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PAPER

The impact of regional resources and technology availability on carbon dioxide removal potential in the United States

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Abstract

To achieve net zero carbon emissions by mid-century, the United States may need to rely on carbon dioxide removal (CDR) to offset emissions from difficult-to-decarbonize sectors and/or shortfalls in near-term mitigation efforts. CDR can be delivered using many approaches with different requirements for land, water, geologic carbon storage capacity, energy, and other resources. The availability of these resources varies by region in the U.S. suggesting that CDR deployment will be uneven across the country. Using the global change analysis model for the United States (GCAM-USA), we modeled six classes of CDR and explored their potential using four scenarios: a scenario where all the CDR pathways are available (Full Portfolio), a scenario with restricted carbon capture and storage (Low CCS), a scenario where the availability of bio-based CDR options is limited (Low Bio), and a scenario with constraints on enhanced rock weathering (ERW) capabilities (Low ERW). We find that by employing a diverse set of CDR approaches, the U.S. could remove between 1 and 1.9 $GtCO_2$/yr by midcentury. In the Full Portfolio scenario, direct air carbon capture and storage (DACCS) predominates, delivering approximately 50% of CO_2 removal, with bioenergy with carbon capture and storage contributing 25%, and ERW delivering 11.5%. Texas and the agricultural Midwest lead in CDR deployment due to their abundant agricultural land and geological storage availability. In the Low CCS scenario, reliance on DACCS decreases, easing pressure on energy systems but increasing pressure on the land. In all cases CDR deployment was found to drive important impacts on energy, land, or materials supply chains (to supply ERW, for example) and these effects were generally more pronounced when fewer CDR technologies were available.

1. Introduction

The United Nations Conference of Parties 28 (COP28) in the Fall of 2023 generated the first global stocktake, which is a way for countries to assess collectively their progress towards climate change goals, and a measure which is pivotal for future climate action. This stocktake concluded that cutting global greenhouse gas emissions by 43% by 2030 (compared to 2019 levels) is needed to limit global warming to 1.5 °C (UNFCCC COP28). COP28 also highlighted the need for a swift and equitable transition away from fossil fuels, emphasizing the importance of deep emissions cuts and greater financing for decarbonization activities (Gao *et al* 2024). The integrated assessment models (IAMs) that form the backbone of many decarbonization plans increasingly show that some amount of carbon dioxide removal (CDR) is required to meet net-zero targets (van Beek *et al* 2020). CDR can be used to offset hard-to-abate emissions and counteract near-term delays in mitigation or offset historical emissions (Bistline and Blanford 2021).

A growing body of literature suggests that CDR will increase energy and resource use in the regions where projects are sited (Beerling *et al* 2020, Bistline and Blanford 2021, Fauvel *et al* 2023, Fuhrman *et al* 2019, 2020, 2023). In that sense CDR approaches can be categorized in terms of their implications for regional resources as being primarily energy-intensive, land-intensive, or material-intensive.

Energy-intensive CDR includes bioenergy with carbon capture and storage (BECCS) as well as all forms of direct air carbon capture and storage (DACCS) technology-which can require biomass resources, process heat and electricity to operate (Pradhan *et al* 2021). The low concentration of CO_2 in the atmosphere implies that DACCS will be highly energy intensive. The compression, transport and injection of CO_2 into geologic reservoirs requires additional energy (Chiquier *et al* 2022). As a result, large-scale deployment of DACCS technologies will increase global thermal and electrical energy demands (Fuhrman *et al* 2019). Although bioenergy technologies involving energy crop cultivation also face well-studied challenges regarding water supply, competition for arable land, and land-use change, sectors such as aviation, shipping and trucking may require advanced biofuels for cost-effective decarbonization in the coming decades (Babin *et al* 2021, Chiquier *et al* 2022).

Land-intensive CDR techniques, such as afforestation and reforestation, would rely on forest ecosystem photosynthesis and management to accelerate biological removal of carbon. Afforestation and reforestation can be effective on the decadal timescale, but in most parts of the world, forest conversion (land-use change) is accelerating, and there is always the risk that climate change and natural hazards, such as wildfires, will reduce the likelihood of both the additionality and permanence of the sequestered carbon (Chiquier *et al* 2022).

Emerging material-intensive CDR approaches, such as enhanced rock weathering (ERW), soil enhancement using biochar, and direct ocean carbon capture with storage (DOCCS) present promising avenues for removal but also potential environmental costs (Stler *et al* 2018, Beerling *et al* 2020, Bekchanova *et al* 2021, Lehmann *et al* 2021). ERW and biochar involve direct land application of byproduct materials from mining and bioenergy production, respectively, where they increase carbon uptake. While they overlap with land-based approaches, they do not change the land use, so the resource challenges exist in the scaling of supply chains for new materials. DOCCS will require material input, seawater pumping, and electrical energy for CO_2 removal. Of the three classes of CDR strategies, material intensive CDR approaches are the newest and least well studied in the IAM literature (DeVries *et al* 2017, Digdaya *et al* 2020, National Academies of Sciences, Engineering and Medicine 2022).

Recent studies have explored the effects of different sectoral decarbonization strategies alongside deployment of CDR (Rogelj *et al* 2015, Iyer *et al* 2018, Feijoo *et al* 2020, Hultman *et al* 2020, Peng *et al* 2021, Bistline *et al* 2022). U.S. net-zero goals could play out in many different ways, especially given the distributed governance in the U.S., where federal, regional, and state decision making all influence how power systems, transportation systems, and other enabling infrastructure will change over the coming decades (Ou *et al* 2023). Fauvel *et al* (2023) analyzed BECCS, afforestation and reforestation, and DACCS in the U.S. and found significant variations in regional deployment occurs, resulting in uneven impacts on energy, water, and land use for the states.

Recent modeling exercises indicate that, at the global scale, more diverse forms of CDR beyond BECCS, afforestation/reforestation, and DACCS can lower the resource requirements of CO_2 removal (Fuhrman *et al* 2023). But the sub-national dimensions of this effect have yet to be explored in detail. At a global scale, Strefler *et al* (2021) looked at interregional tradeoffs of CDR technology choices in terms of deployment and costs and highlighted the importance of carbon capture and storage (CCS) as an enabling technology for many CDR and decarbonization technologies. Indeed, CCS is foundational for both DACCS and BECCS, and the possibility of its low deployment at a global scale needs to be considered alongside the potential that CDR deployment might be shifted to approaches that do not require CCS. Historical data does not show cost reductions in CCS technologies, reinforcing the questionable financial viability and sustainability of scenarios that emphasize CCS most heavily in the transition to net-zero emissions (Bacilieri *et al* 2023).

The deployment of CDR needs to be evaluated in the context of the large-scale changes that will be brought about by the energy transition required for deep decarbonization, and the climate changes that are accelerating as a result of historical and present emissions. Séférian *et al* (2018) showed that the dynamics of water resources, as influenced by climate change, could pose substantial restrictions on the feasibility of BECCS implementation before 2050, emphasizing the need to consider sustainable and resource-efficient alternatives in our net-zero emissions strategies. Prioritizing conventional mitigation methods like renewable energy sources, electrification, the use of carbon negative or neutral fuels, and improving energy efficiency, instead of relying on the uncertain expansion of future CDR technologies can also alleviate the strain on vital resources such as land, water, and fertilizers (Ampah *et al* 2024). These studies collectively inform the importance of diverse, resource-conscious, and economically wise strategies in achieving net-zero emissions.

Here we extend the U.S. focused integrated assessment global change analysis model (GCAM-USA 6.0) to include three additional CDR pathways-biochar, ERW, and direct ocean capture and carbon storage-to investigate their effects, alongside afforestation and reforestation, BECCS, and DACCS, on the interconnected energy–water–land systems. We examined the distribution of CDRs across different U.S. states in the context of a national net-zero CO_2 emissions target by midcentury. We explored how different sectoral demands, economic assumptions, regional resource disparities, and other regional limitations could influence the likely deployment of different CDRs and how these deployments compare to current and projected positive emissions. This study highlights the importance of adopting an integrated and multi-dimensional approach to address the complex interactions between CDR approaches, sectoral decarbonization strategies, and the energy–water–land system to reach a net-zero 2050 CO_2 target.

2. Methods

2.1. GCAM-USA

GCAM is an open source IAM, developed by the Joint Global Change Research Institute (JGCRI) (available at: https://github.com/JGCRI/gcam-core/releases). GCAM simulates the dynamics and interdependencies among energy, water, land, economy, and climate systems across 32 geopolitical regions worldwide and computes equilibrium prices and input-output quantities for all markets in each region and modeling period. GCAM-USA is an extension of the global model providing finer resolution by disaggregating the United States into states and the District of Columbia. This research builds upon the open-source release of GCAM-USA 6.0. Comprehensive documentation for this IAM is accessible via the model's documentation page (https://jgcri.github.io/gcam-doc/gcam-usa.html).

2.2. CDR technologies

GCAM-USA 6.0 includes afforestation and reforestation, BECCS, and DACCS as CDR methods (Fauvel *et al* 2023). We have enhanced the model to include ERW, biochar soil enhancement, and DOCCS, extending the CDR approaches in the global version of the CDR model developed by Fuhrman *et al* (2023).

2.3. Energy intensive CDR approaches

We included both natural gas-based high-temperature DAC and fully electrified types of high and low-temperature DAC systems. High-temperature DAC is based on solvents and depends on aqueous chemical reactions, necessitating the replenishment of water to compensate for losses due to evaporation as detailed by Keith *et al* (2018). On the other hand, low-temperature DAC uses solid sorbents for CO_2 capture and does not require water, as explained by Fasihi *et al* (2019). We assumed gradual enhancements in the efficiency and cost-effectiveness of these technologies, building on earlier DACCS studies within GCAM (Fuhrman *et al* 2020, Fuhrman *et al* 2021).

2.4. Land intensive CDR approaches

In GCAM, afforestation and reforestation are modeled as strategies for increasing forested areas, either by establishing forests on land that has been without tree cover for some time (afforestation) or reintroducing trees to land that recently lost its tree cover (reforestation). The model takes into account various factors such as the availability of suitable land, regional differences in growth rates, and carbon storage potential of different forest types.

BECCS involves growing biomass, using it for energy production, and finally capturing and sequestering the CO_2 emissions produced during bioenergy generation. The use of this technology has important implications for food supply and prices because it requires increased dedication of land and often irrigation as well as fertilizers for biomass cultivation (Beerling *et al* 2020). GCAM-USA's modeling of BECCS includes the land area required for biomass cultivation, the energy conversion efficiency of BECCS technologies, and the potential for CO_2 storage. It assesses the role of BECCS within the broader U.S. energy system, evaluating its competitiveness with other energy sources and its impact on land use. The model explores state-specific deployment potentials, factoring in regional biomass availability, storage site accessibility, and the economic viability of BECCS operations.

2.5. Material intensive CDR approaches

Material intensive CDR technologies involve the use of substantial amounts of natural or synthetic materials to passively capture and sequester atmospheric CO_2. Among the prominent material-intensive CDR technologies, we added three forms of materials intensive CDR to the model, which are described in the subsequent subsections.

2.5.1. Enhanced Rock Weathering (ERW)

ERW accelerates the natural weathering process of rocks rich in calcium or magnesium. This process involves the interaction of CO_2 with rocks in the presence of humidity, leading to the release of dissolved inorganic carbonate ions. These ions are then carried to the ocean, where they are incorporated into the marine carbon cycle. ERW involves grinding rocks (e.g. basalt or olivine) and spreading the fine particles over large areas of land, such as agricultural fields in warm or temperate environments. It can be implemented on lands already in use; therefore, compared to BECCS or afforestation this approach requires less water and does not necessitate a change in land use. ERW not only removes CO_2 but can also potentially improve crop yields and soil health so long as the soil amendments do not contain harmful trace elements (Dupla *et al* 2023).

In GCAM-USA, we modeled the use of crushed basalt on croplands, considering a supply curve based on the U.S. potential for CO_2 removal using ERW developed by Beerling *et al* (2020). We calculated the state-level potential of CO_2 removal by ERW based on the methodology provided by Stler *et al* (2018) (detailed calculations for state-level potential of ERW are provided in the supplementary information) and used them to extract the state level ERW costs from the national level ERW supply curve. To present a more conservative cost estimate for the near term, we adjusted each region's ERW supply curve in 2020 with an additional non-energy cost that declines to zero by 2050 based on Fuhrman *et al* (2023). The non-energy cost of ERW includes capital as well as operation and maintenance costs, mainly energy costs associated with mining and preparation of ground rock, transportation, and their application on the agricultural fields.

2.5.2. Soil enhancement with biochar

Biochar is a solid, carbon-rich byproduct of large-scale thermochemical conversion of biomass into chemicals or fuels that can be applied to the soil and enhance the soil's carbon storage capacity, with the potential to lock carbon *in situ* for centuries. There is growing evidence that biochar can also improve soil fertility, water retention, and crop productivity, leading to both carbon storage and improved agricultural sustainability (Yang *et al* 2021). Here we model biochar as being a byproduct of pyrolysis under low or zero-O_2 conditions (Woolf *et al* 2010). Pyrolysis is categorized as being either fast (heating rate of 10 °C–200 °C s^{-1} with temperatures between 400 °C–800 °C) or slow (heating rate of 0.1 °C–1 °C s^{-1} with temperatures between 300 °C–700 °C) processes, distinguished by the speed of biomass transformation and heating rate (Woolf *et al* 2010, Zhang *et al* 2020, Huang *et al* 2021, Pahnila *et al* 2023). We consider the production of biochar through slow pyrolysis of biomass, with the production of biogas as a by-product. The application of biochar on cropland is considered as a new crop cultivation method competing with the other crop cultivation techniques within the agriculture sector. Application of biochar to a given plot of cropland is assumed to increase the yield at a rate depending on the climate zone (Fuhrman *et al* 2023). Assumptions regarding cost, fraction of carbon removal from total carbon available in biomass feedstock less the carbon available in the co-product biogas, rate of by-product generation, and application rate per hectare land are the same as those previously reported (Fuhrman *et al* 2023). The model incorporates sustainable practices such as using agricultural residues and forestry by-products, which do not demand extra land, as well as cultivating purpose-grown energy crops on marginal or degraded lands to prevent competition with food production. These approaches are crucial in reducing the sustainability challenges associated with biochar production, supporting its contribution to climate mitigation objectives.

2.5.3. Marine CDR (mCDR)

Numerous physical, geochemical, and biological mechanisms play a role in the exchange of CO_2 between the atmosphere and the ocean. Ocean-based CDR strategies have the potential to increase the ocean's natural carbon storage ability (National Academies of Sciences, Engineering and Medicine 2022). One possible way to deploy mCDR is with DOCCS, which uses an electrochemical process to separate input seawater into acidic and basic flows. This process alters the seawater's pH and extracts CO_2 from ocean water, which is then sequestered in geological formations, allowing the ocean to absorb additional atmospheric CO_2 (Digdaya *et al* 2020, Sharifian *et al* 2021). DOCCS is at an early stage of development and faces challenges regarding energy requirements, costs, and potential impacts on marine ecosystems. The projected expenses for a stand-alone DOCCS facility are considerable, with estimates of approximately $1.40 per kilogram of CO_2

Table 1. Modeling assumptions for the four decarbonization pathways considered here. The land carbon pricing, which is the fraction of the carbon price on fossil emissions scaled linearly from 0 in 2020 to 0.5 in 2050. The non-energy cost of ERW, including capital as well as operation and maintenance costs associated with preparation of ground rock, transportation, and their application on the croplands, is kept flat in all scenarios at 80 (2020\$/tCO_2) .

	Constraints		
Scenario	Global biomass constraint	National ERW constraint	Global CCS constraint
Full Portfolio	31EJ in 2025 linearly to 62.5EJ in 2050	0 in 2020 linearly to 320MtCO_2 in 2050	No constraint
Low CCS	31EJ in 2025 linearly to 62.5EJ in 2050	0 in 2020 linearly to 320 MtCO_2 in 2050	3GtCO_2/yr from 2030 to 2050
Low Bio	Constant 31EJ through 2050	0 in 2020 linearly to 320 MtCO_2 in 2050	No constraint
Low ERW	31EJ in 2025 linearly to 62.5EJ in 2050	0 in 2020 linearly to 64 MtCO_2 in 2050	No constraint

(Eisaman *et al* 2018, Digdaya *et al* 2020). Although coupling DOCCS with a desalination unit might lower the levelized cost (as desalinated water can then be sold), the capacity of the facility for CO_2 capture coupled with desalination would be constrained to under 100 thousand tons of CO_2 per year (Digdaya *et al* 2020). In GCAM-USA, we included two types of DOCCS facilities: stand-alone and co-located with a desalination unit, aligned with GCAM's global model (Fuhrman *et al* 2023) and conceptualized by Digdaya *et al* (2020).

2.6. Scenarios and mitigation policy

Our emission mitigation policy scenarios assume linear decreasing CO_2 net emission constraints at the global and U.S. national level, with global emissions capped at 32 billion tons in 2025, reaching net-zero emissions in 2050. For the U.S., the constraint begins at 4.3 billion tons in 2025 and declines to net-zero CO_2 emissions in 2050. U.S. subnational CO_2 emission reduction policies are not considered in this analysis. GCAM, as a closed-economy, partial equilibrium model, solves the markets of all sectors to balance out supply and demand within each economic region. The model solves market dynamics by factoring in economic competition, which involves calculating a CO_2 price endogenously to satisfy the emissions constraints.

We investigated four decarbonization pathways, capturing uncertainties associated with the future quantities of regional biomass resources, land carbon pricing, availability of underground carbon storage reservoirs, and the cost of ERW. Detailed assumptions for the scenario designs are provided in table 1. Results from an additional Low Residual Emissions scenario are included in the SI. Core techno-economic assumptions regarding CDR technologies, and mitigation policy are available in supplementary information tables S.1–S.6. In the ERW model, electricity costs and grid carbon intensity are calculated endogenously within GCAM-USA, and state-level costs are extracted from a national level supply curve for the U.S. More information about the ERW mode is provided in the SI section S.1.A.

3. Results

Our results show steady economy-wide decarbonization over the coming decades in all scenarios coupled with a ramp up in CDR achieving between 1–1.9 GtCO_2/yr of gross negative emissions by 2050 (figure 1). The gray lines behind the emissions bars provide a baseline of the residual emissions and CDR estimates for the Full Portfolio case for ease of comparison with the other scenarios. The amount and type of CDR deployed is sensitive to the assumptions in each scenario. Across all scenarios, land-intensive CDR approaches are deployed at larger scales earlier than energy- and material-intensive approaches. In the Full Portfolio case, DACCS delivers approximately 50.2% of total CO_2 removal in the U.S. and the rest is split between the other technologies; BECCS (25%), ERW (11.5%), afforestation and reforestation (6.9%), bioliquid feedstock (5.9%), and soil enhancement with biochar (0.4%). DOCCS shows lower removal potential in competition with the other technologies, only removing 0.003% of total CO_2 removal in the U.S. Bioliquid feedstock refers to liquids refined through the process of biomass to liquids, which are then consumed by industrial activities (e.g. inputs to chemical manufacturing).

Limitations on specific enabling technologies in the model naturally impact the overall adoption of related approaches for delivering negative emissions, sometimes in ways that are not obvious. As an example, the Low CCS scenario constrains the regional geological storage capacities and even though bioliquid generation technologies with CCS get deployed we see very limited DACCS and bioelectricity available by 2050. In the Low CCS scenario, the model relies on ERW, bioliquid, and afforestation to achieve its emissions targets. With lower CCS available, the model accelerates the rate of decarbonization by mitigation; so,

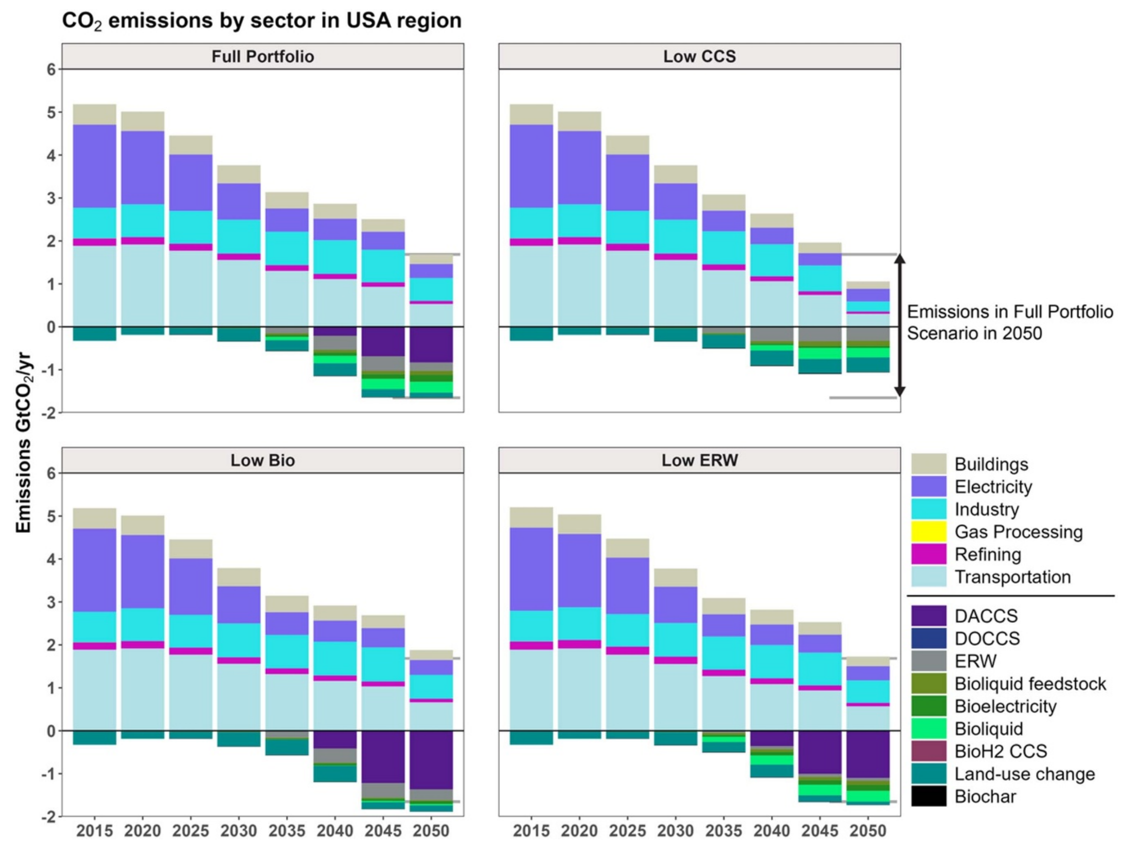

Figure 1. Positive and negative CO_2 emissions across various sectors in the U.S., analyzed under a national net-zero 2050 CO_2 emissions policy across the four different core scenarios.

mid-century positive emissions are lower and consequently the total amount of CDR needed is lower. These results highlight how closely coupled the mitigation trajectory is with the need to deploy CDR for meeting a mid-century goal. The Low Bio scenario, which constrains use of biomass resources, relies heavily on DACCS deployment as well as ERW to meet mid-century net-zero targets. The low ERW scenario is similarly reliant on DACCS but instead of ERW it relies heavily on BECCS to balance the delivery of CDR.

A look at the emissions trajectories of each state (figure 2) reveals regional variations from the national patterns seen in figure 1. The largest absolute magnitude of both emissions and CDR is concentrated in a few states. Texas and California have the highest positive emissions trajectories (figure 2(a)), although Texas has extensive capacity to offset positive emissions using a full suite of CDR technologies by 2050. In contrast, California is projected to maintain high net-positive emissions by 2050 without the same capacity to offset those emissions using CDR. A second tier of states (figure 2(b)) with high gross emissions is plotted next, including Pennsylvania, Louisiana, Ohio, Illinois, Florida, Indiana, Michigan, and New York. While these states have high gross emissions their net emissions in 2050 vary somewhat depending on the availability of cost-effective CDR options. The high positive emissions in these states come from either their large populations or concentration of refining/manufacturing capacity, which can be observed by looking at the sector colors in the positive emissions. The remaining states are plotted as a group in figure 2(c).

The capacity of states to contribute to the national net-zero emission goal varies widely, influenced by the states' economic structure and available resources, such as arable land and geologic carbon storage reservoir capacity. GCAM-USA accounts for 326 distinct geological storage formations across the U.S. figure S.1 depicts the state-level CO_2 storage capacity, extracted from GCAM-USA core model. While some states may continue to emit more than they can offset by mid-century, particularly western and eastern states, the others have the potential to become net-negative due to their low positive emissions and high capacity for deploying CDR technologies. Agriculturally intensive states, like those in the mid-western U.S., deploy large quantities of BECCS, as expected. All the states that have geological storage capacity, which is unevenly distributed across the states, deploy appreciable amounts of DACCS.

Under the Full Portfolio scenario, the U.S. removes 1.65 $GtCO_2$/yr in 2050. This CO_2 removal estimate is lower than the estimates reported in Fauvel *et al* (2023) where more than 2 $GtCO_2$/yr of carbon removal are needed in 2050. When a larger suite of CDR methods is available under the decarbonization pathway

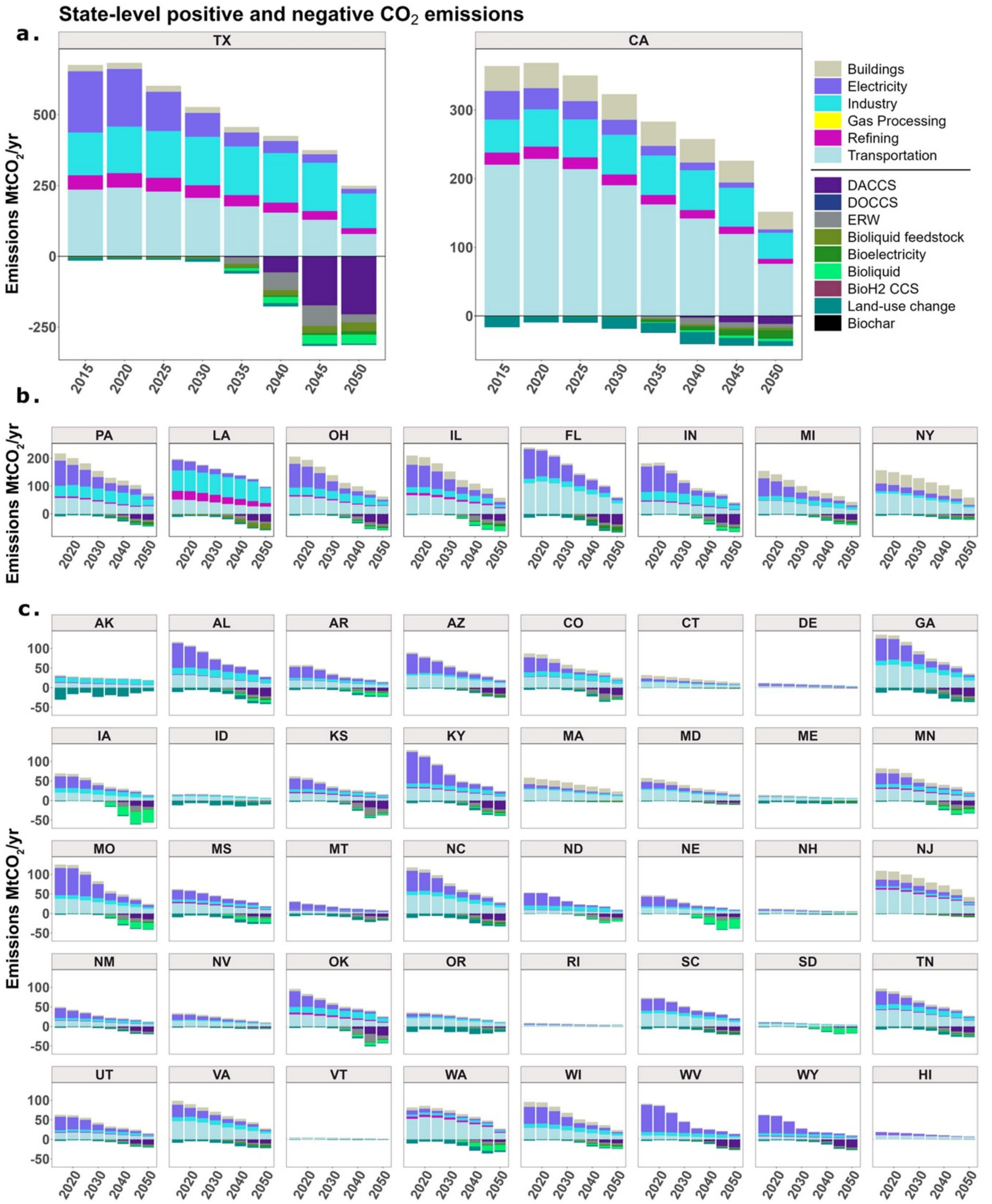

Figure 2. U.S. state-level positive and negative CO_2 emissions across various sectors under the Full Portfolio scenario. The figure does not include the District of Columbia (D.C.) and has different y-axis scales for the different sub-panels. Two states (a) dominate the emissions landscape (Texas and California), a second tier of states (b) is high emitting and many, but not all, have appreciable CDR potential, while the rest of the states (c) vary considerably both in the amount of positive emissions that they generate and their potential to deploy CDR.

modeled here, we also observe near term adoption of lower cost forms of CDR, such as ERW, which make the carbon removal burdens at mid-century less severe. Fauvel's modeling was predicated on significant costs reductions in BECCS and DACCS, which then translate into more significant deployment by mid-century. The CO_2 abatement cost of each CDR technology in the Full Portfolio scenario in 2050 is provided in SI.

To assess the impact of CDR deployment, reaching net-zero CO_2 emissions by 2050, and the enhanced ability to reduce residual emissions on mitigation costs in the U.S., we estimated the average policy costs across the four scenarios, which is available in the SI. The analysis highlights significant variations in the average policy cost from 2025 to 2050 as a share of 2025 GDP, across different states and scenarios, reflecting the diverse economic conditions and energy profiles. States like Wyoming and Louisiana, which have energy-intensive industries and rely heavily on fossil fuels, face greater economic difficulties in transitioning to a net-zero future, especially when key technologies like CCS are limited. In contrast, states like California, with advanced renewable energy infrastructure and lower dependence on carbon-intensive industries, experience lower transition costs. These results emphasize the need for policy approaches that are tailored to each state's unique economic and industrial characteristics to ensure equitable and effective decarbonization strategies.

We analyzed the sensitivity of CDR technological deployment in 2050 under a 30% change in biomass availability, CCS costs, land carbon pricing, slow pyrolysis costs, ERW availability, and ERW costs. The analysis revealed the significant impact of changes in biomass availability, land carbon pricing, and ERW costs on CDR technology deployment. These findings highlight the crucial role of economic and policy measures in determining the future deployment of CDR technologies, providing valuable guidance for policymakers and stakeholders in prioritizing interventions to achieve climate mitigation goals. The result of this sensitivity analysis is provided in the SI.

The deployment of CDR technologies is heavily influenced by the availability of essential resources such as croplands for biochar, crushed rock application for ERW, land and water for biomass crop cultivation, and geological formations for carbon storage. Figure 3 shows the possible impacts of CDR deployment on the energy–water–land system in 2050. The Low Bio scenario shows the highest overall final energy consumption by CDR technologies in 2050, followed by the Low ERW scenario. These two scenarios impose a higher pressure on regional energy systems that reflects the impact of large-scale deployment of DACCS technology. Notably, the impact on the central and southern states indicates a widespread adoption of CDR technologies that are energy intensive. The Low CCS and Full Portfolio scenarios have the potential to offset positive emissions with a lower influence on the states' energy system. Less dependency on CCS reduces pressure on the state's energy system, leading to overall higher deployment of ERW and other land-based form of removal. For instance, in the Low CCS scenario, CDR consumes 10.36% of total final energy in agricultural states such as Kansas where ERW removes 30 $MtCO_2$/yr in 2050. In contrast, for the same year, the highest shares of final energy consumed for CDR in the Full Portfolio and Low Bio scenarios are 33.6% and 42% in Wyoming, accounting for 0.14 and 0.22 EJ/yr, respectively. This high share of final energy consumption in Wyoming is coupled with 21 $MtCO_2$/yr and 34 $MtCO_2$/yr removal by DACCS in the Full Portfolio and the Low Bio scenarios, respectively. In the Low ERW scenario, Wyoming and West Virginia, which both have abundant energy and geologic carbon storage resources, have 0.19 and 0.18 EJ/yr of their final energy consumed by CDR, the highest share of any state for CDR.

Due to the higher deployment of BECCS in the Low ERW and Full Portfolio scenarios, the percentage of water consumption by BECCS technologies from total water consumption in the states is higher in western and eastern states. Like the Full Portfolio scenario, under the Low ERW scenario, CDR by BECCS consumes the highest share of total water consumption in Maine, amounting to 13% of total water consumption for the state by mid-century. This is mainly due to irrigation requirements for biomass crops that gets consumed by BECCS technologies. In 2050, 13.8% of water demand in Maine will be for CDR by BECCS, which accounts for 0.03 $km^3\ yr^{-1}$ water consumption in the state under the Full Portfolio scenario. Low CCS and Low Bio scenarios exhibit a reduced water footprint for BECCS, suggesting that limitations on biomass resources as well as CCS can reduce pressure on water resources.

While forest lands will grow about 9% in the U.S. by 2050 in the Full Portfolio scenario, states will experience decreasing or increasing trends of forestland areas. In this scenario, forestlands in Arizona will increase by about 13 thousand km^2; however, Louisiana will experience a 4.6 thousand km^2 reduction of areas covered by forests. A two-toned color scale was used to depict these results to capture these dynamics in the results.

In the Full Portfolio and Low ERW scenarios, while biomass croplands expand to 155.7 and 154.8 thousand km^2 in the U.S. by 2050 respectively, only up to 10% of total croplands in the western states are biomass croplands for CDR purposes. Higher shares of biomass croplands for CDR of total croplands will be in the northeastern and southern states; however, that accounts for only a total of 4.6 thousand km^2 in Maine, New Hampshire, and Rhode Island in the Full Portfolio scenario. The share of biomass croplands used for BECCS in some southern states goes up to about 20%, Florida for instance, will have the capacity to use 10.2 thousand km^2 land to grow biomass for CDR in 2050. The Low CCS and Low Bio scenarios show a smaller fraction of biomass croplands, reflecting caps on either geological storage capacities or biomass resources, respectively.

The Low CCS scenario shows a greater adoption of croplands incorporating biochar in crop cultivation practices, with higher percentages in western states, which contributes to soil enhancement and carbon

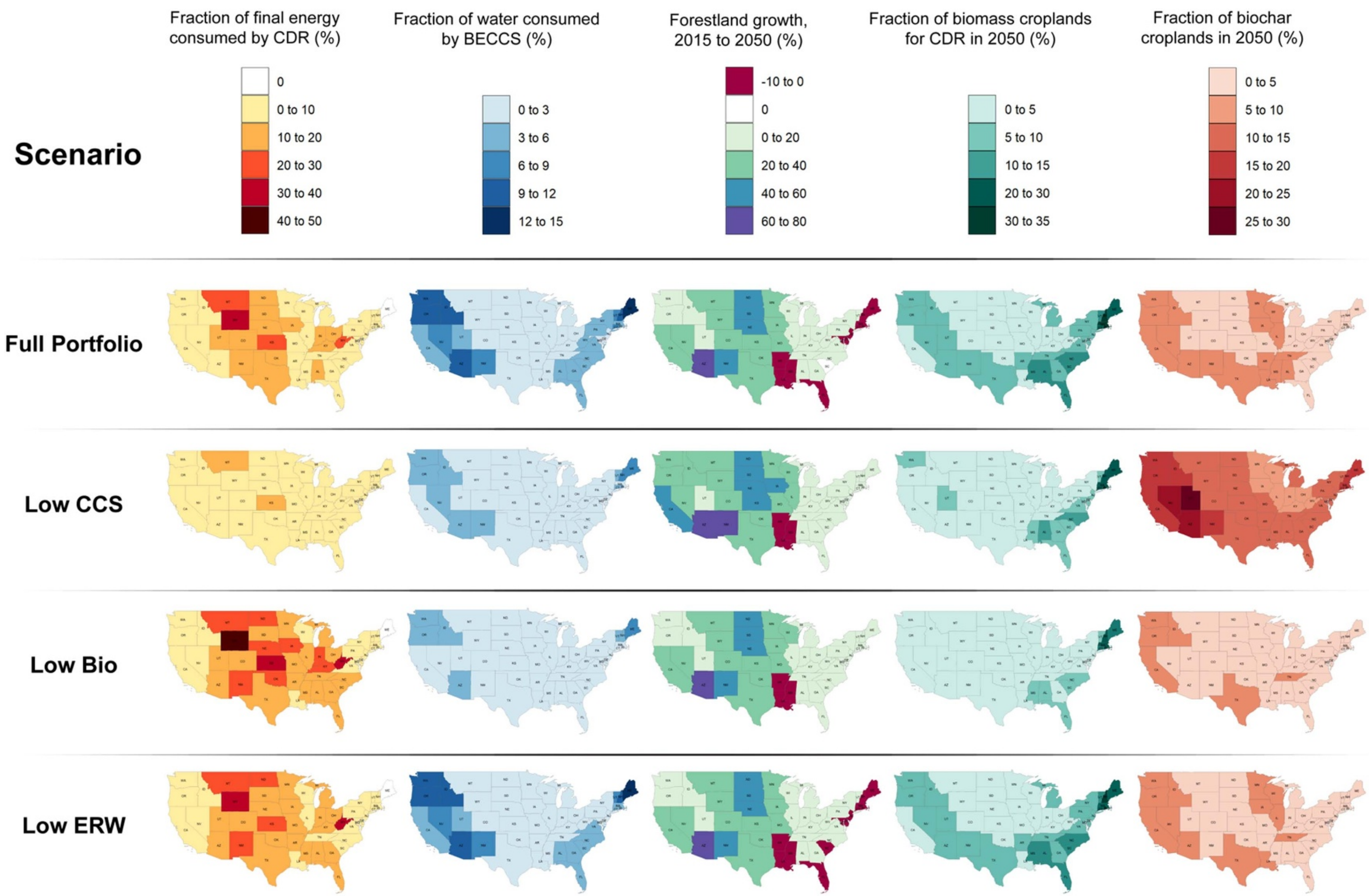

Figure 3. The impact of CDR deployment on the energy, water, forests, croplands, and biochar spreading in 2050 when the country meets a net-zero target. Notice the significant impacts and how much these impacts vary with scenarios modeled here.

storage. In the Low CCS scenario Nevada, Utah, and Arizona will apply biochar on 1.05, 0.46, and 1.35 thousand km^2 of croplands, respectively. Other scenarios show a lower development of biochar croplands, which is due to the higher deployment of other CDR approaches such as DACCS, BECCS and ERW. CO_2 storage through soil enhancement of biochar reaches 6 and 10 $MtCO_2$/yr by 2050 in the Full Portfolio and Low CCS scenarios, which would require 5% and 12% of agricultural lands in the U.S. in 2050, respectively. The possible impact of ERW deployment on the cropland areas in 2050 is provided in the SI.

4. Conclusions

This analysis provides insights on the regional dynamics of CDR adoption across the U.S. in support of a national net zero by mid-century target. This study is the first to integrate three CDR technologies-biochar, ERW, and DOCCS-into the GCAM-USA model, which enabled us to examine the interplay between CDR and its potential cumulative impact on regional resources including energy, water, and land. Our analysis reveals the potential disparate distribution of CDR technology deployment across states, underscored by the resource demands and economic characteristics that shape CDR deployment.

Our modeling results reveal a consistent trajectory towards U.S. economy-wide decarbonization over the upcoming decades, paired with an increase in CDR deployment, which could amount to between 1 and 1.9 $GtCO_2$/yr of gross negative emissions by 2050. This progression is evident across the examined scenarios, with variations in the scale and type of CDR deployed, highly sensitive to specific scenario assumptions. Notably, land-intensive CDR methods are prioritized and implemented at larger scales in the initial stages, before energy- and material-intensive strategies. In particular, the Full Portfolio scenario demonstrates that DACCS accounts for approximately 50.2% of the total CO_2 removal in the U.S., followed by a diverse mix of other technologies such as BECCS, ERW, afforestation and reforestation, and others. Our findings highlight the importance of regional resources on CDR adoption.

We demonstrate that the implementation of CDR technologies across states will depend on the availability of key resources, including land for biomass crop cultivation, biochar application, and geological sites for carbon storage. The projected impact on the energy–water–land system by 2050 suggests substantial variation across scenarios, with implications for state-level policymaking. The Low Bio and Low ERW scenarios, characterized by the largest increase in final energy consumption by CDR technologies, highlights the substantial energy requirements of large-scale DACCS deployment. These scenarios place considerable stress on the energy systems of the central and southern states, indicating a need for policy frameworks that can accommodate the energy demands of widespread CDR technology adoption. Conversely, the Low CCS and Full Portfolio scenarios present opportunities to balance emissions with less strain on energy infrastructures. Water resource management also emerges as a critical policy area, particularly in water-stressed states like Arizona, where the deployment of BECCS in the Full portfolio and Low ERW scenarios could account for 10% of the state's water consumption by mid-century.

The economic advantages of offering cross-state CDR services must be carefully balanced with a variety of other factors, including impacts on the local environment and implementation costs. By considering the unique characteristics and resources of each state, we can navigate the complex interactions between CDR technologies and sectoral demands to devise a strategic path towards a net-zero future.

Data availability statement

GCAM is an open-source model available at https://github.com/JGCRI/gcam-core/releases. The specific version of GCAM, as well as additional input files along with the associated data processing scripts associated with this study are available at https://zenodo.org/records/13349718.

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