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Food–energy–water implications of negative emissions technologies in a +1.5 °C future

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Scenarios for meeting ambitious climate targets rely on large-scale deployment of negative emissions technologies (NETs), including direct air capture (DAC). However, the tradeoffs between food, water and energy created by deploying different NETs are unclear. Here we show that DAC could provide up to 3 $GtCO_2$ yr^{-1} of negative emissions by 2035—equivalent to 7% of 2019 global CO_2 emissions—based on current-day assumptions regarding price and performance. DAC in particular could exacerbate demand for energy and water, yet it would avoid the most severe market-mediated effects of land-use competition from bioenergy with carbon capture and storage and afforestation. This could result in staple food crop prices rising by approximately fivefold relative to 2010 levels in many parts of the Global South, raising equity concerns about the deployment of NETs. These results highlight that delays in aggressive global mitigation action greatly increase the requirement for DAC to meet climate targets, and correspondingly, energy and water impacts.

During the 2015 UNFCCC Conference of the Parties in Paris, world leaders agreed to limit global temperature increase relative to pre-industrial levels to well below 2 °C and pursue efforts to meet a 1.5 °C target by 2100 (refs. [1,2]). These targets require rapid declines in greenhouse gas emissions, reaching net zero by mid-century[3,4]. Recent progress on mitigation has been highly inconsistent with this goal[5,6]. With emissions still rising[7], integrated assessment modelling (IAM) scenarios of the global economy and climate system have increasingly relied on the presumed ability to deploy net-negative emissions activities to meet these ambitious climate targets[8,9]. There are a number of ways by which to remove already emitted CO_2 from the atmosphere[10–14]. Yet the vast majority of IAM scenarios include just two land-based negative emissions technologies (NETs): bioenergy with carbon capture and storage (BECCS) and afforestation (Extended Data Fig. 1)[15,16]. The degree to which these NETs would compete for productive agricultural and natural land, as well as their impact on water resources if deployed at climatically relevant (that is, $GtCO_2$ yr^{-1}) scales has raised concerns about the viability of these approaches[17–21].

In light of the foreseeable tradeoffs inherent to land-based negative emissions approaches, recent work has focused on developing direct air capture (DAC) technology. DAC is an engineered separation process that uses aqueous or amine sorbents to remove CO_2 from ambient air, compress it and inject it into geologic reservoirs. The physical footprint of these units would be much smaller than BECCS or afforestation, and it would not require any particular land type, only proximity to a geologic reservoir for storage[14,22,23]. However, CO_2 exists in low concentrations in ambient air, so DAC is likely to be energy intensive to deploy. This is intuitively the case for DAC processes that require combustion heat, for which fossil fuels are currently the most economical source. However, processes that are capable of using renewable energy or waste heat would still entail large-scale construction of infrastructure (for example, solar photovoltaic) for the purpose of disposing of CO_2 emitted previously. Due to these very high assumed costs, DAC has not been included in many integrated modelling scenarios to date[10,24]. However, multiple companies now have commercial-scale prototypes, claiming much lower costs than previously estimated[25–29], and several recent IAM studies have incorporated DAC into their mitigation and negative emissions portfolios[23,30–32]. In these deep decarbonization scenarios, the availability of DAC can reduce mitigation costs, avoid immediate stranding of fossil fuel assets and benefit energy-exporting countries by preserving the value of their fossil fuel reserves under stringent climate policies[32]. Meeting a 1.5 °C temperature target may now only be possible if large-scale DAC is available[30]. Relying on the future availability of DAC and then failing to achieve the rapid scale-ups to global-scale deployment could risk overshooting this target by up to 0.8 °C (ref. [23]).

Increased near-term mitigation effort is required to avoid the steepest tradeoffs associated with future rapid decarbonization, and to avoid 'lock-in' to large-scale deployment of NETs to meet the Paris targets[31,33]. But the emergence of DAC as a possible climate mitigation strategy makes it important to gain understanding of its side effects if deployed at $GtCO_2$ yr^{-1} scales, weighed against its potential to reduce some of the undesirable impacts of BECCS and afforestation (for example, land and water demand) and to offset emissions from expensive-to-mitigate sectors (for example, liquid fuels for transportation)[34]. The unprecedented financial transfers[35,36] (for example, emissions offsets and direct public subsidies) that would be required to reach net-negative emissions globally make it even more critical to understand these potential side effects in advance, and minimize the extent to which the deployment of any NET generates unintended consequences of its own[16]. Previous work on the potential benefits and side effects of DAC has emphasized its ability to reduce energy system transition burdens (for example, CO_2 prices), while itself requiring large amounts of energy[23,30,32]. It has been shown that DAC would substantially reduce water use for negative emissions compared with total evapotranspiration from bioenergy crop and forest cultivation, plus additional water demand for bioelectricity generation[20,23]. However, it is also

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important to understand how different NETs could affect water quality (for example, through thermal and chemical pollution) associated with withdrawals from surface and groundwater, as well as consumption (that is, evaporative losses) that contribute to water scarcity[37,38]. Proper contextualization of each of these relative to other current and projected anthropogenic perturbations to water resources is also imperative to best inform policymakers and other stakeholders considering multiple environmental objectives (for example, water conservation and climate mitigation). The land-use impacts of DAC are considered negligible compared with BECCS and afforestation, but detailed quantitative assessment of the implications for global agriculture systems (for example, food prices) is largely missing from the IAM literature on DAC and other NETs. In particular, spatially disaggregated results for where different NETs might be deployed under different policies and assessments of the associated impacts on food, water and energy systems are needed to better inform equity considerations of international policymaking.

Here we use the Global Change Assessment Model (GCAM), a technology-rich IAM with detailed treatment of the energy, water and land sectors[39], to evaluate the impacts and tradeoffs of a portfolio of three distinct types of NET (afforestation, BECCS and DAC) in meeting two representative emissions pathways from the IPCC Special Report on Global Warming of 1.5 °C (ref. [3]). We investigated whether DAC could help ameliorate costly food–water–energy tradeoffs when deployed alongside BECCS, afforestation and other technology options for avoiding CO_2 emissions altogether (for example, renewables and point-source CCS). In light of recent, more optimistic estimates for the cost of DAC technology, we investigate when this technology could begin to play a role in the mitigation portfolio under aggressive near-term decarbonization policy that seeks to limit the overdraft of a small and rapidly dwindling 1.5 °C global emissions budget. Additionally, the side effects associated with increased negative emissions requirements resulting from delayed mitigation ambition for meeting the same end-of-century temperature goal are quantified. Finally, we provide greater resolution as to where DAC and other negative emissions activities and associated side effects could take place spatially, at the scale of geopolitical regions. Throughout our analysis, we compare land, water and energy use for each of these NETs with other current-day and projected anthropogenic perturbations to these resources.

Effects of BECCS and afforestation

DAC deployment may never reach $GtCO_2\ yr^{-1}$ scales because it is too expensive or otherwise infeasible. The implications for energy, water and food systems associated with meeting the low-overshoot emissions trajectory without the use of DAC are shown in Fig. 1. The higher overshoot trajectory was infeasible without the availability of DAC due to constraints on agricultural and forested land expansion for agricultural production and climate mitigation. In the low-overshoot trajectory, BECCS is used to produce 226 EJ yr^{-1} in 2100, over 38% of current-day primary energy demand[40]. The use of modern biomass without CCS for heat, electricity generation and liquid fuels production, as well as 'traditional biomass' for fuel, is projected to decline from a combined 83 EJ yr^{-1} at initiation of our imposed climate policy in 2025 to 16 EJ yr^{-1} in 2100. The role of fossil fuels is substantially reduced, and the use of unabated coal rapidly declines to near zero following initiation of the climate policy. Land for dedicated bioenergy crop production expands rapidly to over 5 Mkm^2, a land area equivalent to over 50% of the land area of the United States and over 25% of present-day global cropland area[41]. Net deforestation is halted by 2025, but the largest increases in forested land area occur later in the century as institutions for pricing and enforcing pricing of land-use change carbon are assumed to be phased in. The increase in land devoted to bioenergy crops and afforestation comes at the expense of grasslands, pasture and production of other crops. These results are broadly consistent with previous IAM studies incorporating BECCS and afforestation to meet aggressive climate targets[42]. Evaporative losses from biomass irrigation and thermal bioelectricity generation are large, reaching a peak of 187 $km^3\ yr^{-1}$ in 2050. This is equivalent to nearly 15% of irrigation water consumption in 2010 (refs. [37,43]). Fertilizer use for bioenergy crop cultivation peaks in 2045 at nearly 30% of current-day fertilizer demand. Such drastic increases in fertilizer demand for the purposes of climate change mitigation would have large environmental side effects, such as water quality degradation[44,45], and also climate effects that run counter to CO_2 removal as excess soil nitrogen is converted to N_2O (ref. [21]).

We report results for the lower (that is, more optimistic) estimates of energy and cost inputs for DAC technology to best illustrate the potential impacts of this technology if deployed at large scale (Fig. 2). Because DAC acts as a backstop to the exponential increase in CO_2 price, the mere availability of DAC in the mitigation portfolio has a much stronger effect on the results than variation within the range of cost and energy inputs assessed here. In the low-overshoot case, DAC is deployed at gigaton scales as early as 2035, in contrast to other IAM results, which typically delay such large DAC deployments past mid-century. This primarily follows the imposition of the emissions constraint, wherein we sought to model a scenario in which aggressive mitigation action is taken to limit peak temperature rise, rather than allowing the largest negative emissions requirements to be pushed far into the future to meet an end-of-century target by allowing a large overshoot[46]. Spatially, DAC is projected to be deployed primarily in regions such as the United States, South America, China and Australia, which have abundant geologic storage capacity, large natural gas reserves and the potential for inexpensive, relatively low-carbon electricity.

In all cases, much of the negative emissions requirement is driven by sectors that are recalcitrant to decarbonization (for example, transportation). DAC displaces the use of BECCS and afforestation for negative emissions, but it also reduces the need for emissions abatement in the model. Namely, gross-positive emissions are higher in scenarios in which DAC is available, because those emissions can be offset using DAC while still meeting constraints on net emissions. The negative emissions pathway of using bioliquids to manufacture durable products and thereby storing carbon (that is, bioindustrial feedstocks) is not actively utilized when low-cost DAC is available, as the biomass and land area devoted to its growth can be more profitably used for other purposes such as transportation fuels or food crops. In the high-overshoot case, even relatively modest delays in near-term mitigation greatly increase the reliance on future negative emissions, which must be met by DAC due to constraints on land available for BECCS and afforestation. This highlights the importance of aggressive mitigation in the near term, as DAC, and indeed all NETs, have yet to be deployed at scale, and high overshoot may be irreversible if these technologies prove infeasible or incapable of keeping up with runaway climate change[16].

Crop pricing under NET deployment

We consider three major grain staple crops: corn (maize), wheat and rice, and quantity-weight the results by mass to better reflect regional differences in food supply. Food prices peak at 15% above 2010 levels in the no climate policy case due to population growth and a growing global middle class. This is likely an underestimate of food price increases that would occur in the absence of climate mitigation action, because GCAM does not currently consider climate damage such as reduced yields or crop failures due to extreme drought or flooding that are expected in a warmer world[47–49]. Incorporating such bidirectional feedbacks between the Earth and human socioeconomic systems into GCAM is an area of cutting-edge, ongoing research[50]. To meet a low-overshoot trajectory without the large-scale availability of DAC, end-of-century food prices are projected to increase by sevenfold relative to 2010

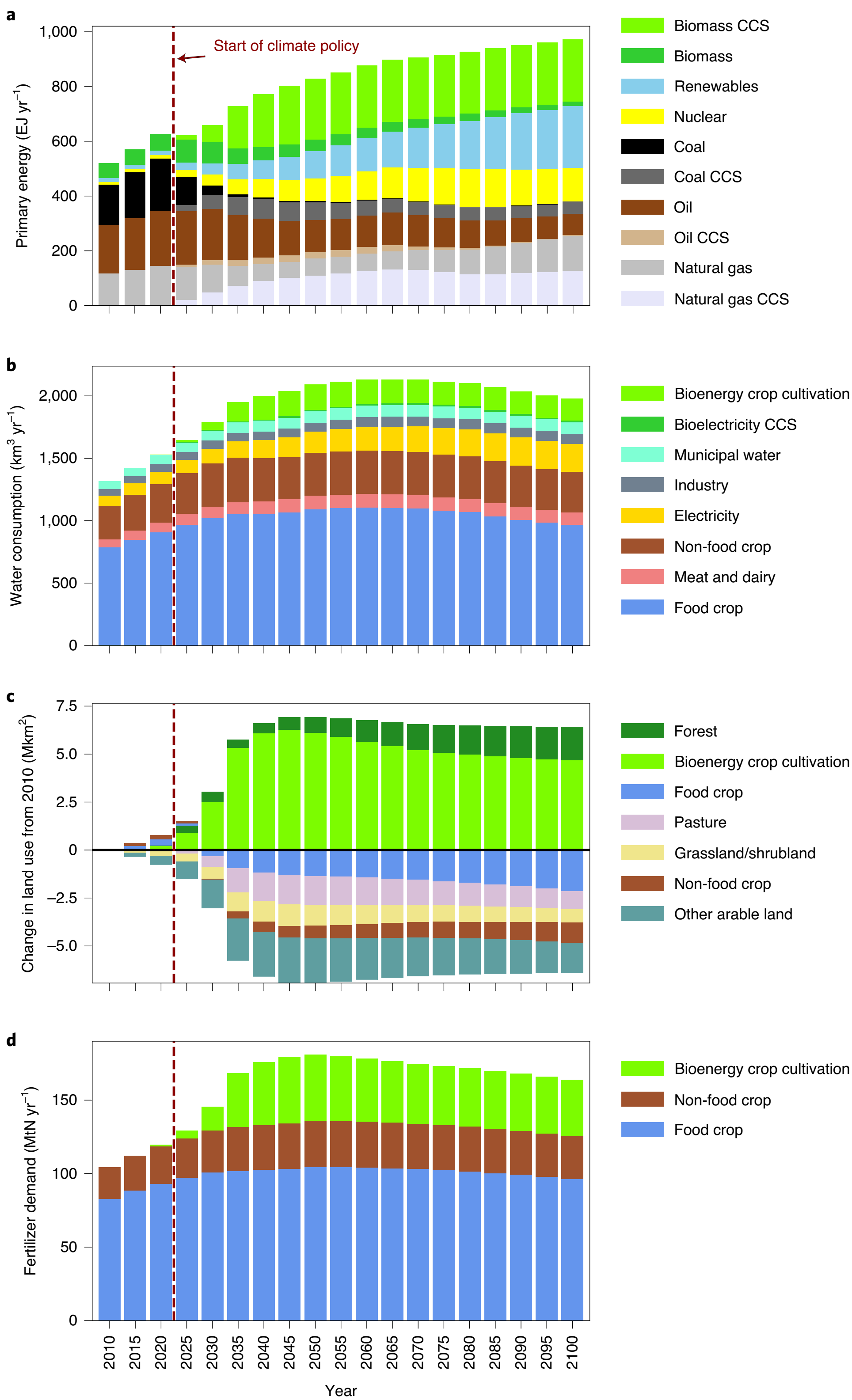

Fig. 1 | Side effects of limiting warming to below 1.5 °C without DAC available. a–d, Projected global energy (**a**), water (**b**), land (**c**) and fertilizer (**d**) demands for meeting a 1.5 °C end-of-century temperature target with low overshoot, assuming only BECCS and afforestation/reforestation will be available for negative emissions. The high-overshoot case could not be solved without the availability of DAC.

levels. Food price impacts are regionally heterogeneous and are projected to be most heavily concentrated in sub-Saharan Africa. The availability of low-cost DAC attenuates the most severe effects of land-intensive negative emissions on food markets, but food prices still increase by approximately threefold globally relative to 2010 levels and regional disparities remain, owing to still-large land

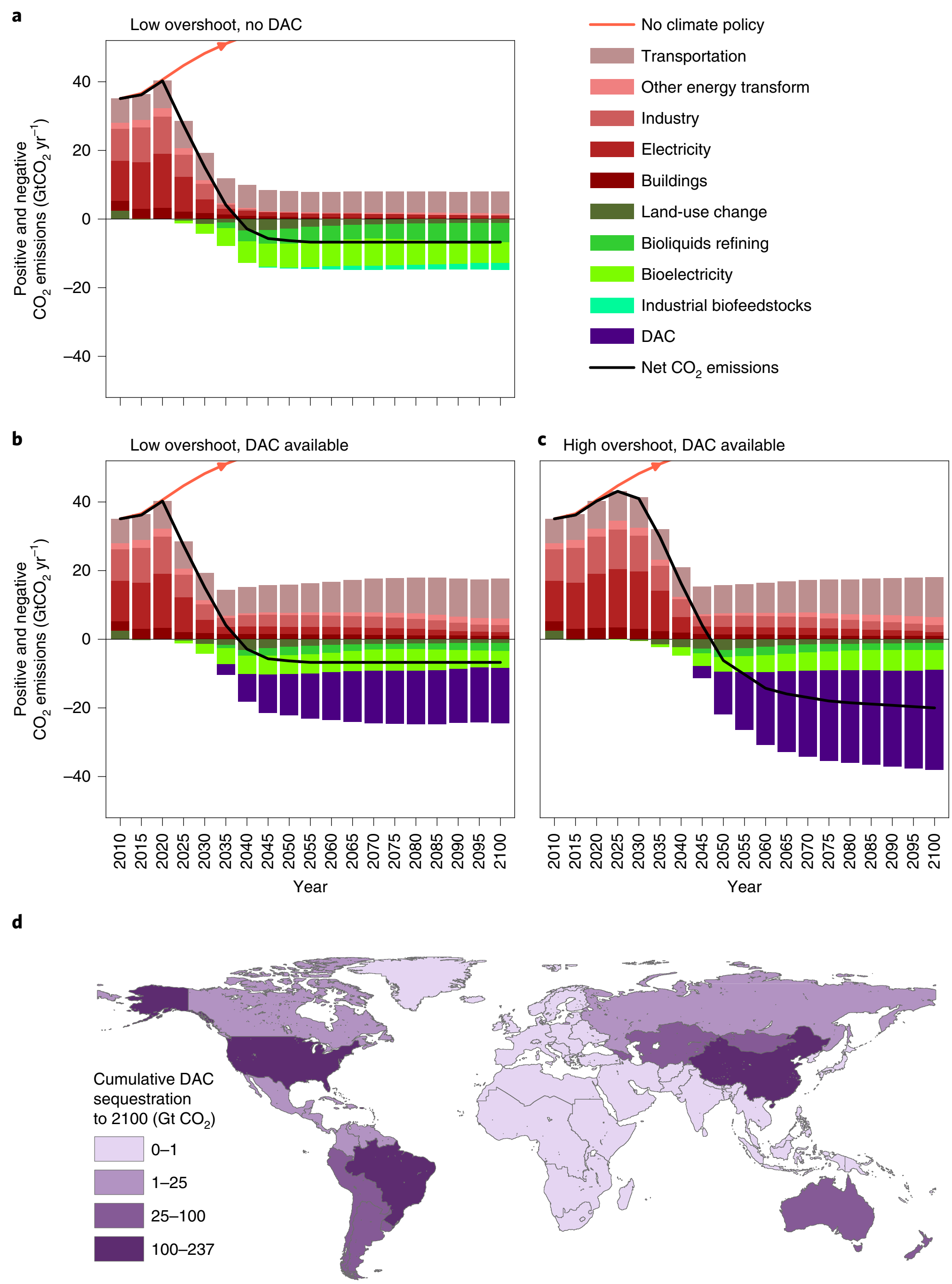

Fig. 2 | Positive and negative CO_2 emissions by sector and region. a–c, Positive and negative CO_2 emissions by sector in the scenario of low overshoot with no DAC (**a**), low overshoot with DAC available (**b**) and high overshoot with DAC available (**c**). **d**, Spatial distribution of DAC deployment in the low-overshoot scenario. Negative land-use-change emissions indicate afforestation (dark green), while BECCS includes the use of biomass to produce carbon-negative electricity, liquid fuels and industrial products (light green). Results from less optimistic parametrizations of DAC can be found in the Supplementary Information.

use for BECCS and afforestation. These severe food price increases are largely attributable to the imposed constraint on the ability of 'commercial land' (for example, agricultural and forestry activities for food, fibre and bioenergy production) to expand into otherwise 'natural' uses of land (Fig. 3). If this land protection constraint is relaxed, food price impacts would be less severe in both the DAC and no-DAC scenarios, but at the expense of even larger-scale conversion of natural lands to agricultural production and managed forest.

Water and energy use of NETs

Water consumption for DAC is comparable to that of bioenergy crop irrigation (Fig. 4). This result is in contrast to a previous report[23] where BECCS and afforestation sequestration was scaled by a water use factor[20] that included the total evapotranspiration of unirrigated bioenergy crop cultivation, without subtracting the evapotranspiration of the food crops as well as native vegetation that the bioenergy crops would be replacing. GCAM calculates water consumption, water withdrawals and crop evapotranspiration for agricultural

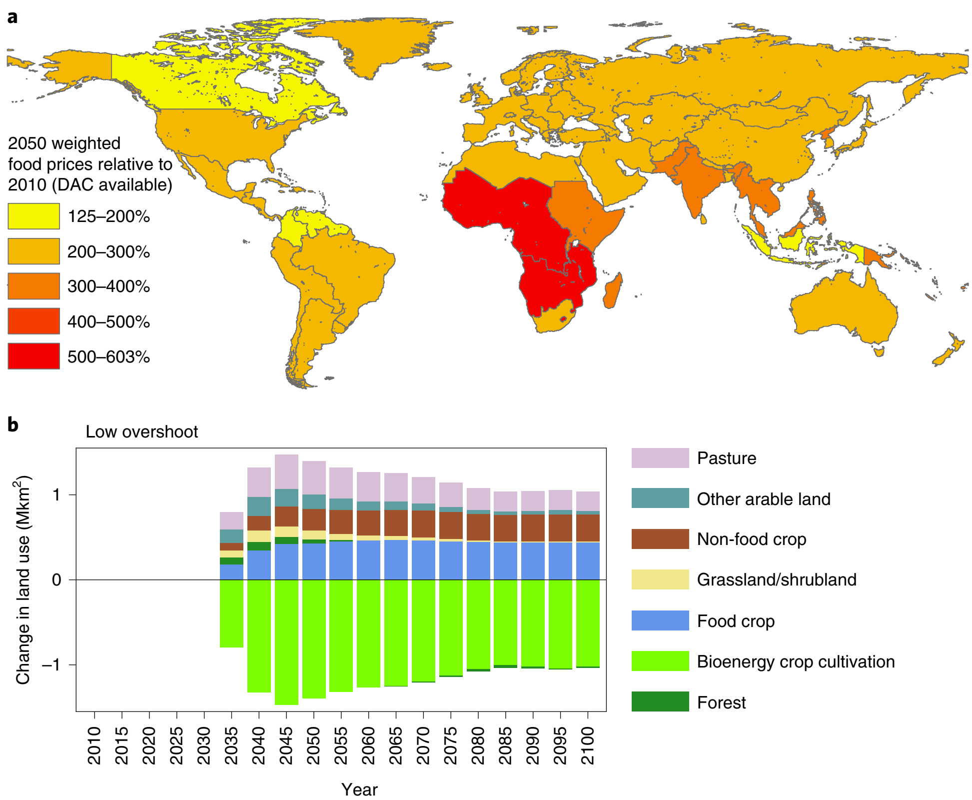

Fig. 3 | Food crop price and global land-use impacts of NET deployment. a, Regionalized food crop prices relative to 2010 levels for the low-overshoot trajectory. **b**, Differential land use between DAC available and no-DAC scenarios. Combined land use devoted to BECCS and afforestation in the no-DAC scenario is over 5 Mkm^2 (see Fig. 1). The availability of low-cost DAC can reduce this requirement by approximately 1 Mkm^2 in 2050, freeing up more land for food production and ameliorating the most severe food price impacts.

and industrial sectors endogenously. This treatment of water use produces a different result than would be obtained by linearly scaling the water intensity of each NET. DAC reduces the demand for negative emissions from BECCS, but also allows for increased positive emissions to the atmosphere, which are then offset by DAC. Therefore, even though DAC is still less water intensive than bioenergy crop irrigation, large DAC deployments result in increased total water use for negative emissions—a phenomenon analogous to a rebound effect. Further, irrigated cropland that would be used for BECCS if DAC were not available is then freed up for other agricultural production, further increasing water demand. To meet the same low-overshoot emissions constraint, the availability of DAC results in a net increase in total water consumption of nearly 35 $km^3\ yr^{-1}$ in 2050, approximately 35% of current-day evaporative losses for electricity production globally. The increased late-century negative emissions requirement in the high-overshoot scenario, which is met by DAC, increases water consumption even further. Input assumptions and calculated intensity factors (tH_2O/tCO_2 sequestered) are reported in the Supplementary Information.

Results for primary energy consumption by source for low and high overshoot of the 1.5 °C temperature target are reported in Fig. 5. As in the no-DAC scenario, fossil fuels continue to play a large role in the global energy system, but their emissions are mostly abated using CCS technology (that is, CO_2 emissions are captured at point sources). Even with DAC, unabated coal shows precipitous drop-offs at the initiation of the climate policy, while unmitigated oil and gas continue to be used for transportation and industrial processes that are recalcitrant to decarbonization. In the low-overshoot case, process heat and electricity requirements for DAC together account for 100 EJ yr^{-1} of energy demand by 2100, with process heat requirements accounting for 85 EJ yr^{-1} of this. For context, global natural gas demand in 2018 was approximately 130 EJ[40]. Even relatively modest delays in aggressive mitigation in the high-overshoot scenario result in increased energy demand from DAC to remove previously emitted CO_2. Differences between low-overshoot scenarios in which DAC is and is not available are shown in Fig. 5c. Increases in demand for other fuels (for example, conventional natural gas and oil) occur because the availability of DAC allows other industries to abate their emissions less aggressively and be offset by DAC. Additional demand for natural gas CCS is due to DAC process-heat requirements.

Conclusions

Modelling results obtained using GCAM suggest that DAC technology can make substantial contributions before mid-century to the deep emissions reductions necessary to meet a 1.5 °C end-of-century temperature increase goal. Given the global ambition to aggressively mitigate climate change in the near term, DAC could begin removing multiple $GtCO_2\ yr^{-1}$ from the atmosphere as early as 2035, even assuming present-day financial and energy inputs. The availability of DAC can reduce the steepest tradeoffs associated with land and fertilizer use for BECCS and afforestation. However, even with large-scale DAC availability, BECCS and afforestation deployment will still have large effects on other commodity markets, food in particular, with expected impacts concentrated heavily in the Global South. We also find that reductions in bioenergy crop irrigation withdrawals and consumption are largely offset by increased water use for DAC. In the case of water consumption, evaporative losses from DAC are over 100% of the reduction in BECCS-related consumptive water use that DAC technology enables. This is due

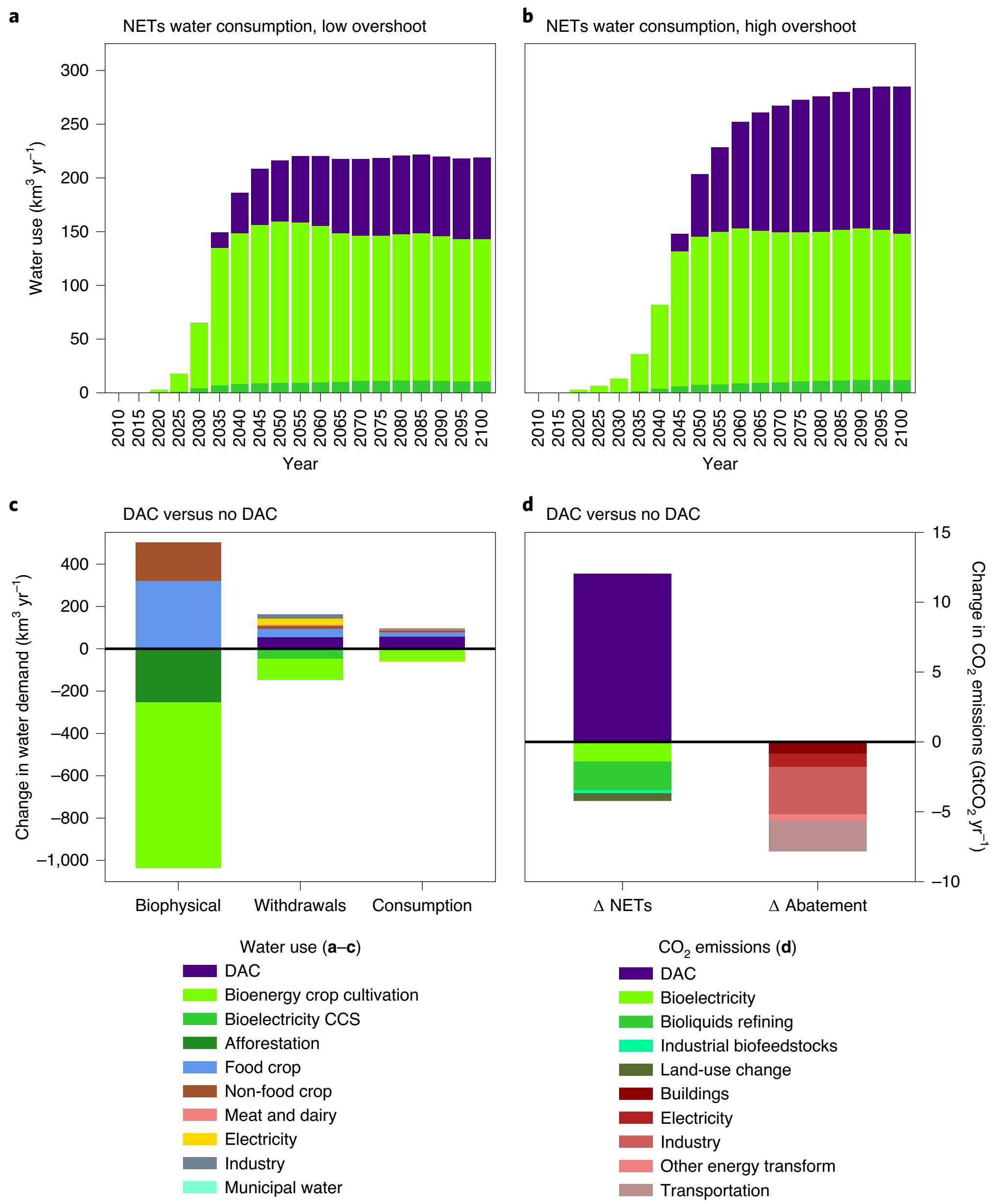

Fig. 4 | Water use and displacement of emissions abatement of large-scale DAC. a,b, Global consumptive water use for BECCS and DAC under low (**a**) and high (**b**) overshoot of the 1.5 °C temperature target. **c**, Differences in the year 2050 for biophysical water demand, withdrawals and consumption by sector for low-overshoot scenarios in which DAC is and is not available. The availability of DAC decreases evapotranspiration related to human activities but increases overall withdrawals and consumption. **d**, Effect of DAC on NET deployments and abatement effort. Decreased abatement effort indicates increased gross positive CO_2 emissions.

to a 'water rebound effect' where the less water-intensive technology (DAC) is used at higher rates because it displaces emissions abatement, increasing overall water use. Indeed, much of the negative emissions requirement in all scenarios is driven by offsets for recalcitrant sectors (for example, liquid fuels for transportation). Thus, research and policies aimed at avoiding emissions from these distributed sources in the first place could substantially reduce the projected tradeoffs associated with all NETs. This highlights the importance of detailed consideration of interaction effects between NETs and emissions abatement by policymakers and the models informing them, as well as environmental impacts (for example, water use) not directly related to climate. IAM research into NETs with potential co-benefits (for example, agricultural soil carbon and coastal wetlands protection and restoration) could further highlight ways to alleviate negative side effects associated with planting trees, growing bioenergy crops or building industrial facilities solely for the purpose of large-scale carbon removal. It is crucial, however, that modelling results projecting large-scale future deployments of 'more sustainable' negative emissions are communicated so as to not justify further delays in implementing ambitious mitigation policy in the near term[51].

Consistent with other IAM studies of DAC, we find that this technology will require large energy input, up to 115% of current-day natural gas consumption for process heat alone[40]. Any robust climate policy including DAC in the mitigation portfolio should therefore consider natural gas life cycle emissions (for example, leakage

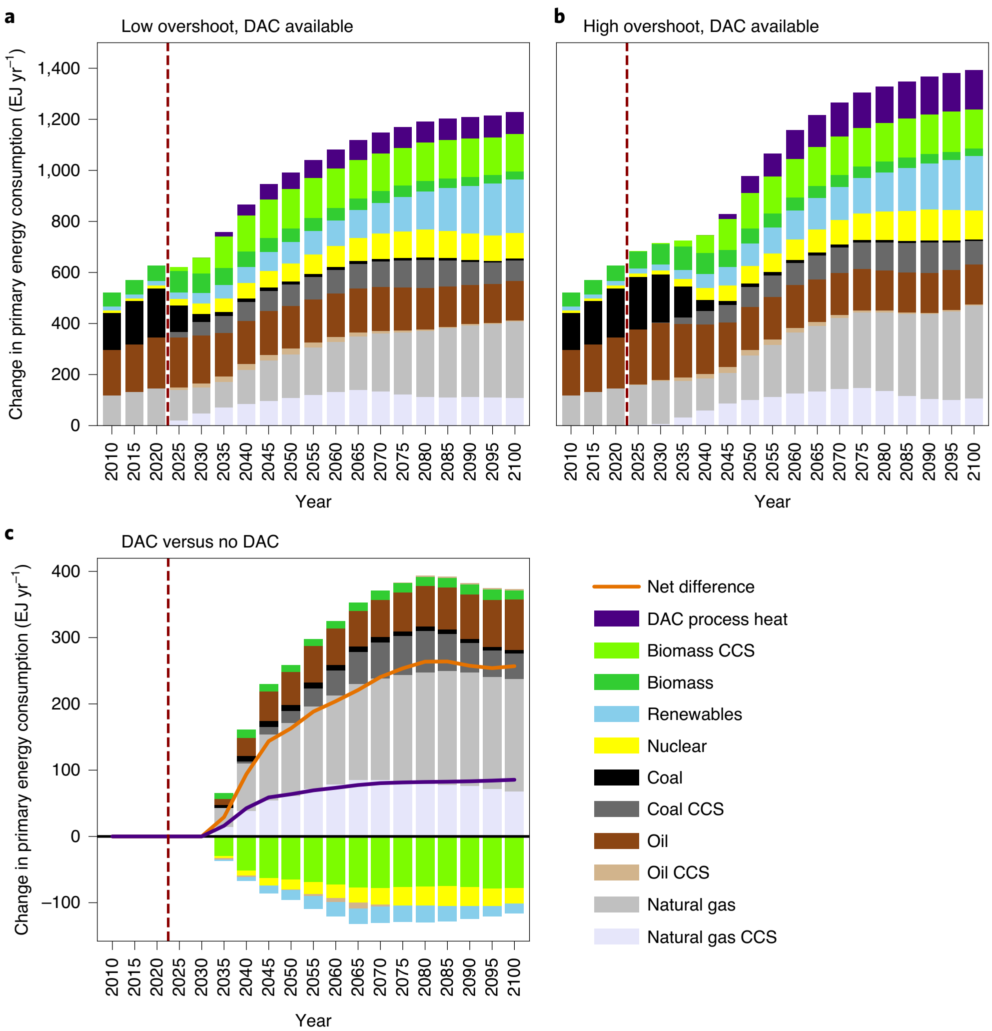

Fig. 5 | Effects of DAC on primary energy consumption. a,**b**, Primary energy consumption by source for low-overshoot (**a**) and high-overshoot (**b**) scenarios with DAC available. Natural gas with CCS for DAC process heat is subtracted to avoid double counting and shown separately in purple. **c**, Differences between two low-overshoot scenarios in which DAC is and is not available, where virtually all of the increase in natural gas CCS is driven by DAC. Increases in energy demand from other sources occur because low-cost DAC enables less aggressive emissions abatement. Electricity consumption for DAC is a secondary energy demand and is not shown separately. The dashed vertical line in each subfigure indicates the start of the climate policy.

during extraction and transport) to avoid offsetting the climate benefit of the CO_2 removal[52]. The fundamental issue of increasing future energy requirements for CO_2 removal to compensate for failure to decarbonize in the near term exists even with DAC processes that can use renewable energy for process heat and electricity. The magnitude and distribution of food price increases projected to result from land-based carbon removal, even with large-scale deployments of DAC, raise profound intra- and inter-generational equity concerns. While these concerns have been well covered in the literature with respect to the risks and burdens of climate change itself (for example, refs. [53,54]), additional attention is needed to address the distribution of burdens of negative emissions intended to mitigate it. Most critically, we emphasize the need for urgent action on decarbonization policy that is the precondition for any kind of large-scale mitigation activity, let alone global-scale net-negative emissions. Just as climate impacts (for example, sea-level rise and extreme weather events) will continue to become more severe with delayed action, the food, energy and water tradeoffs of DAC and other negative emissions technologies will only increase in magnitude the longer mitigation is delayed and the need for their deployment increases.

Online content

Any methods, additional references, Nature Research 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/s41558-020-0876-z.

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Methods

We used GCAM version 5.2, accessed on 8 November 2019, and ran scenario permutations on the University of Virginia high-performance computing cluster, Rivanna. We imposed two constraints on global CO_2 emissions pathways, which represent high- and low-overshoot trajectories of the 1.5 °C end-of-century temperature target from the IPCC Special Report on Global Warming of 1.5 °C. Both emissions constraints are assumed to begin in 2025. The first emissions pathway seeks to limit overshoot of the 1.5 °C temperature target, which is broadly consistent with the scenario design logic suggested by Rogelj et al.[46]. The peak mean global temperature reached in this scenario is 1.56 °C above pre-industrial levels in year 2045, before subsequently declining to 1.32 °C by 2100. The second pathway allows near-term mitigation to proceed more slowly, with associated higher intermediary overshoot of the 1.5 °C temperature target, peaking at 1.78 °C in 2055, before returning to approximately the same temperature as the low-overshoot scenario by 2100. This allows direct assessment of the impact of delays in near-term ambition on longer-term tradeoffs associated with negative emissions. We emphasize that an explicit consideration in our scenario design was to reduce end-of-century warming as well as reliance on future net-negative emissions, and that both emissions trajectories are at odds with current and intended future climate action[56]. Additional delays in mitigation will increase the requirement for negative emissions in the future[5,6]. The emissions constraints imposed, as well as the resulting CO_2 concentrations and global average temperature anomaly trajectories, are reported along with historical data for each of these in Extended Data Fig. 2 (refs. [7,57,58]). GCAM endogenously calculates the CO_2 prices required to meet the emissions constraint imposed in each model period. Land-use change emissions are included under the constraint, and their price is determined as an exogenously specified proportion of the fossil emissions price. This is done because, whereas fossil fuels are largely a market commodity, much of the land use and agriculture occurs outside of regulatory frameworks in many countries[17]. Pricing land-use change emissions immediately at 100% of the fossil carbon price therefore ignores existing institutional barriers to implementing land-use emissions policy, including uncertainties in quantifying fluxes and reversal risks of biospheric carbon storage[59–61]. To represent long-term improvements in institutions for implementing land-use policy, land-use change emissions are priced here as a linearly increasing proportion of fossil and industrial emissions price, from 0% in 2025 to 100% by 2100.

DAC requires energy input in the form of process heat and electricity and financial inputs for capital expenditure and non-energy operations and maintenance. While some DAC processes require negligible water use and may actually produce water from humid air, the process modelled here relies on aqueous reactions between atmospheric CO_2 and a hydroxide solution and has evaporative water losses at the air contactor[22,62–64]. There is large parametric uncertainty with regard to the energy intensity and total cost of DAC, the latter of which depends heavily upon the assumed capital recovery factor, as well as the energy source[65]. We focus on DAC processes requiring high-temperature heat from natural gas combustion, rather than those using lower-quality waste heat or 100% renewable electricity, because detailed and harmonized specifications for these latter processes are not available in the literature due to commercial confidentiality. Energy and financial input parametrizations for high- and low-cost DAC follow those used by Realmonte et al.,[23] representing upper and lower estimates for hydroxide-based DAC processes from recent literature[22,23,66]. Per tCO_2 sequestered from the atmosphere, for low-cost DAC we assume process heat input of 5.3 GJ, electricity input of 1.3 GJ and non-energy financial input of US$180. Parametrization and results for high-cost DAC, for which we used less optimistic parametrizations for energy and financial inputs, are provided in the Supplementary Information. Electricity input for DAC is assumed to come from each region's grid; generation fuel mix and therefore cost and carbon intensity is calculated endogenously[22]. Financial inputs are assumed to remain constant in real terms over time. For water, we assume 4.7 tH_2O/tCO_2 following the detailed material balances provided by Keith et al., with withdrawals and consumption assumed equal[22]. Process heat for DAC is assumed to come from natural gas with a 95% capture rate for combustion CO_2 emissions, consistent with oxyfuel CCS processes[23]. For other CCS processes, the standard GCAM assumptions for CO_2 capture rates are used (85–95%)[67]. The storage cost for carbon captured from DAC and other sources is calculated separately and endogenously by GCAM.

In equilibrium, DAC indirectly competes with other NETs for its share of contribution to the emissions reduction. For instance, given a constraint on emissions, GCAM will endogenously calculate the lowest cost option to achieve the goal by comparing the cost-effectiveness of BECCS (in both bioliquids and bioelectricity) and afforestation. Bioenergy crops can be used to achieve net-negative emissions by displacing the use of fossil fuels with CCS in electricity generation (bioelectricity), converted to liquid transportation fuels and sequestering the resulting high-purity CO_2 streams (biofuels), or used as feedstocks in durable products manufacture such as plastics (bioindustrial feedstocks). BECCS therefore largely competes on the energy supply side, but also competes for carbon-negative subsidies. Afforestation largely competes with other land-use demands, such as food crops and pasture, but also competes for carbon-negative subsidies. We placed no external constraints on the use of DAC and removed the default constraint on the amount of bioenergy used for negative emissions. BECCS was instead allowed to freely compete with other uses of land based on their costs, yield and water demand. However, we kept in place the standard GCAM assumption that 90% of natural lands (non-commercial) are removed from economic competition (that is, not available for expansion for bioenergy, food and fibre production, or afforestation). This is done to place reasonable biophysical constraints on the deployment of land-based mitigation and negative emissions, and to preserve much of the remaining natural land for biodiversity, species, watershed protection, recreation and cultural value as reflected in the UN Sustainable Development Goals and many national-level policies. Descriptions of other GCAM model specifications can be found in the GCAM documentation[68].

Data availability

To enable replication of our work, the input files required to run our scenarios, as well as python scripts used in generating figures for this study, may be downloaded at https://doi.org/10.18130/V3/JKJAOG[55]. Source data are provided with this paper.

Code availability

The full model is available for download at https://github.com/JGCRI/gcam-core.

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Author contributions

J.F., H.M., S.C.D., W.M.S. and A.F.C. led the study design and the writing of the paper, J.F., H.M. and P.P. conducted the modelling.

Competing interests

The authors declare no competing interests.

Additional information

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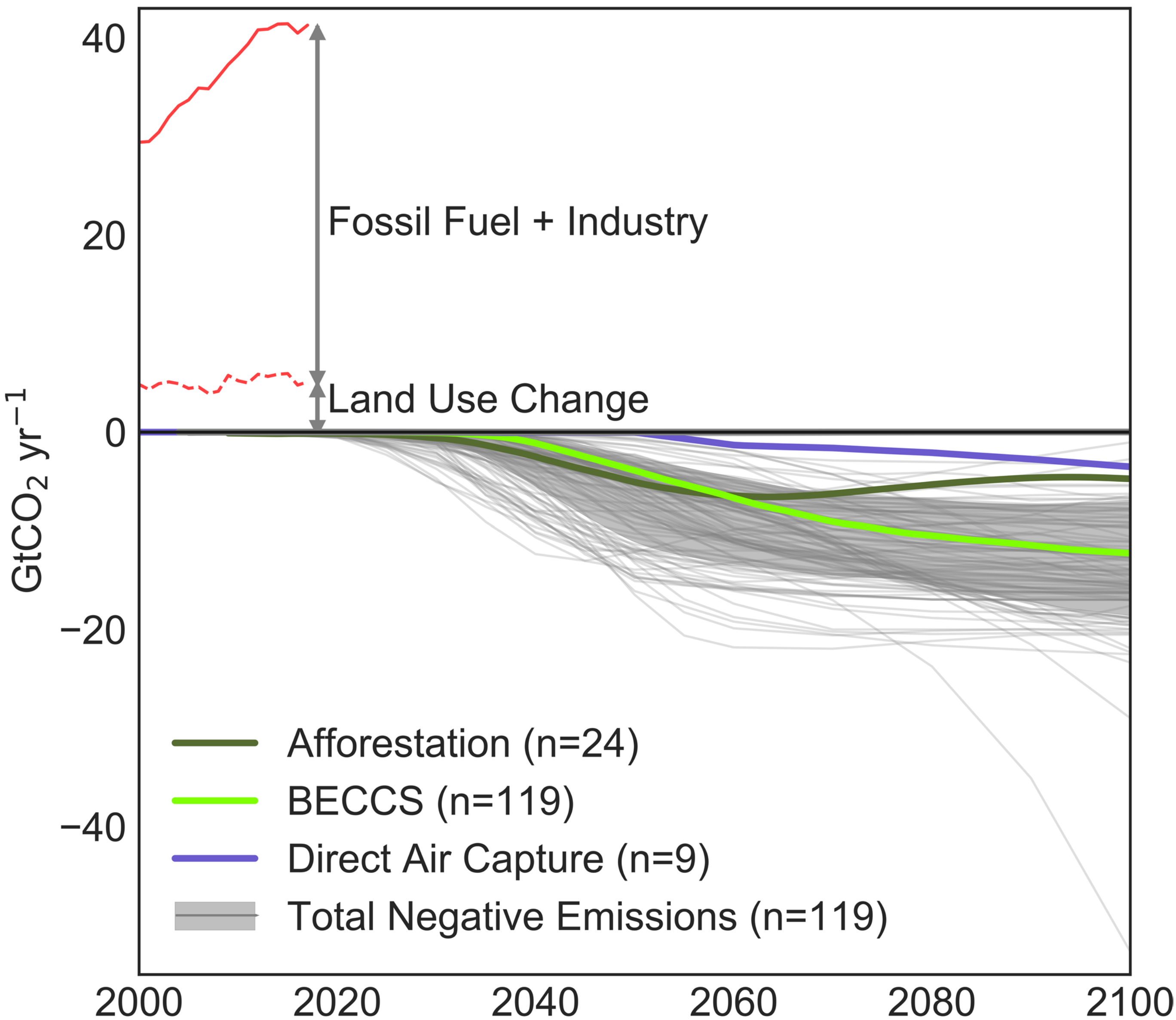
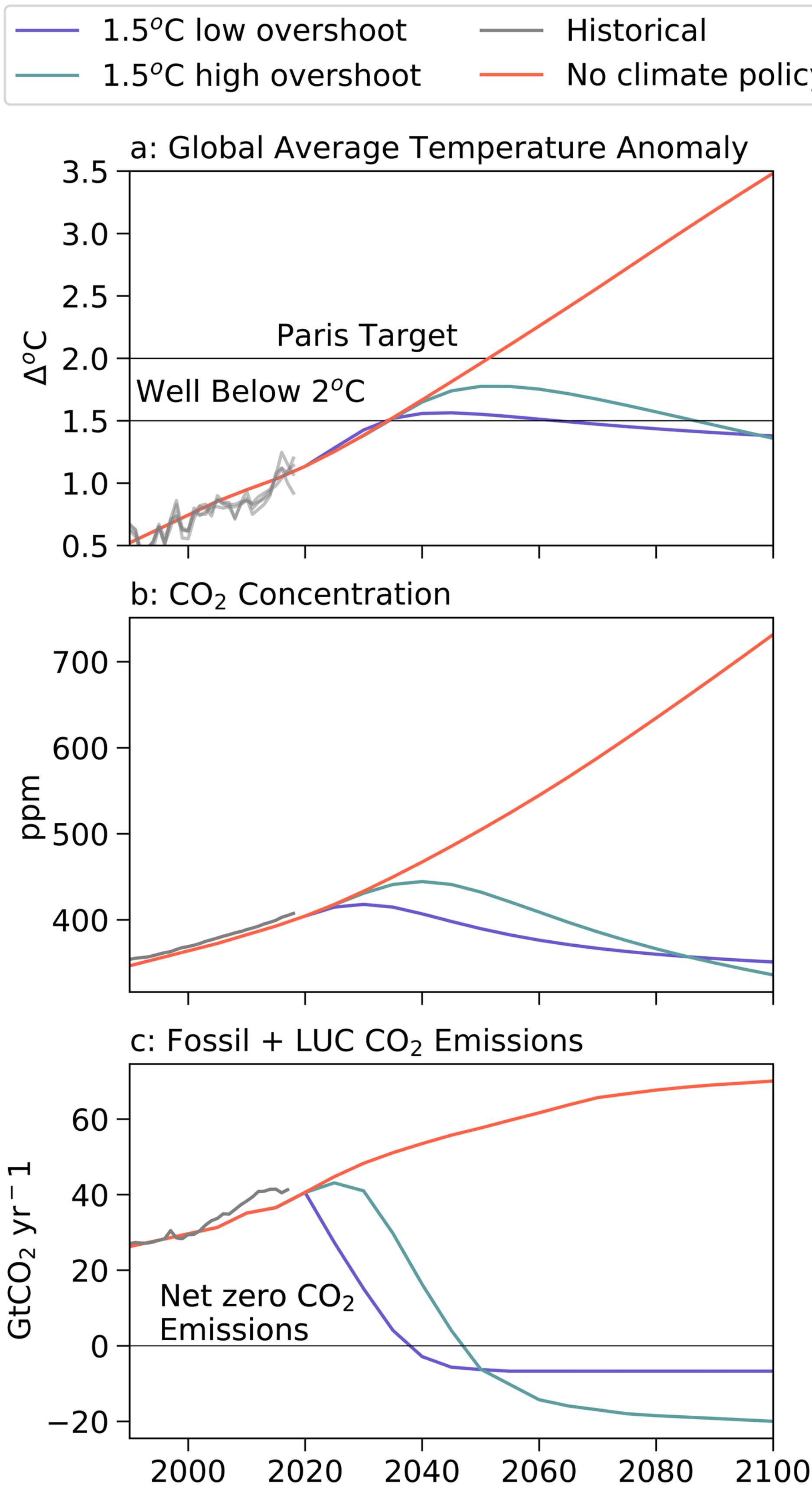


Extended Data Fig. 1 | Projected NET deployments to limit global warming to 1.5 °C. Modelling results underpinning the IPCC's Special Report on Global Warming of 1.5 °C. The thicker coloured lines show the median projected deployments of the individual afforestation, BECCS, and DAC technologies, for those model results which report them. The thin grey lines represent the combined negative emissions deployment for individual scenarios. The grey shading represents the 68% confidence interval (+/− 1 standard deviation) on combined negative emissions deployment.



Extended Data Fig. 2 | Effect of representative high and low overshoot of the 1.5 °C end-of-century temperature target. a, Temperature anomalies from pre-industrial, **b**, CO_2 concentrations, and **c**, emissions trajectories. Historical data for emissions, CO_2 concentrations, and temperature are indicated by grey lines. The "no climate policy scenario" is the GCAM reference scenario. After the year 2020, CO_2 emissions pathways represent imposed model constraints which result in the CO_2 concentration and temperature trajectories reported.