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Diverse carbon dioxide removal approaches could reduce impacts on the energy–water–land system

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Carbon dioxide removal (CDR) is a critical tool in all plans to limit warming to below 1.5 °C, but only a few CDR pathways have been incorporated into integrated assessment models that international climate policy deliberations rely on. A more diverse set of CDR approaches could have important benefits and costs for energy–water–land systems. Here we use an integrated assessment model to assess a complete suite of CDR approaches including bioenergy with carbon capture and storage, afforestation, direct air capture with carbon storage, enhanced weathering, biochar and direct ocean capture with carbon storage. CDR provided by each approach spans three orders of magnitude, with deployment and associated impacts varying between regions. Total removals reach approximately 10 $GtCO_2$ yr^{-1} globally, largely to offset residual CO_2 and non-CO_2 emissions, which remain costly to avoid even under scenarios specifically designed to reduce them.

The IPCC's Sixth Assessment Report finds that to limit the global temperature increase to 1.5 °C or well below 2 °C, carbon dioxide removal (CDR) will be unavoidable: all feasible modelling pathways that limit end-of-century warming to below 1.5 °C, as well as virtually all below-2 °C pathways, require globally net-zero or net-negative end-of-century CO_2 emissions[1]. CDR will be required to offset difficult-to-abate GHG emissions and to reverse the continuing accumulation of anthropogenic atmospheric and oceanic GHG stocks[2–5]. Full implementation of updated Nationally Determined Contributions—some of which include CDR—may keep peak warming to just below 2 °C, but increased near-term mitigation and/or deeper levels of future net-negative CO_2 emissions are needed to bring the temperature down to the aspirational 1.5 °C goal after overshoot[6–10]. Many nations' Nationally Determined Contributions and supporting deep mitigation strategies reference new or continued carbon storage capacity in vegetation and soils but are often vague on the specific removal methods or quantitative details[11–16]. Corporate decarbonization strategies have also outlined investments in CDR, but like national strategies they often lack detail on the quantities achieved by specific removal pathways[17].

In 2020, the US Congress identified bioenergy with carbon capture and storage (BECCS), afforestation (AF), direct air capture with carbon storage (DACCS), enhanced weathering (EW), soil carbon enhancement and direct ocean capture with carbon storage (DOCCS) in its legislative definition of CDR[18]. These CDR approaches have all been extensively studied using techno-economic, biogeochemical and ecosystem models of individual technologies and/or regions that can inform the input assumptions of integrated assessment models (IAMs)[19–27]. Yet, despite interest by policymakers in additional CDR pathways, most IAM studies have included only land-intensive BECCS and AF, and more recently, energy-intensive DACCS, for CDR[28–32]. These studies have revealed critical side effects on land, water and energy systems from these three CDR pathways because they often project deployments on a scale of gigatonnes of CO_2 per year with concomitant impacts on associated infrastructure[33–36]. EW and soil carbon enhancement have

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been included in only two IAM studies[37,38]. Furthermore, no IAM study has assessed DOCCS. This has prevented a full understanding of how these additional CDR pathways might contribute alongside other forms of mitigation, as well as their collective implications for energy, water and land systems under deep emission-reduction efforts.

We used the Global Change Analysis Model (GCAM), a technology-rich IAM with detailed treatment of climate and global energy, land and water systems[39], to assess these six CDR approaches under ambitious mitigation consistent with limiting end-of-century warming to the 1.5 °C goal of the Paris Climate Accord[40]. GCAM has been used extensively to assess AF[33], BECCS[33,41–43] and DACCS[34,35,44,45]. It has also recently incorporated the soil carbon enhancement effects of biochar[46]. In this study, we model all of these CDR pathways and further add EW and DOCCS for comprehensive coverage of CDR technologies identified in recent US legislation[18]. Table 1 provides a brief description of the CDR pathways considered here. A detailed description of the implementation of these technologies in GCAM is provided in the Methods and Supplementary Tables 1–9.

We considered three main scenarios, in which (1) no climate policy is applied, (2) CO_2 emissions are constrained to limit warming to below 1.5 °C in 2100 and (3) the 1.5 °C emissions constraint from scenario 2 is applied, but with technological and behavioural changes that enable GHG emission reductions independent of carbon policy. Scenario 3 ('sectoral strengthening') follows the 1.5 °C scenario from Gambhir et al.[47], assuming demand reduction through lower population growth, higher energy and material efficiency, rapid electrification, reduction in non-CO_2 GHGs, limits on bioenergy use and geologic storage, and gradual AF[47,48]. This scenario represents efforts to reduce residual GHG emissions that must be offset or drawn down later with a now-expanded portfolio of CDR. Considering the rapidly closing window to limit warming to 1.5 °C without a large temperature overshoot, scenario results limiting end-of-century warming to below 2 °C are also reported in Supplementary Figs. 3–8.

Emissions and removals

Total GHG emissions continue to increase in scenario 1, reaching 80 $GtCO_2e\ yr^{-1}$ by 2100 and resulting in approximately 3.5 °C of warming relative to pre-industrial levels in 2100. CO_2 emissions reach net zero around 2045 in scenarios 2 and 3, but total CO_2-equivalent emissions from all GHGs remain net positive for much of the century. Non-CO_2 GHGs comprise 55% of residual emissions in scenario 2 and 60% in scenario 3. Total gross CDR is approximately 12 $GtCO_2\ yr^{-1}$ by 2050 in scenario 2 and 10 $GtCO_2\ yr^{-1}$ in scenario 3 (Fig. 1a). The assumed limit on bioenergy in scenario 3 reduces the share of BECCS and increases the share of DACCS and land-use negative emissions compared with scenario 2. Lower DACCS and BECCS deployment (especially in the second half of the century) in scenario 3 reduces the cumulative CDR amount by 16% through 2100 compared with scenario 2. Scenario 3 also reduces geologic carbon storage rates by approximately a factor of two relative to scenario 2 in 2050, with the greatest decrease in CCS from fossil electricity (Supplementary Fig. 4).

CDR from EW scales up quickly, reaching around 4 $GtCO_2\ yr^{-1}$ by 2050 and remaining relatively constant thereafter. China, the United States, India, Brazil and EU-15 countries all reach the scale of hundreds of megatonnes of CO_2 per year by 2050, with smaller deployments in Mexico, Indonesia and sub-Saharan Africa (Fig. 1e).

Global CO_2 removals from biochar reach 300 $MtCO_2\ yr^{-1}$ in scenario 2 in 2050; biochar deployment is lower at 200 $MtCO_2\ yr^{-1}$ in scenario 3 due to limits on biomass supply. India has the largest deployment of biochar, reaching the scale of hundreds of megatonnes of CO_2 per year in 2050, followed by western Africa, the United States and Southeast Asia, each with tens of megatonnes per year in CO_2 removals (Fig. 1f).

DOCCS is dominated by systems paired with desalination plants because the cost and energy requirements are shared between desalination and carbon removal; stand-alone DOCCS deployment is prohibitively costly. The demand for desalinated water therefore limits its removal potential of DOCCS to under 10 $MtCO_2\ yr^{-1}$ and limits its deployment to regions such as the Middle East with large projected demands for desalinated water (Fig. 1g).

Table 1 | Overview of CDR technologies modelled in this study

CDR technology	Description
BECCS	Biomass paired with geologic carbon storage for electricity, liquid fuel refining, hydrogen production and industrial energy use
AF	Storage of atmospheric carbon by restoring deforested lands or planting new forests where none existed previously
DACCS	Solvent- and sorbent-based processes using a combination of electricity and natural gas to separate and geologically store CO_2 from the atmosphere
EW	Crushed basalt application to global croplands
Biochar	Slow pyrolysis of second-generation biomass
DOCCS	Electrochemical stripping of CO_2 from seawater paired with geologic storage, in a stand-alone plant or co-located with water desalination facilities

Primary and final energy

In scenario 1, oil, gas and coal continue to dominate primary energy consumption despite substantial increases in renewables globally. Coal, oil and gas account for 50% of the primary energy demand in 2050 in scenario 2 and 35% in scenario 3. This reduction in fossil fuel use reduces residual CO_2 and non-CO_2 emissions that must be offset with CDR in scenario 3. In 2050, BECCS accounts for 14% of the primary energy consumed in scenario 2 and 7% of the primary energy in scenario 3. Natural gas and electricity for DACCS, EW and DOCCS together account for around 1% of the total final energy consumption in 2050, in both scenarios 2 and 3. In scenario 3, this proportion is higher because reduced demand for other energy services and limits on biomass energy supply lead to higher deployments of energy-consuming DACCS and EW, increasing their respective proportions of the final energy demand (Fig. 2a).

The energy system impacts of CDR deployment are unevenly distributed in scenarios 2 and 3 (Fig. 2b,c). In scenario 2, BECCS accounts for over 20% of the total primary energy consumption in Central America, Mexico and European countries. Electricity and natural gas for CDR account for over 2% of the final energy consumption in northeastern South America and Brazil, with smaller fractions elsewhere in South and Central America, the United States and Central Asia. Scenario 3 decreases BECCS as a proportion of primary energy but increases consumptive energy use for CDR as a fraction of final energy across all regions.

Land use

In scenario 2, bioenergy cropland grows to 2.8 Mkm^2, and forested area remains relatively constant at approximately 30 Mkm^2 by 2050. In scenario 3, bioenergy cropland expands to a lower level of 0.6 Mkm^2, with a 1 Mkm^2 expansion of forested land globally. Food production land in scenario 3 is reduced by 1 Mkm^2 relative to 2015 levels due to assumed lower population growth and improved land-use efficiency. The reduced bioenergy cropland area in scenario 3 is attributable to behavioural changes that reduce the role of biofuels in mitigation (Fig. 3a).

Biochar croplands are the most heavily concentrated in India and Southeast Asia, as these regions have already-large cropland areas as well as warm and humid climates that allow the highest increases in yields when biochar is applied[49]. Europe, the central North American

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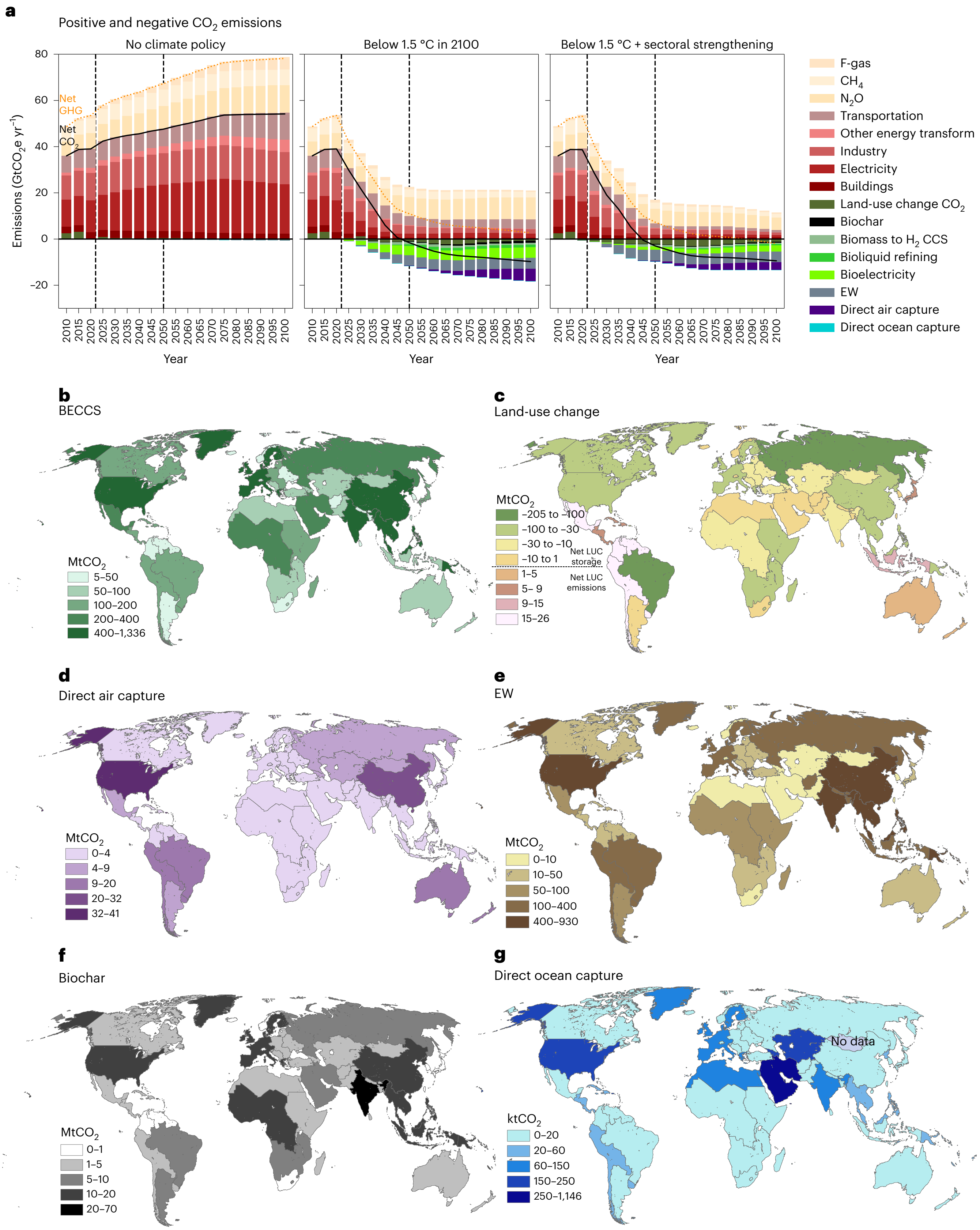

Fig. 1 | CO_2 emissions and removals. a, Positive and negative annual CO_2 emissions. F-gas refers to halocarbon gases with very high global warming potential. **b**–**g**, Negative CO_2 emissions by CDR method and GCAM region in 2050. LUC, land-use change. The items on the charts appear in the same vertical order as in the key. Greenland is plotted as part of the EU-15. Mongolia is considered as part of GCAM's Central Asia region but does not have meaningful data on DOCCS potential. Land-use change CO_2 emissions are reported as the net of AF minus any deforestation in each region. Some regions are projected to have net-positive land-use emissions in 2050. The fossil and industrial CO_2 emission constraints in both 1.5 °C scenarios 2 and 3 are the same, but reduced non-CO_2 emissions in scenario 3 lead to lower end-of-century warming.

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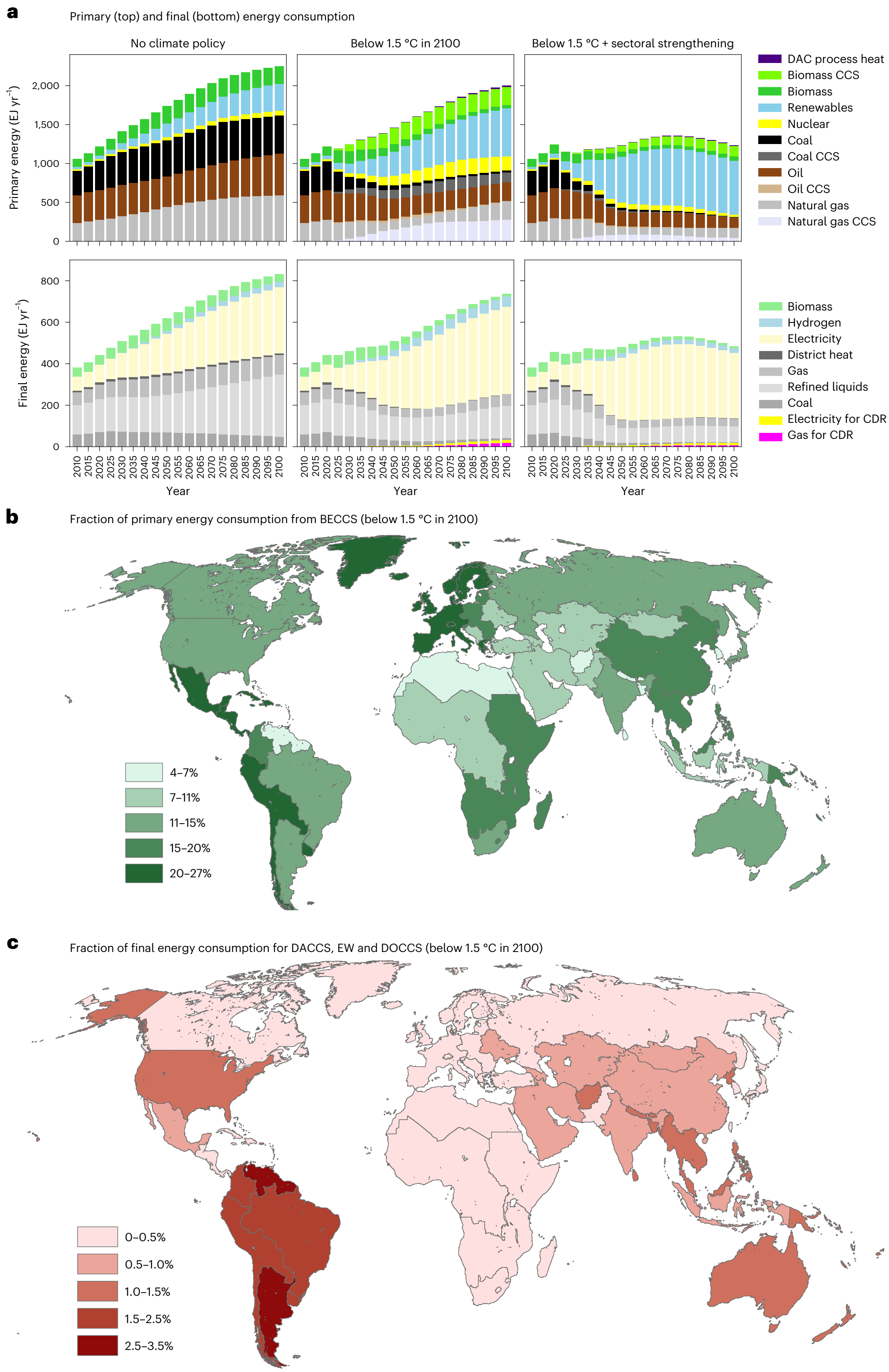

Fig. 2 | Primary and final energy impacts. a–c, Global primary (top) and final (bottom) energy consumption by end-use sector (**a**) and proportions of primary and final energy for CDR in 2050 (**b**,**c**). The items on the charts appear in the same vertical order as in the key. Following the IPCC reporting convention, we report non-combustion energy sources as direct equivalents, while fossil fuels and bioenergy are reported as their primary energy content[50]. Under this convention, renewable electricity may appear smaller—and bioenergy larger—in reported primary energy shares.

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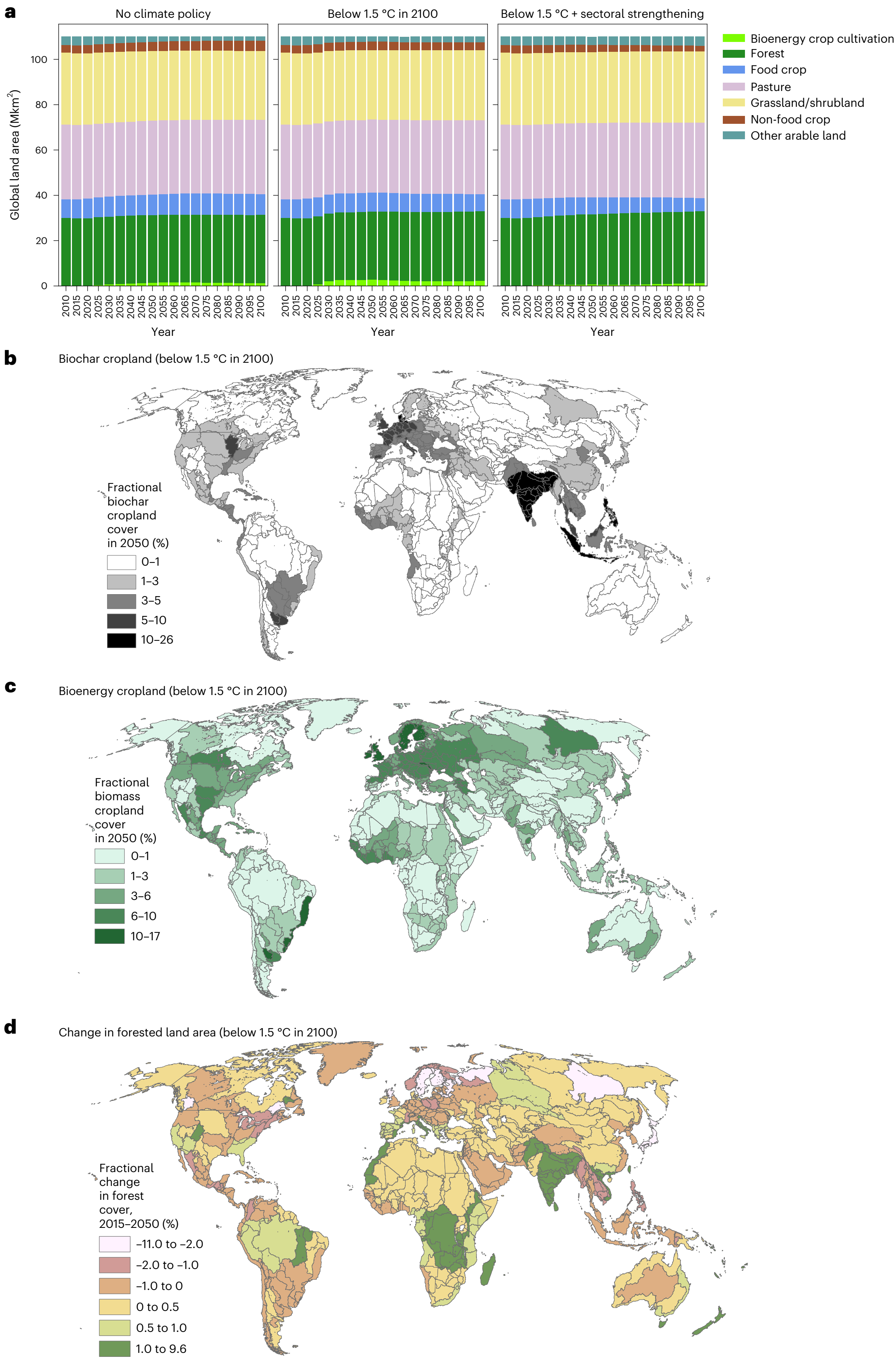

Fig. 3 | Land-use impacts. a–d, Global land use (**a**) and regional land-use impacts (**b**–**d**) of CDR in 2050 for scenario 2. The items on the charts appear in the same vertical order as in the key. Note that the proportions shown on the maps of biochar-utilizing cropland and bioenergy crops are not mutually exclusive. For example, bioenergy and other cropland may also deploy biochar.

plains, sub-Saharan Africa and the Southern Cone of South America also have large projected biochar-using croplands. Bioenergy cropland is projected to have the largest land-use impacts in northern and eastern Europe, the southern US Great Plains, and the South American east coast, all of which have at least 10% of their land area devoted to bioenergy crop cultivation in scenario 2. Forested land cover remains relatively constant in most regions but decreases between 1% and 10% in some temperate and boreal regions in North America, Europe, Russia and the Southeast Asian tropics, with similar increases in forested area in tropical Central Africa, India and interior Brazil (Fig. 3b–d).

Water

Irrigation for bioenergy crops dominates the water impacts of CDR deployment, accounting for 3% of global consumptive water use in scenario 2. This percentage is approximately 1% in scenario 3, primarily due to the assumed limits on bioenergy and associated irrigation. In both 1.5 °C scenarios, DOCCS paired with desalination provides up to 70% of the desalinated water demand, and total desalinated water production is increased relative to the no-climate-policy scenario. This occurs because the carbon removal subsidy makes this technology more financially attractive than desalination technologies not paired with DOCCS (Fig. 4a).

The regional water impacts of CDR rollout are heterogeneous: bioenergy crop irrigation, cooling water for BECCS and DACCS process water account for over 10% of consumptive water use in Russia, the United States, Mexico and Argentina (Fig. 4b). Desalinated water accounts for substantial fractions (2–9%) of total water withdrawals in the arid Sinai and Arabian peninsulas, northern Chile and the Mediterranean and Caspian Sea coasts (Fig. 4c).

Sensitivity analysis and comparison with AR6 results

In addition to scenarios 2 and 3, we assessed CO_2 removals and residual CO_2 emissions for five other 1.5 °C scenarios for which we limited the assumed cost improvements or availability of individual CDR pathways, or societal willingness to pay for carbon removal (Fig. 5a). We finally compared these scenarios with those meeting a 1.5 °C end-of-century temperature goal with high or limited overshoot in the AR6 scenario database[50] (Fig. 5b). EW has gigatonne-per-year-scale removals by 2050 in all scenarios, including if its cost and improvement are assumed to not improve over time. As in scenario 3, the limited biomass scenario increases DACCS deployment. Biochar removals reach hundreds of megatonnes per year by 2100 in all scenarios that include this approach. Our projected mid-century BECCS deployments are within 50% of the interquartile range of the AR6 scenarios and below the 2100 median. Our AF estimates are at or below the AR6 median for both 2050 and 2100. Our projected DACCS deployments are within 50% of the AR6 interquartile range. Biochar scales more slowly and reaches lower removal rates than the two scenarios that report it in the database. Caution should be used in comparing the results for both EW and biochar given the limited number of scenarios considering them. No scenario in the AR6 database includes DOCCS, for which we find removal rates under 10 $MtCO_2\ yr^{-1}$ across all scenarios.

Discussion

Our results suggest that under global ambition sufficient to limit end-of-century warming to below 1.5 °C, a portfolio of CDR approaches each contribute vastly different removals, ranging from megatonnes to gigatonnes of CO_2 per year. Ambitious cross-sectoral efforts to decrease residual GHG emissions reduce but do not eliminate the requirement for CDR. This is largely driven by non-CO_2 GHGs, with approximately 10 $GtCO_2\ yr^{-1}$ of CDR offsetting over 90% of their annual CO_2-equivalent emissions in 2050 across all scenarios. Non-CO_2 GHGs therefore represent a crucial—and, to date, underassessed—component of future negative emissions requirements, even if all residual CO_2 emissions could be zeroed out. Developing technologies[51] and improved IAM frameworks[52] for non-CO_2 GHG mitigation and removals could help further diversify solutions. Phasing down fossil fuels and hedging against over-reliance on any one CDR pathway (and geologic carbon storage more generally) can reduce risks if any one CDR pathway fails to materialize as expected. This is particularly true for DACCS: our sectoral strengthening scenario results in over double the DACCS deployment of the central scenario in 2050, but approximately 40% less in 2100. This result highlights the importance of early action on both reducing emissions and scaling up a balanced CDR portfolio that includes 'backstop technologies' such as DACCS.

EW may provide up to several Gt $CO_2\ yr^{-1}$ of removals at a lower cost than DACCS without relying on subsurface storage, in line with recent IAM results[53]. EW removals of around 4 $GtCO_2\ yr^{-1}$ projected in many of our scenarios should be considered upper limits on potential in light of uncertainty over the efficacy of this approach in real-world environmental conditions, including changes in soil pH due to climate change[54–56]. Deployment at this level would require transporting and crushing over 13 Gt yr^{-1} of rock, roughly double the mass of global coal consumption in 2019[57]. Electricity for rock crushing for this amount of EW could also reach up to 3% of present-day global electricity consumption. EW, DACCS and DOCCS account for up to several percent of final energy consumption in several regions—mostly in the Global South—by 2050. These results are of similar magnitude to recent estimates of additional (low-carbon) electricity capacity required for DACCS alone by the end of the century, with corresponding upstream impacts on, for example, metal depletion and ecotoxicity[58].

DOCCS is limited to a removal potential on the scale of single megatonnes per year. However, carbon removal subsidies could increase the financial viability of seawater desalination by pairing it with DOCCS and enable DOCCS to provide up to 70% of the global desalinated water demand. This could help arid regions build adaptive capacity as surface and groundwater resources become scarcer in a warming world[59,60]. Additional research is needed to understand and minimize local ecological and biogeochemical impacts (for example, seawater oxygen depletion) of DOCCS. Furthermore, although it represents a small fraction of water use globally, CDR-related water demand (mainly for bioenergy cropland irrigation) could account for over 10% of the water consumption in several regions by 2050. Because water is not effectively priced at its social marginal cost in many regions[61], careful attention to water impacts by national and regional policymakers is needed to avoid its use for CDR at socially inefficient rates.

Like DOCCS, biochar may help some regions that are the most vulnerable to climate change impacts (such as India and Southeast Asia) build resilience while removing CO_2 at the hundred-megatonne scale. To ensure the efficacy of biochar (or any CDR pathway that enhances natural processes, such as EW and AF), field trials in different geographies as well as further biogeochemical and land–ecosystem modelling are needed to compliment the results of this and other IAM studies. Additional research is needed to incorporate other forms of agricultural soil organic carbon sequestration, as well as peatland and coastal wetland restoration, into IAM frameworks, with special emphasis on understanding the often-sub-grid spatial heterogeneity of these approaches that adds greatly to the challenge of modelling them even in regionally resolved IAMs[62]. Efforts to leave existing carbon-rich ecosystems such as forests, grasslands and wetlands undisturbed (that is, avoided emissions) are similar from a GHG standpoint to leaving fossil fuels in the ground and may be more important than any carbon removal provided by enhancing or expanding these ecosystems[63–65]. Finally, just as for 'natural' CDR, detailed, regionally specific life cycle assessment and integrated policy planning are needed for more fully engineered CDR pathways such as DACCS, DOCCS and BECCS (for example, ref. [66]). Future work that bridges disciplinary boundaries between the holistic multi-sector capabilities of IAMs and the very fine spatial detail of Earth system and land-use models will be critical

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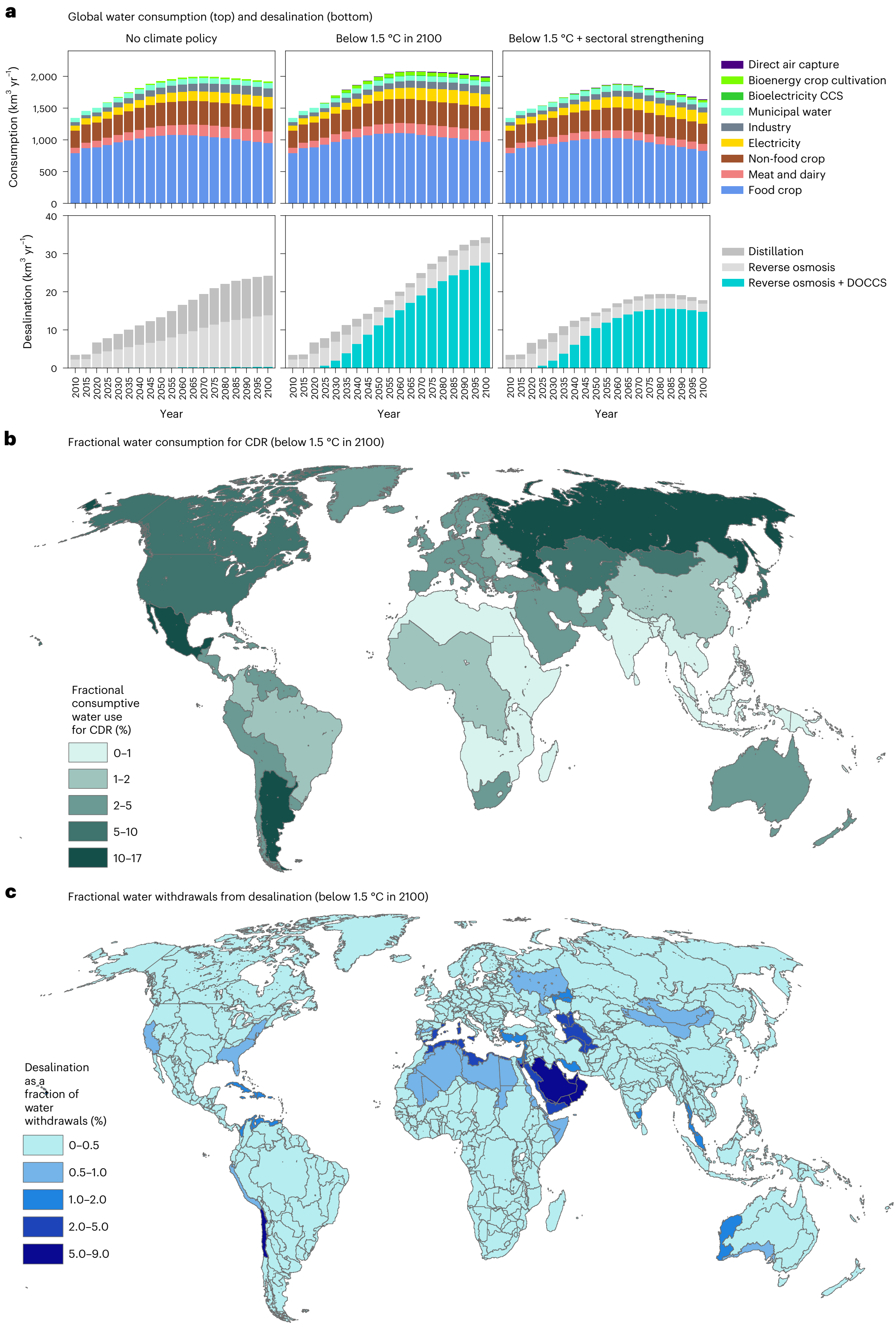

Fig. 4 | Water use impacts. a, Global water consumption by end-use sector (top) and desalinated water production by technology (bottom). The items are plotted on the charts in the same vertical order as they appear in the chart keys. **b**, Water consumption for bioenergy crop irrigation, BECCS electricity generation and DACCS process water by GCAM region, as a proportion of the total water consumption. **c**, Desalinated seawater and groundwater as a fraction of total water withdrawals by GCAM water basin.

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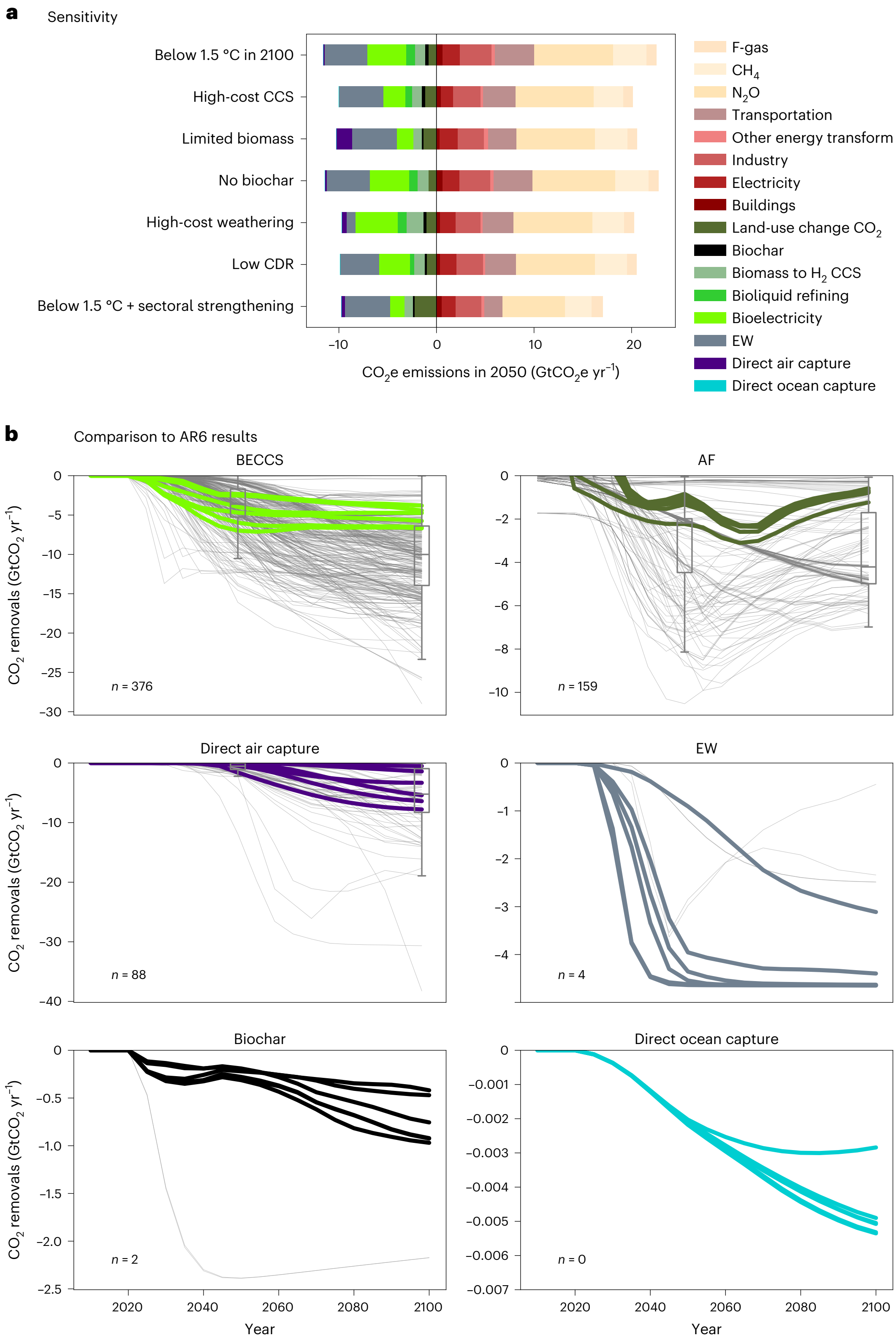

Fig. 5 | Sensitivity analysis and comparison with AR6 removals. a, Sensitivity analysis. The chart items appear in the same order as in the key, with CO_2 removals plotted on the far left of the chart, corresponding to the bottom of the key, and non-CO_2 GHGs plotted on the far right of the chart, corresponding to the top of the key. **b**, Comparison with AR6 removals. Note the differences in the *y*-axis scaling. The box-and-whisker plots provide summary statistics for removals from the AR6 scenarios (indicated by thin grey lines), but not our scenarios (indicated by bold coloured lines), in 2050 and 2100. The boxes indicate the first and third quartiles of the AR6 scenarios. The median is used here as the measure of central tendency and is indicated by the lines within the boxes. The whiskers extend the boxes by 150% of the interquartile range. Outliers are not reported separately using the box-and-whisker diagrams as they are indicated by the grey lines for each scenario. The number of AR6 scenarios reporting non-zero removals at any point in the century for each pathway is reported as *n* in the lower left corner of its respective subplot. We do not include box-and-whisker plots for EW or biochar due to the low number of scenarios reporting them in the AR6 database.

for planning where both 'natural' and engineered CDR are placed. Together, these efforts can help ensure that resources dedicated to CDR are leading to additional, long-term CO_2 drawdowns instead of being wasted or, worse, increasing GHG emissions.

CDR can be beneficial if it helps avoid higher costs of mitigation, adaptation and residual climate damages, and it will be essential to meeting the well-below 2 °C and below 1.5 °C goals, alongside rapid scale-up of renewables and other low-carbon technologies[67,68]. But CDR at anywhere approaching the scales projected here would require strong policy incentives, extensive monitoring and verification, and public investment in and acceptance of the associated infrastructure and supply chains[53]. This can be conceptualized similarly to landfills and wastewater treatment facilities, which would probably not be financially viable without similar societal commitments to avoid the effects of their absence (that is, raw sewage in rivers and garbage in streets). Unlike solid waste or wastewater treatment, which generally use standardized technologies, CDR could be delivered via a diverse portfolio based on regional benefits and costs, and each element of this portfolio will require innovations in mechanisms for funding and governing its use. IAMs can help us understand and prepare for these global and regional costs and benefits, as well as help direct research and development funding towards CDR technologies with high potential for future breakthroughs. But to date, IAM scenarios have relied disproportionately on BECCS and AF as proxies for all CDR. This has constituted an omission bias in a field that is used heavily by policymakers to understand the profound sociotechnical transitions necessary to meet international climate goals. Our work reveals the importance of representing a wide variety of CDR pathways on a level playing field with one another and with emissions abatement technologies to gain a detailed understanding of the costs, benefits, risks and ultimate removal potential of each. This understanding is essential for crafting an efficient and effective portfolio of climate policies.

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41558-023-01604-9.

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Methods

We used GCAM version 5.4, which we updated with the capability to model two additional pathways for CDR: EW and DOCCS. We also incorporated recent model development to reflect the soil carbon sequestration potential of biochar. The model assumptions related to biochar follow Bergero et al.[46] and are detailed briefly below. Parametric derivations and structural detail for biochar relevant to our modelling exercises are provided in Supplementary Table 9. All scenarios were run on the Pacific Northwest National Laboratory's high-performance computing cluster.

For DACCS, we considered three distinct archetypes: a high-temperature aqueous solvent-based process using natural gas, the same solvent-based process with fully electric high-temperature (>900 °C) heat and a low-temperature process wherein the heat for sorbent regeneration is provided by an electric heat pump. We assume moderate improvements in the cost and performance of each of these three technologies over time, following our previous work on DACCS[35]. GCAM includes BECCS technologies in refining, electricity generation, hydrogen production and industrial sectors. The land, water and fertilizer use of the bioenergy supply as well as AF and the resulting interactions with food crop production and natural lands are resolved endogenously among GCAM's 384 land-use regions, which are based on the intersection of 32 geopolitical regions and 235 water basins; the characteristics of each are parametrized from upscaled spatially explicit raster and vector data[69–73]. GCAM results for land cover and water demand can be subsequently downscaled to grid-scale spatial resolution and account for climate-warming-induced changes in water availability[74–79]. Similar to DACCS, our treatment of BECCS (including biomass collection, distribution and pelletization costs) and AF follows previously published GCAM studies of these CDR pathways[33,36,42,43,80–83].

Along with the addition of the new CDR modelling capabilities outlined above and described in detail below, we disaggregated GCAM's modelling of industrial energy use to enable detailed representation of individual industrial sectors' decarbonization pathways including the use of BECCS[84]. We also modified GCAM's hydrogen sector to feature updated parametric assumptions from the National Renewable Energy Laboratory's Hydrogen Analysis Production models and to reflect distribution infrastructure and end-use pathways more realistically[85]. Assumptions for all other technologies and socio-economic parameters not mentioned here follow those in the GCAM core release, which is accessible on GitHub and documented in an accompanying wiki[86,87]. We first briefly introduce the emerging CDR pathways and our modelling implementation of them in GCAM, and we then give a more detailed description of our scenario design.

EW

EW accelerates naturally occurring processes that modulate Earth's carbon cycle on longer-than-millennial timescales[88–90]. Calcium- or magnesium-bearing minerals, or alkaline industrial waste material, are crushed to increase surface area, resulting in a much higher reaction rate of atmospheric CO_2 to bicarbonate ions[91–93]. EW has been demonstrated in the laboratory, small-scale field trials and idealized land–ecosystem modelling experiments[19,20,94,95]. Compared with DACCS, EW may have a lower cost of removal per tCO_2 even when taking into account the energy requirement for crushing and transporting the rocks[96–99]. EW incurs fewer concerns over land and water competition than BECCS or AF because it can occur on already-perturbed lands (for example, cropland, managed forests and grasslands) and the addition of alkalinity may increase crop yields and reduce irrigation requirements in some climates and soil types[100,101]. A portion of the resulting bicarbonate ions would precipitate as solids into soils, with the remainder running into the oceans, which can help ameliorate ocean acidification[102]. However, the efficacy of EW may be substantially reduced if the dissolved alkalinity passes through regions of even temporarily lower pH along the land–aquatic–ocean continuum[54]. Large bulk material requirements from EW may result in local environmental degradation associated with extracting, transporting, crushing and spreading the materials[103].

We considered EW using crushed basalt spread on croplands and used country-level data on annual potential from Beerling et al.[93] to develop aggregated supply curves for the corresponding GCAM regions (Supplementary Fig. 9). This pathway appears to have lower risks (including trace metal contamination of soils) than other forms of EW[96]. For those regions not included in Beerling et al., we linearly scaled the fully aggregated supply curve derived from that study, by the regionally explicit potentials in Strefler et al.[104] (Supplementary Tables 1–2 and Supplementary Fig. 10). Electricity costs and grid carbon intensity are calculated endogenously in each of GCAM's 32 regions, so the fixed electricity cost assumption from Strefler et al.[104] was subtracted from the derived supply curves (Supplementary Table 3). We assumed an electricity input consistent with their upper-bound estimate for rock comminution to 20 µm of 2 GJ tCO_2^{-1} in 2020, declining to their best estimate of 0.66 GJ tCO_2^{-1} by 2050 (Supplementary Table 4). We also subtracted the cost of rock transport and allowed the associated freight transportation mode, fuel mix and associated cost to be determined endogenously by GCAM, leaving only supply curves for levelized non-fuel cost in each GCAM region. Assuming an average transport distance of 300 km and 0.3 tCO_2 per rock from Strefler et al.[104], this leads to an assumed freight transport input of 1,000 tonne-km per tCO_2. This approach results in regionally explicit cost curves for surface-based inorganic carbon storage via basalt that are distinct from GCAM's existing markets for geologic carbon disposal from fossil CCS, DACCS and BECCS[105]. For a more conservative near-term cost estimate, in 2020, we translated each region's EW supply curve upward by a non-energy cost equal to the difference in "upper bound" and "best estimate" investment and operations-and-maintenance costs from Strefler et al.[104] ($138 per tCO_2). Except in the "high-cost weathering" scenario, this cost adder declines to zero by 2050 such that only the regionally explicit supply curves remain.

DOCCS

DOCCS takes advantage of the higher effective CO_2 concentration in ocean water, which exceeds that of the atmosphere by an approximate factor of 120 due to dissolved inorganic carbon[106–108]. Electrochemical processes are used to shift the pH of the water and result in the off-gassing of CO_2; when the aqueous CO_2 is removed and stored in geologic reservoirs, the discharged seawater is able to take up more gaseous CO_2 from the atmosphere to restore equilibrium[21,109]. Existing techno-economic studies indicate that the cost of stand-alone DOCCS systems is far higher per tCO_2 than DACCS due to the construction cost and energy penalty associated with the seawater intake and outfall, which may be many times that of the electrodialysis unit[110]. The co-location of DOCCS with desalination plants could substantially reduce this cost[21,111]. The co-production of renewable hydrogen and/or synthetic fuels may also reduce the costs of DOCCS, but we do not consider this technology here due to the lack of data availability, especially of cost data, in the existing literature[109].

We considered two technologies for direct ocean capture, both parameterized from the work of Digdaya et al.[21]. The first is a stand-alone technology that within GCAM is structurally analogous to DACCS, but with uniquely defined cost and performance parameters. The second is far less electricity intensive and captures carbon as a co-product of seawater desalination. This second technology competes with other desalination technologies in GCAM, beginning to be deployed when the carbon capture subsidy (equal to the carbon emissions price) exceeds that of the additional non-energy and electricity costs for CO_2 capture. The cost and performance assumptions for these technologies are provided in Supplementary Table 8, and the detailed derivations are reported in Supplementary Tables 5–7. For the direct ocean capture technology co-located with desalination, the input assumptions in Supplementary Table 8 were converted to a per-m^3-freshwater basis assuming a 13.1 m^3 $kgCO_2^{-1}$ capture rate from seawater and 2.5 m^3 seawater processed per m^3 freshwater, and then added to the cost and electricity inputs of the existing GCAM reverse osmosis desalination technology[112].

Biochar

The use of biochar on croplands can increase recalcitrant carbon stocks in soils[62,63]. The process for biochar includes biomass feedstocks that are pyrolysed (that is, heated under anoxic conditions), making the remaining photosynthetically fixed carbon resistant to reoxidation and enabling carbon storage on centennial timescales[113]. This makes biochar unique relative to other soil carbon sequestration pathways that have lower potential scales and/or higher uncertainty regarding saturation and permanence[114]. Like soil amendments for EW, biochar application can occur on existing croplands and may increase yields and reduce water and fertilizer requirements, depending on the climate zone and soil type where it is applied[49,115–117]. Biochar requires energy input but can also produce useful energy such as biogas as a co-product, at the expense of reducing the net removal efficiency[118–121]. Biochar may also be produced as a co-product of biomass electricity generation[122].

We modelled biochar as being produced via slow pyrolysis of lignocellulosic biomass feedstocks and producing syngas as a co-product. The competition between direct use of the biomass feedstock for energy (including BECCS) and biochar is endogenously modelled by GCAM. Biochar can then be demanded as an input option to improve crop yields, similar to GCAM's existing treatment of fertilizer and irrigation water[39,79]. The yield improvements resulting from biochar deployment are specified on the basis of the use or lack thereof of irrigation, as well as the climate (that is, temperate versus tropical) of each water basin (Supplementary Table 9). Croplands utilizing biochar are assumed to apply it at a rate of 20 t biochar per hectare. Biochar application is assumed to occur only once per unit of land, with 70% of the carbon content in the biochar remaining in the soil for centennial timescales.

Scenario design and assumptions

Supplementary Table 10 reports the key assumptions for our scenarios, wherein we varied the cost and performance or availability of CDR pathways (that is, scenarios 6 and 7), their components (that is, scenarios 4 and 5) or CDR overall (scenario 8). For the scenarios reported in the main manuscript, we imposed a stylized constraint on global CO_2 emissions that limited warming to below 1.5 °C in 2100. We report the results for scenarios meeting a below 2 °C but not a 1.5 °C end-of-century warming limit in Supplementary Figs. 3–8. The emissions constraints are first assumed to begin in 2025—the first of GCAM's five-year timesteps after the present day. Non-CO_2 GHG emissions and their radiative forcing effects are tracked by GCAM but not explicitly constrained. Land-use CO_2 emissions are priced at an exogenously defined, increasing proportion of the fossil carbon emissions price but are not included in the constraint. That is, carbon storage via changes in land-use patterns is incentivized by the carbon pricing mechanisms but is in addition to emission mitigation and negative-emission activities to meet the constraint placed on energy system CO_2 emissions. This scenario design choice was made to represent gradual institutional improvements required to implement and enforce land-use emissions policy globally, and to account for uncertainties in quantifying fluxes and reversal risks of gigatonne-scale biospheric carbon storage[123,124].

To understand how greater ease of mitigation and an emphasis on sustainable development might influence the need for and share of different CDR pathways in pursuit of well below 2 °C, we also modelled a 'sectoral strengthening' scenario (3) that incorporates and, in some cases, goes beyond many of the 'sustainable development' (SSP1) assumptions detailed in the Shared Socio-economic Pathways scenario exercises[125]. These include assumptions regarding higher preference for renewables; the gradual phase-out of new internal combustion vehicles for road transport; more rapid improvements in material and energy efficiencies for buildings and industries; reduced demand for industrial and consumer goods; limitations on future biomass, geologic carbon storage and nuclear power generation; and dietary changes leading to reduced meat consumption, particularly beef. We also adjusted the emissions coefficients for HFC gases to meet phase-down targets set under the Kigali Amendment to the Montreal Protocol[47]. In light of concerns over the feasibility of scaling up CCS deployment rates to gigatonnes per year, reducing reliance on geologic carbon storage more broadly (that is, for both CDR and fossil emissions abatement) was a key element of this scenario's design[126]. Supplementary Table 11 provides further details on the assumptions for scenario 3. Supplementary Fig. 2 reports the resulting temperature trajectories for the scenarios overlaid on historical temperature anomaly data through the year 2019[127,128]. The GCAM model version, as well as all input files, derivations, output data and processing code used in figure generation are available in a public zenodo archive[128].

Data availability

All model output data for this study are available in a public repository accessible at https://doi.org/10.5281/zenodo.7492895.

Code availability

GCAM is an open-source community model available at https://github.com/JGCRI/gcam-core/releases. The particular version of GCAM, additional input files and data-processing scripts associated with this study are available at https://doi.org/10.5281/zenodo.7492895.

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Competing interests
The authors declare no competing interests.

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