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Regional implications of carbon dioxide removal in meeting net zero targets for the United States

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Abstract

Net-zero greenhouse gas emission targets are central to current international efforts to stabilize global climate, and many of these plans rely on carbon dioxide removal (CDR) to meet mid-century goals. CDR can be performed via nature-based approaches, such as afforestation, or engineered approaches, such as direct air capture. Both will have large impacts in the regions where they are sited. We used the Global Change Analysis Model for the United States to analyze how regional resources will influence and be influenced by CDR deployment in service of United States national net-zero targets. Our modeling suggests that CDR will be deployed extensively, but unevenly, across the country. A number of US states have the resources, such as geologic carbon storage capacity and agricultural land, needed to become net exporters of negative emissions. But this will require reallocation of resources, such as natural gas and electricity, and dramatically increase water and fertilizer use in many places. Modeling these kinds of regional or sub-national impacts associated with CDR, as intrinsically uncertain as it is at this time, is critical for understanding its true potential in meeting decarbonization commitments.

1. Introduction

The United Nations framework convention on climate change uses nationally determined contributions (NDCs), which are established by governments to coordinate global efforts to limit warming over the coming decades (UNEP 2017). These NDCs are typically set using integrated assessment models (IAMs), which facilitate modeling of net-zero carbon or total greenhouse gas targets by linking the main features of society, economy, land, and climate under a consistent modeling framework (Meinshausen *et al* 2022). Current IAM results regularly show the need for deep reductions in emissions in the near term along with large-scale carbon dioxide removal (CDR) to manage recalcitrant and legacy emissions in order to limit warming to 1.5 °C (Fuss *et al* 2018, Minx *et al* 2018). While CDR is a compelling idea, the negative emissions technologies (NETs) needed to deliver CDR have yet to be demonstrated anywhere near the scales that the IAM results suggest will be needed in the coming decades (Fuhrman *et al* 2019). This raises important questions about the actual viability of the proposed limits on warming. (Anderson and Peters 2016)

In the United States, for example, the most-recent NDC seeks to reduce economy wide greenhouse gas emissions by 50%–52% below the 2005 baseline by 2030 (Ou *et al* 2021). Over the coming few years, most of that decarbonization activity will come from retiring coal-fired power generation, building renewable energy capacity and electrifying passenger transport (Horowitz *et al* 2022). IAM results suggest that CDR will be most important beyond 2030, and consequently several recent US legislative initiatives are designed to support demonstration and investment in NETs (Anon 2022, Office of Fossil Energy and Carbon Management Department of Energy 2023). But these approaches, when deployed at climatically-relevant scales of hundreds- to thousands-of-million metric tons of CO_2 per year will have substantial, and as yet poorly understood, impacts on regional food, energy, and water systems of the communities that will host them (Griscom *et al* 2017, Fuhrman *et al* 2020).

There are two main classes of terrestrial NETs that will have different impacts on local communities: land-based processes that increase carbon densities in the biosphere and deep-subsurface processes that store CO_2 in geologic formations. Land-based NETs include afforestation and reforestation (Roe *et al* 2019), soil carbon sequestration (Bellassen *et al* 2022), biochar (Lehmann *et al* 2021), and enhanced weathering (Beerling *et al* 2020). Many of these are low cost, but they could result in carbon removal that is less permanent, if for example, land uses change (LUC) or fires release sequestered CO_2 (Holz *et al* 2018). Land-based sequestration is also subject to constraints on the availability of arable land and to increasing competition from other land uses (NASEM 2019). Moreover, not all regions have the biophysical resources needed to deploy forest management improvements, reforestation and afforestation to contribute CDR (Domke *et al* 2020). Walker *et al* recently published an upper bound on terrestrial carbon storage which assesses its capacity without considering the range of competing approaches that could impact ultimate deployment (Walker *et al* 2022). Consistent with other papers focused on so-called nature-based climate solutions, they conclude that these approaches could contribute to but are insufficient for achieving our decarbonization goals (Dooley *et al* 2022).

In contrast, a second broad class of approaches relies on removing CO_2 from the atmosphere and injecting it into porous rock formations in the subsurface for permanent storage. These approaches are broadly considered to be unconstrained since the aggregate storage capacity is very large, if unevenly distributed by region (Middleton *et al* 2020). One such form of CDR involves direct air carbon capture and sequestration (DACCS), in which chemical solvents or sorbents are used to concentrate CO_2 out of ambient air (Realmonte *et al* 2019). This technology is thermodynamically challenging and economically prohibitive at present even though several pilot plants are being built (Keith *et al* 2018). Ocean-based NETs are of growing interest to the scientific community but are less technologically mature than some forms of terrestrial NETs (National Academies of Sciences, Engineering, and Medicine 2022).

Bioenergy with carbon capture and sequestration (BECCS) has elements of both land- and subsurface-based CDR (Bennett *et al* 2021). The premise is that biomass can be grown and then converted into electricity or liquid fuels, with some fraction of the biogenic carbon captured and disposed of in the deep subsurface (Butnar *et al* 2019). When deployed at scale, BECCS would compete with other food and fiber crops and put pressure on water and fertilizer systems (Baik *et al* 2018). In contrast, DACCS would require very little land but much more energy (Fuhrman *et al* 2021). The full environmental and economic cost of these technologies is coming into focus but is still uncertain given the low technology readiness level of many of these approaches (Nemet *et al* 2018).

Given this uncertainty, IAMs have included only a limited number of NETs, even though the role of CDR is large in almost all simulations that meet net-zero greenhouse gas emissions and Paris Agreement climate targets (IPCC 2018). Those IAMs that have included CDR have generally not considered the broader set of consequences these approaches would entail, especially at sub-national scales. Strefler *et al* (2021) analyzed the comparative advantages of different CDR options given varying portfolios of available technologies and found regional CDR deployment shifts depending on the technology options available (Strefler *et al* 2021). If, for example, enhanced weathering of rocks is the only available NET, Latin America and Asia are almost solely responsible for global CDR whereas DACCS was found to be the most evenly distributed NET among regions. Fuhrman *et al* recently modeled a full suite of CDR approaches and found significant heterogeneity in where and at what levels CDR is deployed around the globe (2023).

A growing number of studies have begun to explore the role that individual nations can play in delivering carbon removal and the concomitant impacts. Förester *et al* recently produced a framework for assessing the feasibility of CDR in Germany that considers the range of environmental, technical, economic, social, institutional and systemic impacts of CDR deployment (Förster *et al* 2022). Recognizing that regional specialization and global goal-setting could lead to leakage, Franks *et al* developed a pricing scheme for carbon removal assuming inter-regional leakage (Franks *et al* 2023). Other studies have begun to quantify the environmental benefits of carbon removal, such as the recent work by Yang intended to understand how haze pollution might be reduced once emissions are traded (Yang *et al* 2022).

In countries such as the United States, with relatively decentralized governance, subnational jurisdictions will play a key role in determining regional responses to achieving net-zero emissions (Larson *et al* 2022). However, IAMs have traditionally placed less emphasis on the role that sub-national governments are likely to have in determining climate futures, and so most exploration of NETs deployment to date has been at the global or national scale (Peng *et al* 2021). At least one study has simulated a state-specific plan for participation in a decentralized climate policy regime in the US, but little is known about the total impact of having all 50 states follow a similar process (Baker *et al* 2020). Peng *et al* found that allowing states to set their own pathways to net zero increased the overall system costs considerably. Even in the absence of variation in local policy, differences in resource endowments will lead to differentiation in the comparative advantage of implementing different types of CDR in a given jurisdiction. Larson *et al* provide granular spatial and temporal resolution of the energy and industry infrastructure changes needed for the US to reach net-zero greenhouse emissions by 2050 (2022). Their study focuses on mitigation technologies with some consideration of the land-use effects of these deployments, but the authors do not explicitly address negative emissions capacity across states. Several studies have examined how US states could individually achieve net-zero emissions (Baker *et al* 2020). Baik *et al* conducted geospatial analysis of BECCS in the United States, particularly the colocation of suitable CO_2 storage basins and biomass availability, to highlight the near-term deployment opportunities for BECCS specialization within certain states but does not consider BECCS deployment within the larger context of decarbonization and CDR deployment pathways (2018).

This study fills a gap in the current literature by addressing the distribution of NETs in different US states under conditions where the states collectively achieve a mid-century, net-zero emissions national goal. We explore how the variation in regional resources influences where different NETs are likely to be deployed and how those deployments contrast with present day and projected positive emissions. Our hypothesis is that regions will differ greatly in the extent to which carbon removal is deployed based on regional costs of the resources that underpin these approaches. To test this hypothesis, we added DACCS to the Global Change Analysis Model for the United States (GCAM-USA), which already included afforestation and BECCS. This set of carbon removal approaches was not meant to be exhaustive but rather to capture a representative cross section of approaches representing natural (afforestation), engineered (DACCS) and hybrid (BECCS) approaches. This enabled us to explore the multi-sector dynamics and better understand how these technologies would be implemented across the 50 US states.

2. Methods

The GCAM is an open-source, global IAM available at https://github.com/JGCRI/gcam-core (JGCRI 2022). GCAM represents the behavior of, and interactions between, the energy, water, land, economy, and climate systems for 32 geopolitical regions globally. GCAM is a market equilibrium model, solving for a set of prices that ensure supply equals demand among all markets from 1990 to 2100 in five-year time steps. GCAM-USA is an extension of the global model that further breaks down the United States region into state-level resolution (including the District of Columbia). In this study, we ran GCAM-USA on the University of Virginia's high-performance computing cluster, Rivanna.

2.1. NETs

GCAM-USA features BECCS and land-use change pathways for negative emissions, and for this study we added the capability to model DACCS at the state level, building upon the treatment of DACCS in the global version of the model (Fuhrman *et al* 2020).

2.2. DACCS

DACCS requires energy inputs in the form of either natural gas or electricity (Keith *et al* 2018). Other inputs include capital and non-energy operations and maintenance which are aggregated into a levelized non-energy cost term in GCAM. There is considerable uncertainty regarding the future energy intensity and total cost of DACCS once it is implemented on a commercial scale (McQueen *et al* 2021). Our assumptions for the cost of DACCS in GCAM-USA follow those of the 'middle of the road' scenario from Fuhrman *et al* (2021) and are applied to each of the 50 states + the District of Columbia as described in the supporting information (Fuhrman *et al* 2020). The costs of energy, as well as geologic carbon storage, are determined endogenously for each state. The cost curves for these technologies are used as developed for the core GCAM-USA model.

DACCS indirectly competes in GCAM against (a) emissions abatement; and (b) other NETs such as BECCS and land-use change, based on its cost and the subsidy paid for CO_2 removal (that is, the carbon price). DACCS technologies begin to be deployed when the carbon price exceeds their levelized energy and non-energy costs. DACCS functions effectively as a backstop technology, which sets an upper limit on the carbon price. DACCS deployment is limited in each of GCAM's 32 global regions as described previously (McFadden 1973, Train 2009, Fuhrman *et al* 2020). At extremely high carbon prices, this sum sets a ceiling on the amount of DACCS that can take place in any given region. This ceiling on DACCS deployment was apportioned based on each region's cumulative amount of onshore carbon storage relative to the global total (Fuhrman 2020).

To allow exploration of the sub-national implications of DACCS, we extended this approach, to enable modeling of state-level DACCS deployment in GCAM-USA (Fuhrman *et al* 2021). Here, we used each state's share of U.S. total cumulative onshore carbon storage capacity to proportionally allocate the defined maximum possible total DACCS deployment for the United States from 32-region global version of GCAM (set at 2 GtC per year or 7.3 $GtCO_2$ per year) among the states. This methodology assumes that new DACCS plants are most likely to be sited in states with abundant suitable geologic storage, minimizing the need for CO_2 transportation infrastructure from point of capture to injection sites.

2.3. Land-use change

GCAM tracks carbon flows to and from the atmosphere resulting from land-use change (for example, from forest or grassland, to cropland). Under a carbon price, GCAM imposes a cost penalty for land-use change emissions, and conversely, receive a subsidy for land-use carbon sequestration (for example, expanding forested land area). While emissions from fossil fuels can, in principle, be priced at the point of extraction or combustion, emissions from land-use change and agriculture occur without regulatory frameworks or mature markets in place today. There will need to be a carbon pricing infrastructure in place to account for biospheric carbon emissions and sequestration from land-use change. The carbon price set by GCAM applies to all carbon flows in the human-earth system, but this does not reflect the current lack of governance infrastructure for pricing land-use carbon. Therefore, we set a separate carbon price from land-use change to be an exogenously determined fraction of the carbon price on fossil emissions, growing linearly from 0 in 2020 to 1 in 2100. A carbon price on land-use change emissions gradually approaching the fossil carbon price reflects the long-term effort required to implement land-use policy and infrastructure that will address the current barriers to land-use policy, including reversal risks of biospheric carbon storage. Sensitivity cases also consider a pricing market for land-use change maturing at a faster rate and reaching a fraction of 1 to fossil fuel carbon price by 2050.

2.4. BECCS

GCAM-USA includes BECCS technologies in the refining and electricity generation sectors, as well as biomass energy technologies which do not capture any carbon emissions from the biomass (for example, corn ethanol as it is currently produced) (Abotalib *et al* 2016). The parameterization of all biomass energy technologies including those for BECCS is based upon previously published GCAM studies (Wise *et al* 2009, 2014, Muratori *et al* 2017). In GCAM, land area for biomass competes with other land uses including other cropland and natural lands. GCAM endogenously solves for the amount of irrigation water (as opposed to rainfed crops), as well as fertilizer use for biomass and all other agricultural commodities in each major river basin, taking into account the yield effects of both irrigation and fertilizer, as well as any land-use emissions tax or carbon storage subsidies.

2.5. Emissions constraint

We imposed emissions constraints for the world and the United States to decline linearly from historical emission levels of 35.6 $GtCO_2$ and 5.1 $GtCO_2$ in 2015, respectively, to net-zero CO_2 emissions by 2050. GCAM endogenously calculates the carbon price required to reach the emissions constraint at each model period. This carbon price along with GCAM's market equilibrium structure determines the market share of each technology in each sector that satisfies the demand.

2.6. Carbon accounting

GCAM treats consumption of biofuels as carbon-neutral unless the CO_2 emissions are sequestered, with endogenous treatment of land-use emissions and non-CO_2 GHG emissions associated with biomass production. The model tracks bio-derived carbon through the global economy and reports temporary carbon uptake in biomass through photosynthesis, which can then be re-emitted to the atmosphere when combusted, or it can be stored in long-lived industrial products or geologic reservoirs. Only the latter two cases represent negative emissions. We processed our model output to disaggregate bio-derived carbon emissions and storage at the state level plus a residual that represents temporary carbon storage in bio-derived liquid fuels such as ethanol and biodiesel. Although this does not represent true CDR, this method enables accounting for conventional biofuels which are not linked to geologic storage. Currently, this is by far the dominant form of biofuels in the U.S. and globally.

2.7. Summary of scenario cases

Initial analysis revealed that model results are sensitive to land-use change emissions and geologic carbon storage costs, both of which are defined exogenously. Previous studies have performed hindcasting of GCAM results and more formal sensitivity analysis (Calvin *et al* 2017, Lamontagne *et al* 2018). We performed a sensitivity analysis consisting of a 2×2 scenario matrix, in which we permuted both the fraction of the fossil emissions price at which land-use carbon emissions or storage was priced, as well as geologic carbon storage costs. More details and results from this sensitivity analysis are available in the supplementary information.

3. Results

Our results suggest that, to achieve net-zero CO_2 emissions by mid-century, the United States will need to grow a CDR industry that can deliver between 1.4–2.3 $GtCO_2$ per year by 2050. Considering this CDR together with actions that mitigate current

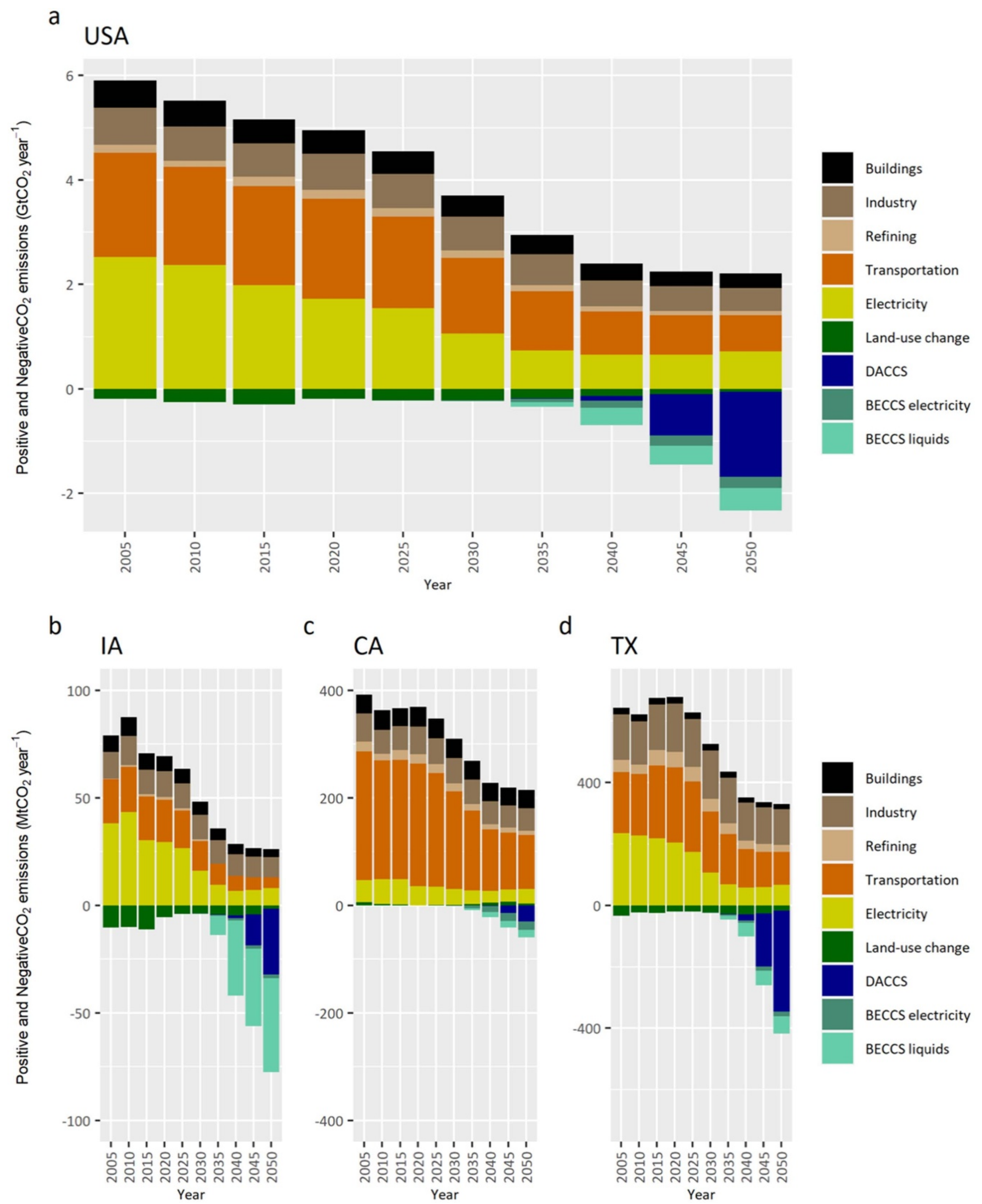

Figure 1. Sector emissions breakdown for the United States under a national 2050 net-zero carbon dioxide emissions scenario: United States (a), Iowa (b), California (c), and Texas (d). Note the different axis scales for each state.

positive emissions provides insights about regional differentiation in the use of NETs for achieving a national net-zero target. Figure 1(a) shows a trajectory for decarbonization of the entire United States with sector-based breakdowns of positive and negative emissions. These results indicate that rapid near-term emissions mitigation will slow as more recalcitrant emissions are offset by CDR in 2035 and beyond. Most of this CDR comes from direct air capture with somewhat less coming from bioenergy with carbon capture.

These pathways look very different when considered at the state level. Figures 1(b)–(d) present decarbonization trajectories for three states: Iowa, California, and Texas. These states represent three contrasting economic structures that are useful for understanding how regional resources impact CDR deployment. Noting differences in the y-axes between these three plots, Iowa has relatively low positive emissions today as well as high capacity to deploy CDR such that, by mid-century, it has the potential to be net-negative. In contrast, California and Texas will continue to have high positive emissions in 2050 from the building, industrial and transportation sectors. Even though California is expected to cut its emissions rapidly over the coming

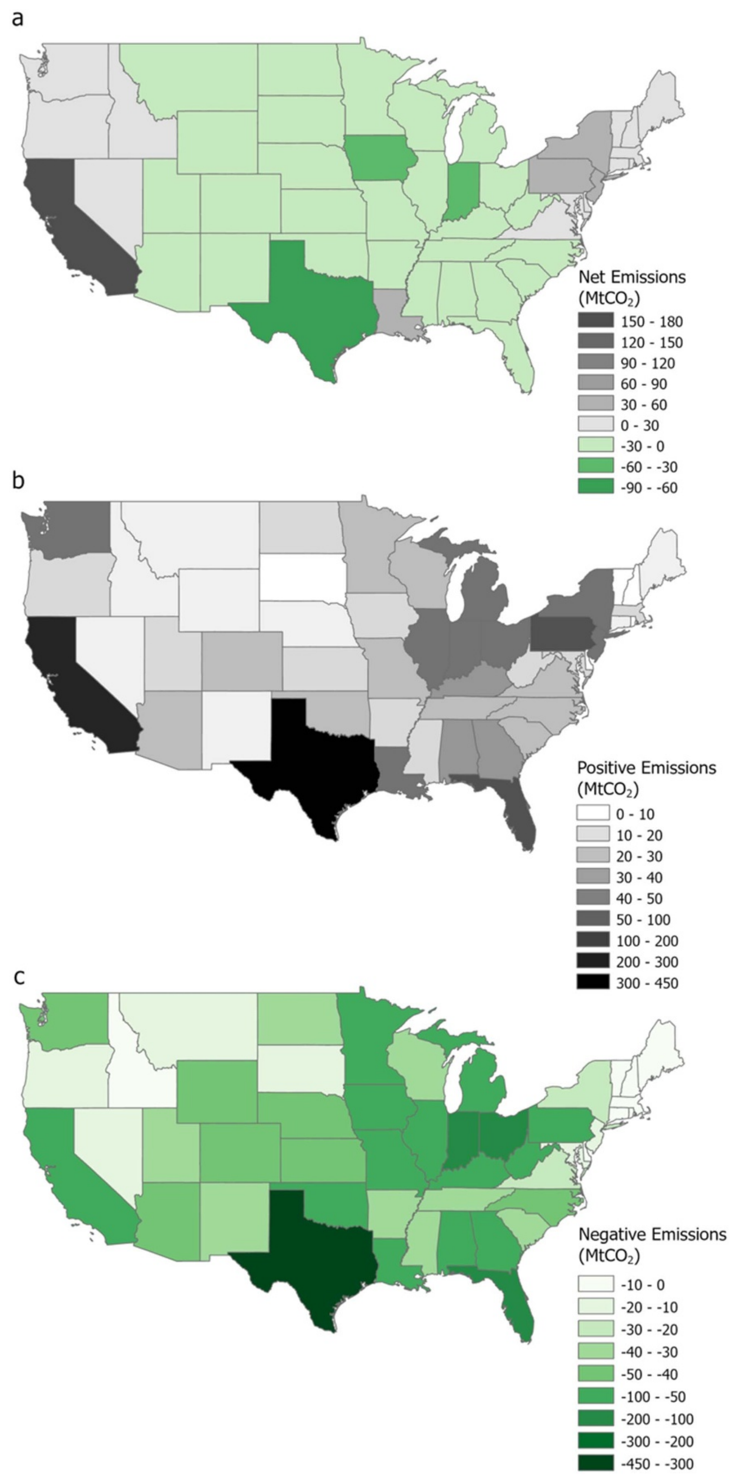

Figure 2. State-by-state emissions in 2050 under a national net-zero carbon dioxide emissions scenario: net (a), gross positive (b), and gross negative (c). NETs include BECCS, DACCS, and land-use change.

decades, California's transportation sector still makes up 46% of their positive emissions compared to a United States' total of 30% in 2050. Similarly, Texas is expected to reduce their gross positive emissions by almost one half between 2005 and 2050. California's overall negative emissions capacity is not enough to offset its own positive emissions, making it a net-positive emitting state in 2050. In contrast, Texas has a high negative emissions capacity, which could offset its high positive emissions to achieve net-zero.

The contributions of states to achieve the national US net-zero target varies considerably across the 50 states because of both existing resources, such as arable land availability and geologic carbon storage, and because some states have residual positive emissions that will be difficult to offset. As seen in figure 2, some states will continue to be net positive

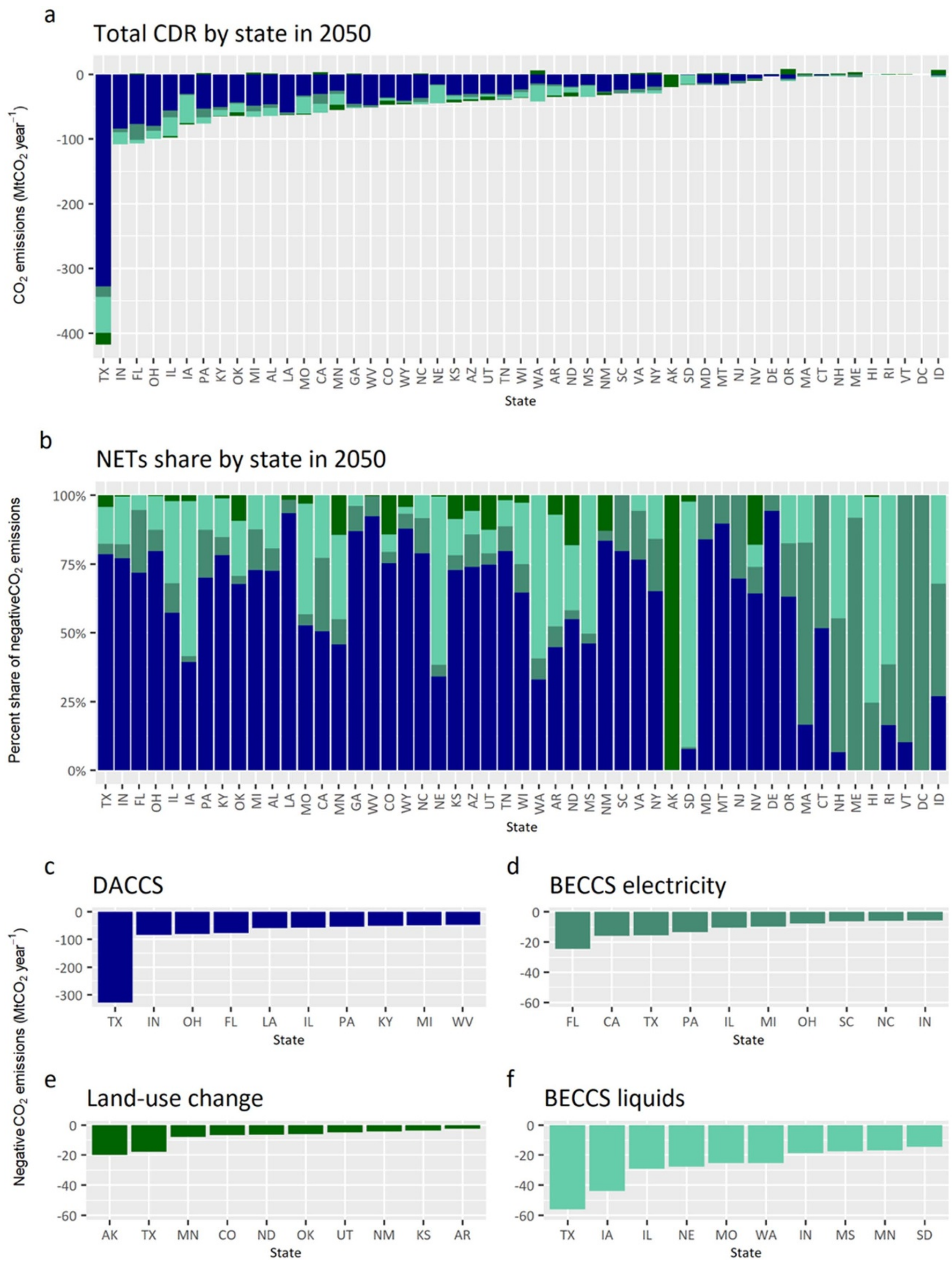

Figure 3. CDR by state in 2050. (a). Total CDR shown for all 50 states and the District of Columbia, (b). Share of each NET in each state, (c)–(f). Leading states in CDR capacity for DACCS (c), BECCS electricity (d), land-use change (e), and BECCS liquids (f).

by mid-century, while others will have excess negative emissions capacity. California and Texas have the highest positive emissions in 2050 as shown in figure 2(b), but California has only a modest potential to offset those emissions, while Texas, as well as many Midwest states, have a large potential for CDR deployment (figure 2(c)). Many states, particularly agricultural states in the Midwest have the potential to be net negative. These states have relatively low net positive emissions and high land available to deploy negative emissions such as large-scale BECCS. These results suggest that many states will not need to achieve net-zero independently for the nation to reach net zero as whole.

Figure 3 provides a state-by-state breakdown of NETs types and deployment quantity. Our results suggest that Texas will be the largest contributor of negative emissions because of its large area and geology that make it extremely favorable for carbon capture and storage (NETL 2015). CCS underpins both DACCS and BECCS and Texas has about 13% of all estimated underground CO_2 storage capacity in

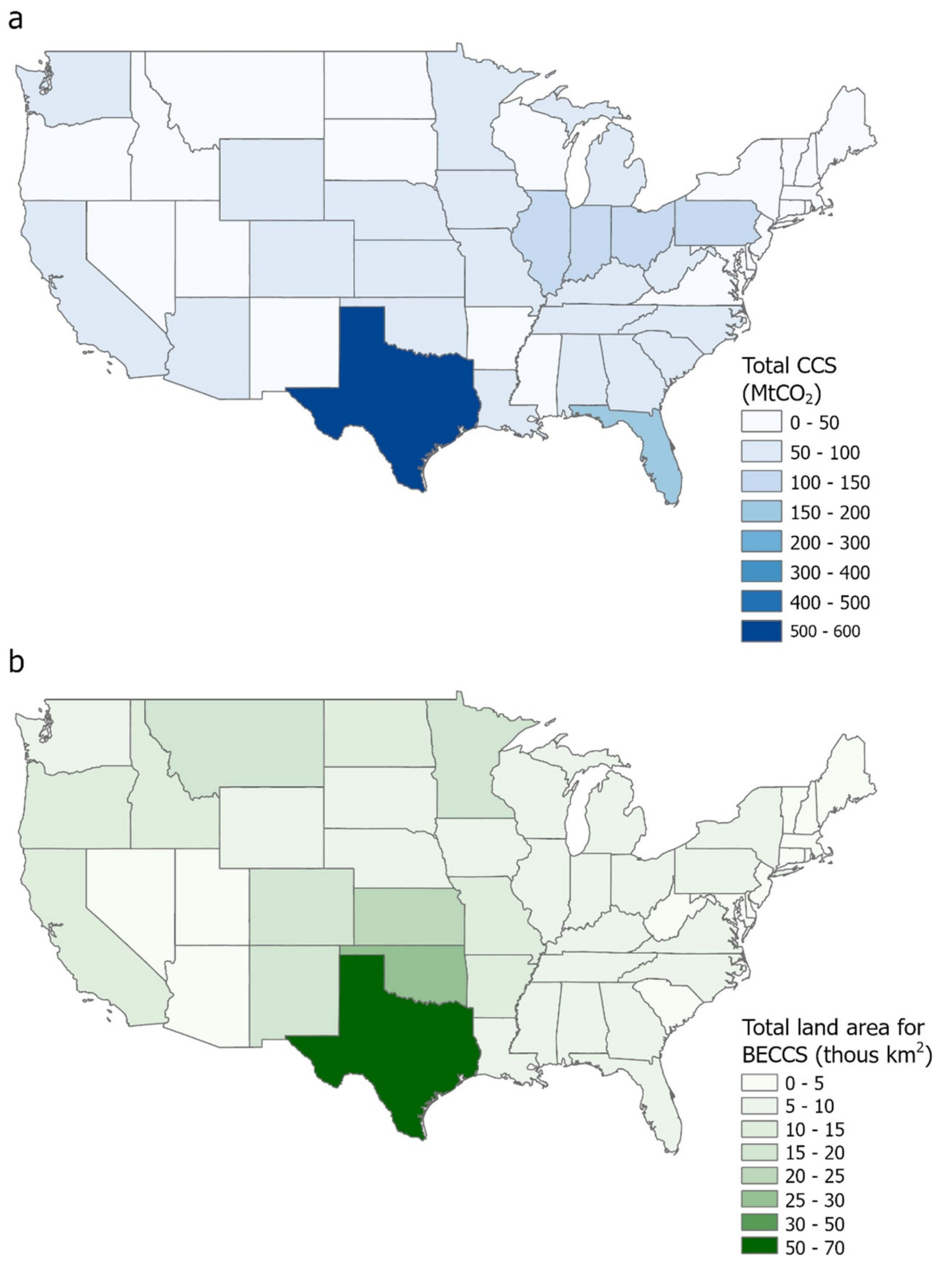

Figure 4. (a) Total state-level carbon captured and stored geologically in 2050 (fossil fuel CCS, BECCS, DACCS) and (b) land area devoted to biomass in each state needed to support the bioenergy with carbon capture industry.

the United States. The next two largest DACCS contributors, Indiana and Ohio, are also the next two states with the most geological CO_2 storage capacity in the United States, 5.6% and 5.4%, respectively. We note that this result depends critically on our modeling treatment of DACCS, which assumes the maximum DACCS capacity in each state is directly proportional to that state's geologic storage amount.

DACCS was found to be the most widely deployed form of CDR across all states, constituting 68% of the carbon removal potential on average. The absolute quantity of this carbon removal potential is largest in Texas, where our results suggest that 328 $MtCO_2$ of carbon will be removed per year by 2050. This is an enormous amount of negative emissions to be coming from one technology alone. It is equivalent in magnitude, but opposite in sign, to all the positive emissions generated by the state of California today. In effect, these results suggest that meeting our national decarbonization goals will create enormous

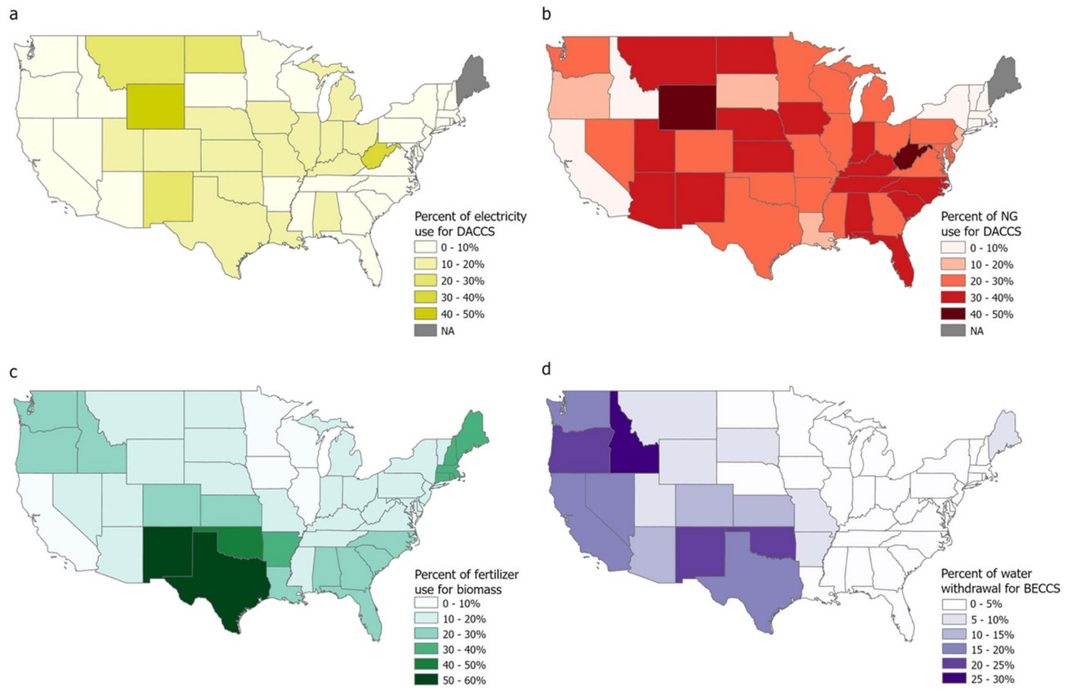

Figure 5. The deployment of NETs at scale will increase demand for (a) electricity; (b) natural gas; (c) fertilizer, and (d) freshwater withdrawals.

market opportunities. In Texas, that activity will generate new industry that will remove carbon on the scale of the entire California energy economy today in order to meet US national decarbonization goals.

While DACCS is the most widely deployed form of CDR, BECCS is also a large source of carbon removal in 2050 (figure 3(b)). The median share across states' NET portfolios is 9% for BECCS electricity and 13% for BECCS liquids (that is, ethanol and Fischer–Tropsch biofuels refining processes with CCS). Texas deploys significant amounts of BECCS liquids because of the abundant agricultural land and geologic storage capacity. After Texas, BECCS liquids deployment is primarily concentrated in the Midwest states, where large amounts of land are dedicated to crop growth for bio-refining. Land-use change contributes a median of just 0.2% of negative emissions across states, with land-use change even contributing to positive emissions in a few states (figure 3(a)).

CDR deployment will be concentrated in certain regions based on critical resources needed to deploy NETs, namely carbon storage capacity and land. Figure 4 shows how geologic carbon storage capacity and land area are pivotal resources in identifying where CDR will be deployed at scale. Geologic carbon storage is an important constraint on CDR, and our modeling suggests that most, 2.2 $GtCO_2$ per year of the estimated 2.3 $GtCO_2$ per year (98%), negative emissions in 2050 will be sequestered in the subsurface. In our modeling scenarios, there is also a large deployment of conventional CCS from point sources, but these technologies are unlikely to compete for pore-space in subsurface geologic reservoirs (Kelemen *et al* 2019). Combined CCS, for NETs and for fossil-fuel stationary sources, reaches 3.2 $GtCO_2$ per year in 2050 (NETL 2015). As shown in figure 4(a), this CCS is concentrated in Texas, in the Midwestern states, and in Florida. In addition to geologic storage capacity, carbon removal will require land. Figure 4(b) shows that tens of thousands of square kilometers of agricultural land will need to be dedicated for planting bioenergy crops that can be used for bioenergy with carbon capture. In some states, this represents upwards of 15% of a state's land area. It is important to note that these results are partially influenced by the subset of NETs modeled here. Emerging approaches such as enhanced weathering, soil sequestration, and biochar additions do not rely on CCS storage capacity but will be proportional to land availability. These techniques could be done in conjunction with food agriculture and so some of these approaches might not compete for land in the same way.

CDR deployment at the large scales needed to meet the national net-zero GHG emissions goal will have important implications on regional energy, agricultural, and water resources. The amount of electricity that would be dedicated to DACCS expressed as a percentage of a state's total present electricity generation is shown in figure 5(a). These results differ from the CCS results insofar as some states will have a larger percentage of their electricity demand used to support CDR. Similarly, DACCS deployment could account for large proportions of natural gas final energy (i.e. excluding electricity generation) in many states, as gas-fired, solvent-based

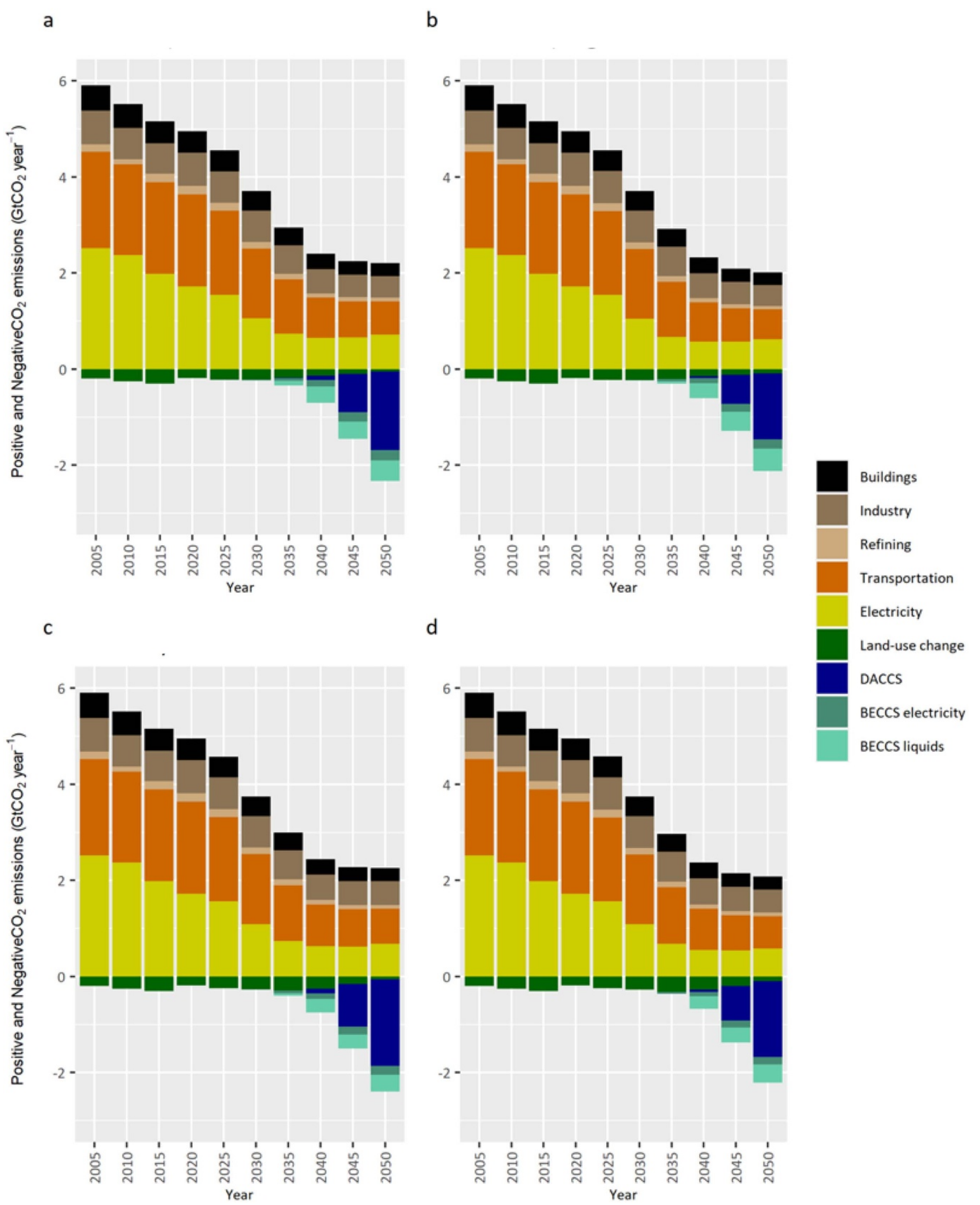

Figure 6. Sector-based net-zero trajectories for the United States under a range of scenarios including (a) low LUC + low-cost CCS (main scenario); (b) low LUC + high-cost CCS; (c) high LUC + low-cost CCS; and (d) high LUC + high-cost CCS.

DACCS is less expensive than processes using only electricity for their sorbent regeneration (figure 5(b)). The states with the most land brought into cultivation also see the most fertilizer and water consumption (figures 5(c) and (d)). These increases, which are appreciable across all these key indicators, are likely to put pressure on local communities and create regional environmental and economic tradeoffs.

To understand how sensitive our modeling results are to key parameters, we ran scenarios, where carbon pricing of LUC emissions matures more quickly and CCS costs are higher, to understand the extent to which land—intensive practices could absorb those emissions. A full description of these scenarios is presented in the SI document. These changes resulted in a mid-century decrease in CDR from 2.33 $GtCO_2$ per year to 2.13 $GtCO_2$ per year. In this scenario, DACCS remains expensive, so it is more favorable to offset positive emissions with other technologies. BECCS plays a larger role in allowing the US to achieve its net-zero targets, especially in the last decade (figure 6). With a 60% non-energy cost increase for DACCS (from \$186/tCO_2 to \$296/tCO_2), total DACCS deployment drops from 1.6 $GtCO_2$ of negative emissions in 2050–541 $MtCO_2$ with a rapid DACCS deployment in the last 5 years, compared to a more early and gradual DACCS deployment in the low-cost scenario (figures 6(a) and (c)). A NETs portfolio more heavily reliant on BECCS results in even larger acreage shifts for biomass growth than the low-cost DACCS scenario. Additional results are presented in the supporting information.

4. Conclusions

Net-zero emissions pathways often rely on CDR delivered using NETs that have yet to be deployed at scale. Meanwhile, institutional investment in carbon removal is burgeoning, and the effects of these investments on the regions where the projects will be sited is poorly understood (Fankhauser *et al* 2022). This paper demonstrates that, at the regional scale within the US, the impacts of this CDR deployment will have profound impacts on regional resources. Modeling results demonstrate that in order to meet a national net-zero goal by mid-century, NETs will need to deliver 2–3 Gt CO_2 removal each year. Our modeling suggests that this deployment will be concentrated in certain regions of the country, based largely on regional resource endowments. Some states have an opportunity to become net exporters of negative emissions under national efforts to reach net-zero emissions. The estimates presented here are based on the best technology currently available for understanding how regional differentiation could evolve over future decades where carbon removal is practiced (Carton *et al* 2020).

The regional economic benefits of exporting interstate sequestration services will need to be weighed against other considerations, such as regional environmental quality (for example, combustion of natural gas, use of fertilizer, water use) and economic tradeoffs (for example, costs on energy resources, land availability) some of which will have impacts on the equity dimensions of CDR. These potential impacts (both positive and negative) will need to be contextualized with a range of economic and political conditions that will impact the deployment of CDR technology. There are also a range of important biophysical dynamics that integrated models do not take into account including ecosystem service or climate damages, which would affect the results of our projections (Jägermeyr *et al* 2021). Nevertheless, this study puts much-needed focus on the regional resource dynamics that CDR deployment at scale is likely to create. A better understanding of the costs, benefits, and tradeoffs will be vital for assessing the viability of national plans for decarbonizing the US economy using negative emissions and could have relevance to sub-national variations within other countries or regional variations across coordinated national efforts.

Data availability statement

GCAM is an open-source integrated assessment model available at https://github.com/JGCRI/gcam-core (version 5.2). Additional scenario inputs are summarized in the supplementary information. The full set of input files, source code, and scripts used to generate the figures are available at the following github repository: https://github.com/chloe-fauvel/state_cdr.

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References

Abotalib M, Zhao F and Clarens A 2016 Deployment of a geographical information system life cycle assessment integrated framework for exploring the opportunities and challenges of enhanced oil recovery using industrial CO_2 supply in the United States *ACS Sustain. Chem. Eng.* **4** 4743–51

Anderson K and Peters G 2016 The trouble with negative emissions *Science* **354** 182–4

Anon 2022 26 U.S. Code § 45Q—Credit for carbon oxide sequestration U.S. Code, US Law (LII/Legal Information

Institute) (available at: www.law.cornell.edu/uscode/text/26/45Q)

Baik E, Sanchez D L, Turner P A, Mach K J, Field C B and Benson S M 2018 Geospatial analysis of near-term potential for carbon-negative bioenergy in the United States *Proc. Natl Acad. Sci. USA* **115** 3290–5

Baker S E, Stolaroff J K, Peridas G, Pang S H, Goldstein H M, Lucci F R, Li W, Slessarev E W, Pett-Ridge J and Ryerson F J 2020 *Getting to Neutral: Options for Negative Carbon Emissions in California* (Lawrence Livermore National Lab. (LLNL))

Beerling D J *et al* 2020 Potential for large-scale CO_2 removal via enhanced rock weathering with croplands *Nature* **583** 242–8

Bellassen V, Angers D, Kowalczewski T and Olesen A 2022 Soil carbon is the blind spot of European national GHG inventories *Nat. Clim. Change* **12** 324–31

Bennett J A, Abotalib M, Zhao F and Clarens A F 2021 Life cycle meta-analysis of carbon capture pathways in power plants: implications for bioenergy with carbon capture and storage *Int. J. Greenh. Gas Control.* **111** 103468

Butnar I, Li P-H, Strachan N, Pereira J P and Gambhir A 2019 A deep dive into the modelling assumptions for biomass with carbon capture and storage (BECCS): a transparency exercise., *Environ. Res. Lett.* **15** 084008

Calvin K, Wise M, Kyle P, Clarke L and Edmonds J 2017 A hindcast experiment using the GCAM 3.0 agriculture and land-use module *Clim. Change Econ.* **8** 1750005

Carton W, Asiyanbi A, Beck S, Buck H J and Lund J F 2020 Negative emissions and the long history of carbon removal *WIREs Clim. Change* **11** e671

Domke G M, Oswalt S N, Walters B F and Morin R S 2020 Tree planting has the potential to increase carbon sequestration capacity of forests in the United States *Proc. Natl Acad. Sci.* **117** 24649–51

Dooley K, Nicholls Z and Meinshausen M 2022 Carbon removals from nature restoration are no substitute for steep emission reductions *One Earth* **5** 812–24

Fankhauser S *et al* 2022 The meaning of net zero and how to get it right *Nat. Clim. Change* **12** 15–21

Förster J *et al* 2022 Framework for assessing the feasibility of carbon dioxide removal options within the national context of Germany *Front. Clim.* **4** 758628

Franks M, Kalkuhl M and Lessmann K 2023 Optimal pricing for carbon dioxide removal under inter-regional leakage *J. Environ. Econ. Manage.* **117** 102769

Fuhrman J 2020 Replication data for "Food energy water tradeoffs of negative emissions technologies in a + 1.5C future" *Nat. Clim. Chang.* **10** 920–7

Fuhrman J, Bergero C, Weber M, Monteith S, Wang F M, Clarens A F, Doney S C, Shobe W and McJeon H 2023 Diverse carbon dioxide removal approaches could reduce impacts on the energy–water–land system *Nat. Clim. Change* **13** 341–50

Fuhrman J, Clarens A, Calvin K, Doney S C, Edmonds J A, O'Rourke P, Patel P, Pradhan S, Shobe W and McJeon H 2021 The role of direct air capture and negative emissions technologies in the shared socioeconomic pathways towards 1.5 °C and 2 °C futures *Environ. Res. Lett.* **16** 114012

Fuhrman J, McJeon H, Doney S C, Shobe W and Clarens A F 2019 From zero to hero?: why integrated assessment modeling of negative emissions technologies is hard and how we can do better *Front. Clim.* **1** 11

Fuhrman J, McJeon H, Patel P, Doney S C, Shobe W M and Clarens A F 2020 Food–energy–water implications of negative emissions technologies in a +1.5 °C future *Nat. Clim. Change* **10** 920–7

Fuss S *et al* 2018 Negative emissions—part 2: costs, potentials and side effects *Environ. Res. Lett.* **13** 063002

Griscom B W *et al* 2017 Natural climate solutions *Proc. Natl Acad. Sci.* **114** 11645–50

Holz C, Siegel L S, Johnston E, Jones A P and Sterman J 2018 Ratcheting ambition to limit warming to 1.5 °C–trade-offs between emission reductions and carbon dioxide removal *Environ. Res. Lett.* **13** 064028

Horowitz R, Binsted M, Browning M, Fawcett A, Henly C, Hultman N, McFarland J and McJeon H 2022 The energy system transformation needed to achieve the US long-term strategy *Joule* **6** 1357–62

IPCC 2018 IPCC special report on the impacts of global warming of 1.5 °C—Summary for policy makers

Jägermeyr J *et al* 2021 Climate impacts on global agriculture emerge earlier in new generation of climate and crop models *Nat. Food* **2** 873–85

JGCRI 2022 GCAM v5.4 documentation (available at: http://jgcri.github.io/gcam-doc/)

Keith D W, Holmes G, Angelo D S and Heidel K 2018 A process for capturing CO2 from the atmosphere *Joule* **2** 1573–94

Kelemen P, Benson S M, Pilorgé H, Psarras P and Wilcox J 2019 An overview of the status and challenges of CO_2 storage in minerals and geological formations *Front. Clim.* **1** 9

Lamontagne J R, Reed P M, Link R, Calvin K V, Clarke L E and Edmonds J A 2018 Large ensemble analytic framework for consequence-driven discovery of climate change scenarios *Earth's Future* **6** 488–504

Larson E *et al* 2022 *Net-Zero America: Potential Pathways, Infrastructure, and Impacts* (Princeton University) p 77 (available at: https://netzeroamerica.princeton.edu/img/Princeton NZA FINAL REPORT SUMMARY (29Oct2021).pdf)

Lehmann J, Cowie A, Masiello C A, Kammann C, Woolf D, Amonette J E, Cayuela M L, Camps-Arbestain M and Whitman T 2021 Biochar in climate change mitigation *Nat. Geosci.* **14** 883–92

McFadden D 1973 Conditional logit analysis of qualitative choice behavior *Frontiers in Econometrics* ed P Zarembka

McQueen N, Gomes K V, McCormick C, Blumanthal K, Pisciotta M and Wilcox J 2021 A review of direct air capture (DAC): scaling up commercial technologies and innovating for the future *Prog. Energy* **3** 032001

Meinshausen M, Lewis J, McGlade C, Gütschow J, Nicholls Z, Burdon R, Cozzi L and Hackmann B 2022 Realization of Paris agreement pledges may limit warming just below 2° C *Nature* **604** 304–9

Middleton R S *et al* 2020 Great SCO2T! Rapid tool for carbon sequestration science, engineering, and economics *Appl. Comput. Geosci.* **7** 100035

Minx J C *et al* 2018 Negative emissions—part 1: research landscape and synthesis *Environ. Res. Lett.* **13** 063001

Muratori M, Kheshgi H, Mignone B, Clarke L, McJeon H and Edmonds J 2017 Carbon capture and storage across fuels and sectors in energy system transformation pathways *Int. J. Greenh. Gas Control.* **57** 34–41

NASEM 2019 *Negative Emissions Technologies and Reliable Sequestration* (available at: www.nap.edu/catalog/25259)

National Academies of Sciences, Engineering, and Medicine 2022 *A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration* (The National Academies Press) (https://doi.org/10.17226/26278)

Nemet G F, Callaghan M W, Creutzig F, Fuss S, Hartmann J, Hilaire J, Lamb W F, Minx J C, Rogers S and Smith P 2018 Negative emissions—part 3: innovation and upscaling *Environ. Res. Lett.* **13** 063003

NETL 2015 *Carbon Storage Atlas—Fifth Edition (Atlas V)* (available at: www.netl.doe.gov/File)

Office of Fossil Energy and Carbon Management Department of Energy 2023 DOE is addressing climate change by removing carbon pollution from the air *DOE* (available at: https://www.energy.gov/fecm/articles/doe-addressing-climate-change-removing-carbon-pollution-air)

Ou Y N *et al* 2021 Can updated climate pledges limit warming well below 2 °C? *Science* **374** 693–5

Peng W, Iyer G, Binsted M, Marlon J, Clarke L, Edmonds J A and Victor D G 2021 The surprisingly inexpensive cost of state-driven emission control strategies *Nat. Clim. Change* **11** 738–45

Realmonte G, Drouet L, Gambhir A, Glynn J, Hawkes A, Köberle A C and Tavoni M 2019 An inter-model assessment of the role of direct air capture in deep mitigation pathways *Nat. Commun.* **10** 3277

Roe S, Streck C, Obersteiner M, Frank S, Griscom B, Drouet L, Fricko O, Gusti M, Harris N and Hasegawa T 2019 Contribution of the land sector to a 1.5 C world *Nat. Clim. Change* **9** 817–28

Strefler J, Bauer N, Humpenöder F, Klein D, Popp A and Kriegler E 2021 Carbon dioxide removal technologies are not born equal *Environ. Res. Lett.* **16** 074021

Train K E 2009 *Discrete Choice Methods with Simulation* (Cambridge University Press)

UNEP 2017 The emissions gap report 2017—a UN environment synthesis report

Walker W S *et al* 2022 The global potential for increased storage of carbon on land *Proc. Natl Acad. Sci.* **119** e2111312119

Wise M A, McJeon H C, Calvin K V, Clarke L E and Kyle P 2014 Assessing the Interactions among U.S. climate policy, biomass energy, and agricultural trade *Energy J.* **35** 165–80

Wise M, Calvin K, Thomson A, Clarke L, Bond-Lamberty B, Sands R, Smith S J, Janetos A and Edmonds J 2009 Implications of limiting CO_2 concentrations for land use and energy *Science* **324** 1183–6

Yang H, Gan T, Liang W and Liao X 2022 Can policies aimed at reducing carbon dioxide emissions help mitigate haze pollution? An empirical analysis of the emissions trading system *Environ. Dev. Sustain.* **24** 1959–80