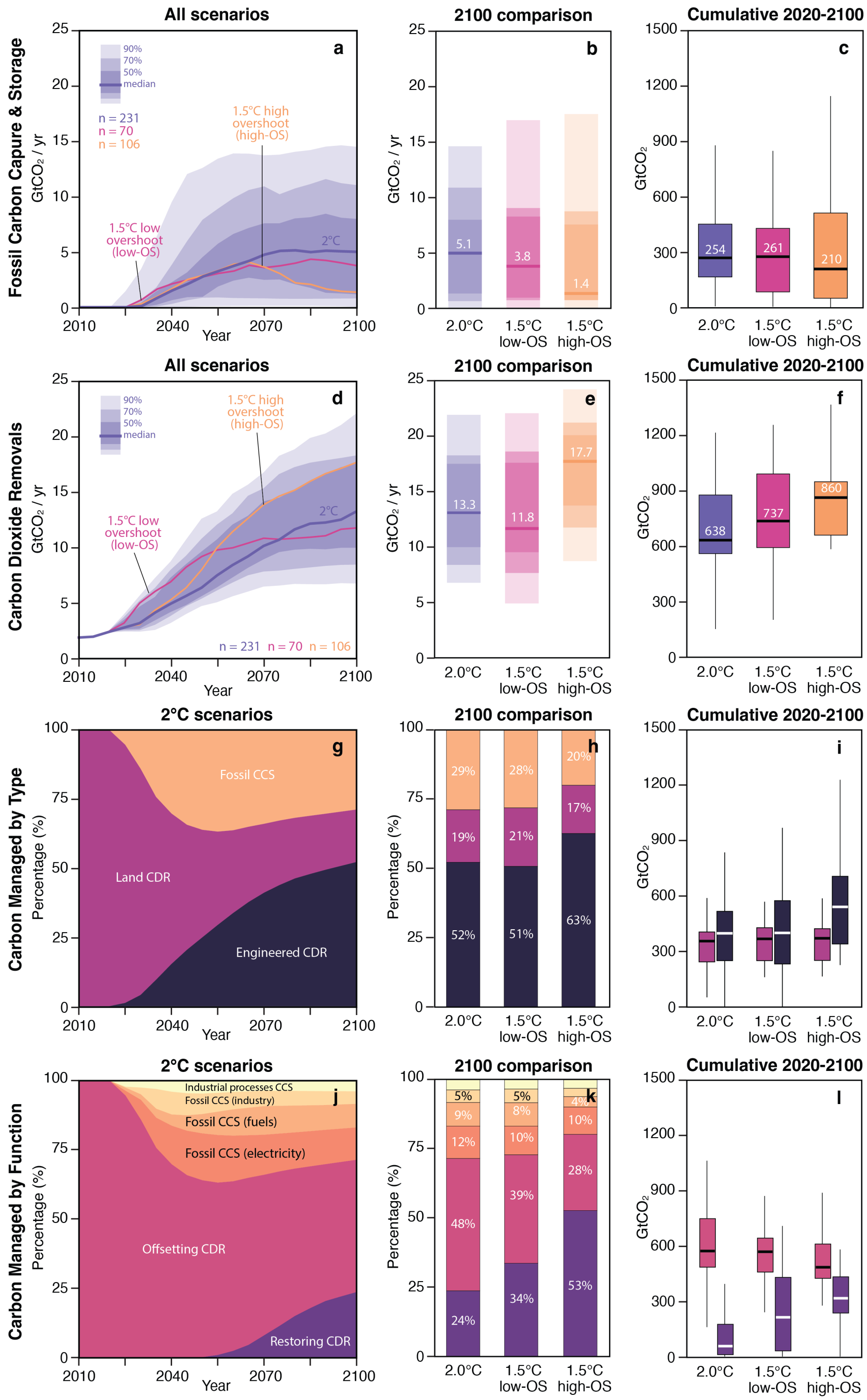

Figure 1 | Carbon management in AR6 scenarios. Panels **a–c** show fossil CCS across 1.5°C and 2°C scenarios (categories C1–C3). Panels **d–f** show carbon dioxide removals for the same scenarios, including land- and engineered CDR. Panels **g–i** show carbon managed by type, including fossil CCS, land CDR, and engineered CDR. Panels **j–l** show carbon managed by function, including what fossil CCS is used for, and whether CDR is used to offset emissions or to restore temperature by achieving net-negative emissions.

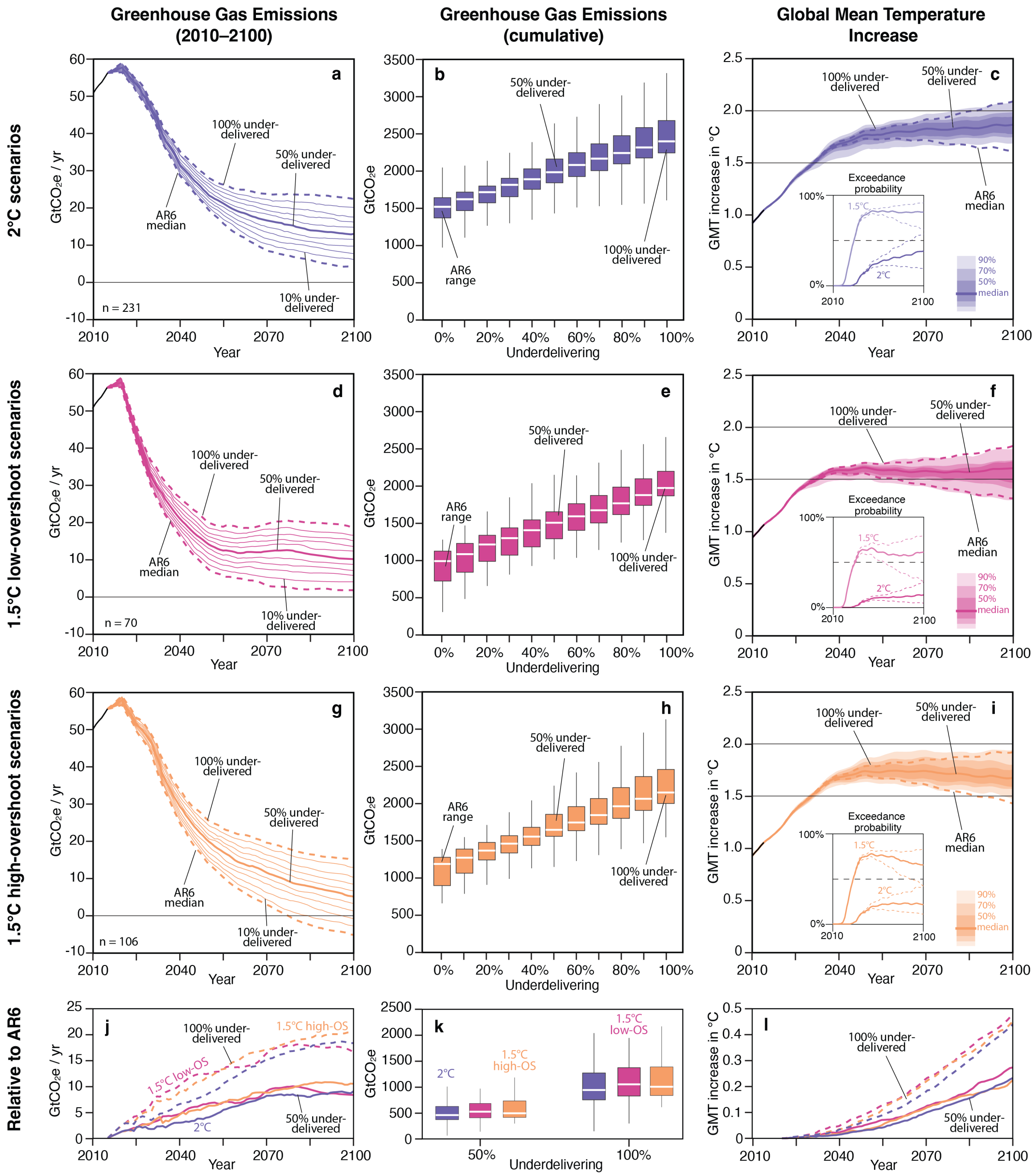

Figure 2 | Greenhouse gas emissions and global mean temperature increase compared to 1850–1900 for original and underdelivering carbon management scenarios. Panels **a–c** show results for 2°C scenarios, **d–f** for 1.5°C with low-overshoot, **g–i** for 1.5°C with high-overshoot, and **j–l** show the difference in the scenarios compared to the original (i.e. 0% underdelivering) runs. Insets show the probability of exceeding a temperature threshold in each year from 2010–2100.

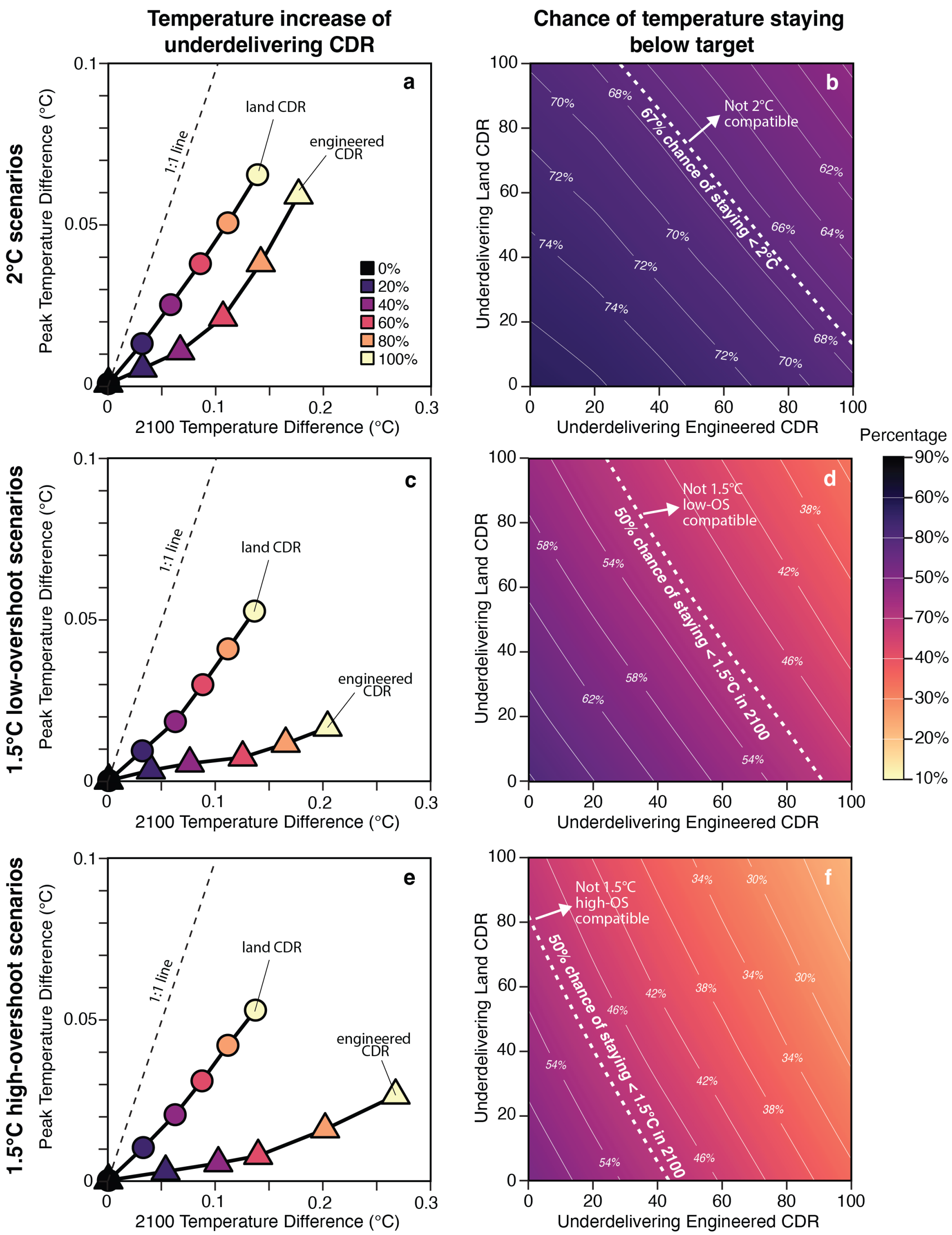

Figure 3 | Temperature increases of underdelivering CDR and chances of staying below temperature targets. Panels **a**, **c**, and **e** show the difference between underdelivering percentages compared to the original runs (i.e. how much temperature increases by underdelivering different percentages compared to delivering all carbon managed in the original scenario) for land CDR (circles) and engineered CDR (triangles) for peak-temperature and 2100 temperatures (values represent the median across scenarios). Panel **b** shows the probability of staying below the 2°C target through the 21st century for those scenarios with 600 ensembles each (representing the mean across scenarios). Panels **d** and **f** show the probability of staying below the 1.5°C threshold in 2100 for all scenarios with 600 ensembles each. Dashed lines in the last column represent the target definition threshold. Note only CDR is modified in the scenarios (and not fossil CCS).