# ROADS TO REMOVAL:

## Options for Carbon Dioxide Removal in the United States

DECEMBER 2023

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# Roads to Removal

## Options for Carbon Dioxide Removal in the United States

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The remaining authors declare no conflicting interests.

An accessible version of the entire report is available at:
*https://roads2removal.org/*

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# Preface

The *Roads to Removal* report assesses key factors and pathways for physically removing $CO_2$ from the air at the scale of gigatonnes (billion-tonne) per year and then storing it away from the atmosphere through either ecological or geological means. This gigatonne $CO_2$-removal target is the climate clean-up needed in addition to dramatic reductions of emissions of greenhouse gases (GHGs) if the United States is to reach net-zero carbon emissions by or before 2050. In this report, sixty-eight authors examine (1) forestry, (2) cropland soils, (3) biomass (such as agricultural waste or municipal trash), (4) direct air capture (machines that remove $CO_2$ from the air), (5) transportation, (6) available zero-carbon energy, (7) geologic storage, and (8) environmental and socio-economic impacts. What you will read here integrates published data with original research on the major elements of negative emissions. Our granular analysis, with county-level resolution, shows that it is feasible for the United States to accomplish the carbon drawdown needed for net-zero emissions by the year 2050.

The focus and scope of this report is unique. We chose to only address practices and technologies that remove $CO_2$ from the air. We cover a breadth of strategies where we could make reliable estimates of what their application will require, ranging from land management to the latest technological options. We evaluate the costs for every step of the solution, from collection to transport to $CO_2$ storage. Our methods are intended to be transparent—we included details of our calculations in the body of this report and the appendices, and the underlying data are available at the report website: https://roads2removal.org/.

We purposefully chose to avoid discussing policies or current incentives. Rather, Roads to Removal provides a range of options, tradeoffs, and costs, aiming to enable informed decision-making in every community, region, and state in our country. Specifically, our goal is to give decision-makers the lens to see options clearly and make choices that will keep us all safer in the places we call home.

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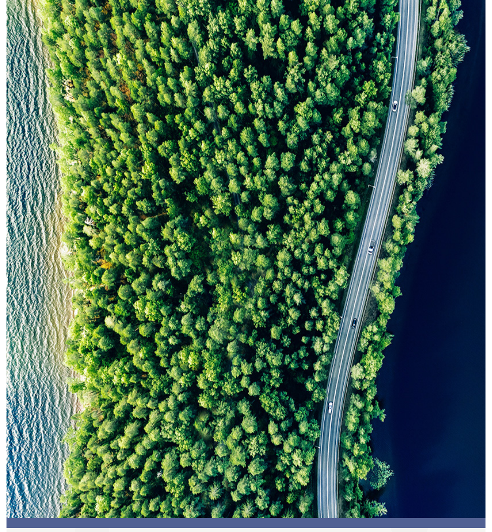
# EXECUTIVE SUMMARY



## The US has many ways to remove enough $CO_2$ from the air to meet its goal of net-zero emissions by 2050

Our analysis shows it is feasible for the United States to remove a staggering amount of $CO_2$ from the air—this will be critical to becoming carbon neutral by 2050. Our comprehensive, first-of-its-kind, county-resolution analysis indicates that our country can accomplish this goal by relying on demonstrated technology, natural resources, and workforces we already have. Additionally, ongoing technology development can lower costs, shorten timelines, and deliver new solutions. Our analysis evaluated how we can use forests, cropland soils, and waste biomass, along with purpose-built machines, to get us to net-zero. Further, we considered community impacts and identified locations where certain solutions could be uniquely beneficial or potentially counterproductive. Our findings enable decision-makers to weigh both opportunities and constraints and to decide what roads to use to meet our national climate goal for net-zero $CO_2$ emissions.

The US strategy for achieving net-zero [1] and eliminating ongoing, climate-warming pollution has many possible pathways. We scaled our report's summary presentations to one gigatonne (1000 million tonnes) to be consistent with the 2021 Biden Administration Carbon Negative Earthshot goal of removing and storing $CO_2$ at the gigatonne-per-year scale [1,2,3]. But our analysis indicates that much more $CO_2$ removal is possible—up to and beyond the 1500 million tonnes per year that some studies suggest will be needed by 2050 (**Figure ES-1**) [4]. The total amount of

**We assessed:** How much $CO_2$ is it possible to remove in the United States and at what cost?

The result is a supply analysis built from the highest-resolution data available. Our bottom-up approach to calculate overall $CO_2$ removal capacities is distinct from prior integrated assessments or top-down models, and provides encouraging, location-specific findings.

We provide current estimates for costs, resource demands and impacts of key $CO_2$-removal approaches by county.

This report is designed to enable informed decision-making. Equipped with our data, leaders at local, regional, and state levels can help promote new economic opportunities while protecting the health of our environment. Our results can be used to weigh alternatives and determine local benefits for specific projects.

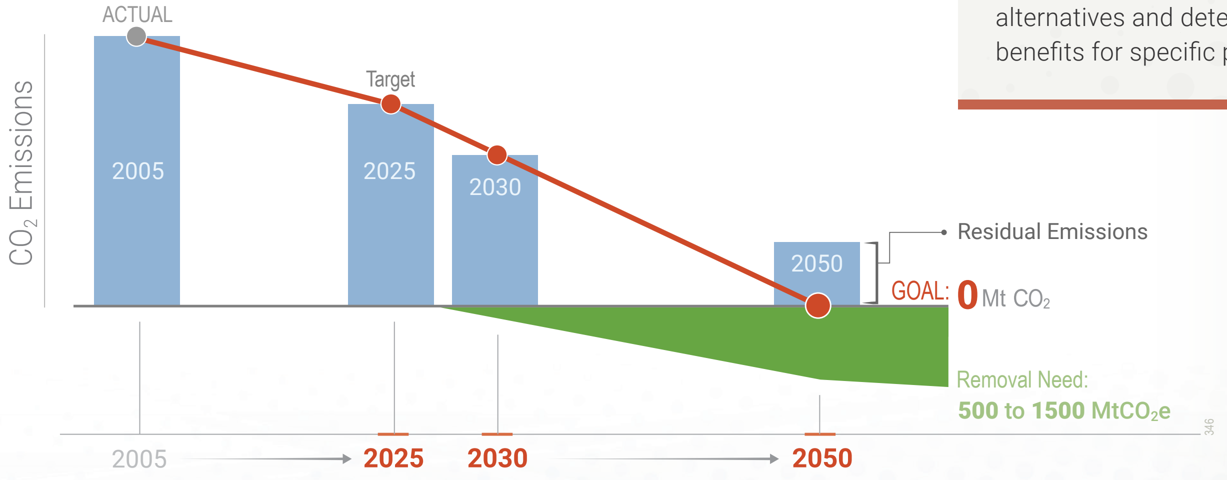


**Figure ES-1.** *Conceptual illustration of the need for $CO_2$ removal. Values for planned emissions-reductions and the likely residual emissions in 2050 (in blue) based on published reports [1,2,3]. Range of $CO_2$ removal (in green) needed for the US economy to reach net-zero by 2050. Significant $CO_2$ removal activities must begin now to reach the necessary scale by mid-century and could continue to expand if desired.*

*As a country, the* ***United States*** *has the* ***needed resources****—every region has ways to* ***contribute to our success.***

*The United States can remove at least* ***1 billion tonnes of $CO_2$ per year by 2050*** *creating more than more than* ***440,000 long-term jobs***

*Keeping the carbon from organic wastes out of the air can clean up to* ***800 million tonnes per year without impacting land*** *where we grow food*

*With* ***ecological carbon storage we can capture 2.7 billion tonnes of $CO_2$ by midcentury*** *while we develop and scale up geologic carbon storage*

## TOP-LEVEL CONCLUSIONS

*Roads to Removal* enables informed decision-making. Every region can weigh their unique opportunities and constraints to decide what contributions they can pursue to help our nation meet its net-zero climate goal.

In concert with urgent emissions reduction ('decarbonization'), the United States can increase uptake of carbon in our natural and working lands, convert biomass waste into fuels and $CO_2$, and use purpose-built machines to reach economy-wide net-zero emissions, removing at least 1 billion tonnes of atmospheric $CO_2$ per year by 2050.

With today's technologies, removing 1 billion tonnes of $CO_2$ will cost roughly $130 billion per year in 2050, or about 0.5% of current gross domestic product (GDP). New technologies and approaches will likely reduce that total cost.

The overall $CO_2$ removal capacity for forestry, cropland soil, biomass carbon removal and storage (BiCRS), and direct air capture with storage (DACS) is considerably larger than estimates of what the United States needs to remove. This extra removal capacity will make it feasible to pick regional implementations that match local needs.

With the information in this report, communities can clearly see their local opportunities and determine a best course of action as they discuss their role in averting our climate crisis. Optimizing early projects to maximize community benefits can help accelerate initial adoption and learning.

We can put cropland-soil management and forest-based solutions into action immediately; these approaches have rapid scale-up potential, a plethora of co-benefits, and low implementation costs. Geologic storage following biomass carbon removal or direct removal from the air will take longer to scale up, and in some regions is limited by local geology and the supply of zero-carbon energy.

At least 22% of US land mass has extraordinary potential for safe underground $CO_2$ storage due to its geology. These regions are ideal for DACS and BiCRS facilities co-located with storage.

By implementing methods that remove $CO_2$ from the air, we can create new jobs, improve air and water quality, increase our resilience to a changing climate, and protect life and property.

$CO_2$ removal the United States ultimately needs will depend on the success of policy and technology choices. Since the United States may decide to clean up larger amounts of $CO_2$ to compensate for historical pollution, this report also outlines ways to attain higher removal levels.

This report focuses on location-specific opportunities for removing and storing $CO_2$ in all 3143 counties in the United States. We examined these opportunities in the context of resource constraints and energy equity and environmental justice (EEEJ) considerations. Alongside the urgent and much larger national goal of rapidly cutting current greenhouse gas (GHG) emissions, $CO_2$ removal is required for the United States to achieve its net-zero emissions goals, meet international obligations, and help constrain global climate impacts [1].

Achieving the net-zero target will require the nation to hit both cost and volume goals for $CO_2$ removal [2, 3], while also meeting the needs of individual communities, states, and regions to avoid conflict with other critical priorities. This report evaluates $CO_2$-removal options with sufficient detail to inform these important decisions. Our analysis enables counties and $CO_2$-removal practitioners to work together to decide where, when, and how much of each approach fits into their local needs and what contribution each county can make to the national effort to eliminate $CO_2$ pollution.

We chose to evaluate $CO_2$-removal options from five sectors which are mature enough today to allow reasonable estimates of that approach's specific needs and its future costs. We assessed data for **forestry, cropland soils, biomass carbon removal and storage (BiCRS), direct air capture with storage (DACS), and geologic storage (Figure ES-2)** with county-level geographic resolution (where possible) and targeted locales of special opportunity. In our cross-cutting analyses, we assessed linkages and interdependencies, considering each $CO_2$-removal approach in light of realities imposed by the other approaches (e.g., heeding EEEJ concerns, ensuring that land surface area was not double counted, and prioritizing carbon-free energy for the electrical grid). We analyzed land-use change for all $CO_2$-removal strategies. We also integrated region-specific constraints driven by climate (fire risk), geology (geothermal, depth to basement), and relevant EEEJ metrics, such as land tenure, social vulnerability, air/water pollution, and persistent job-loss trends.

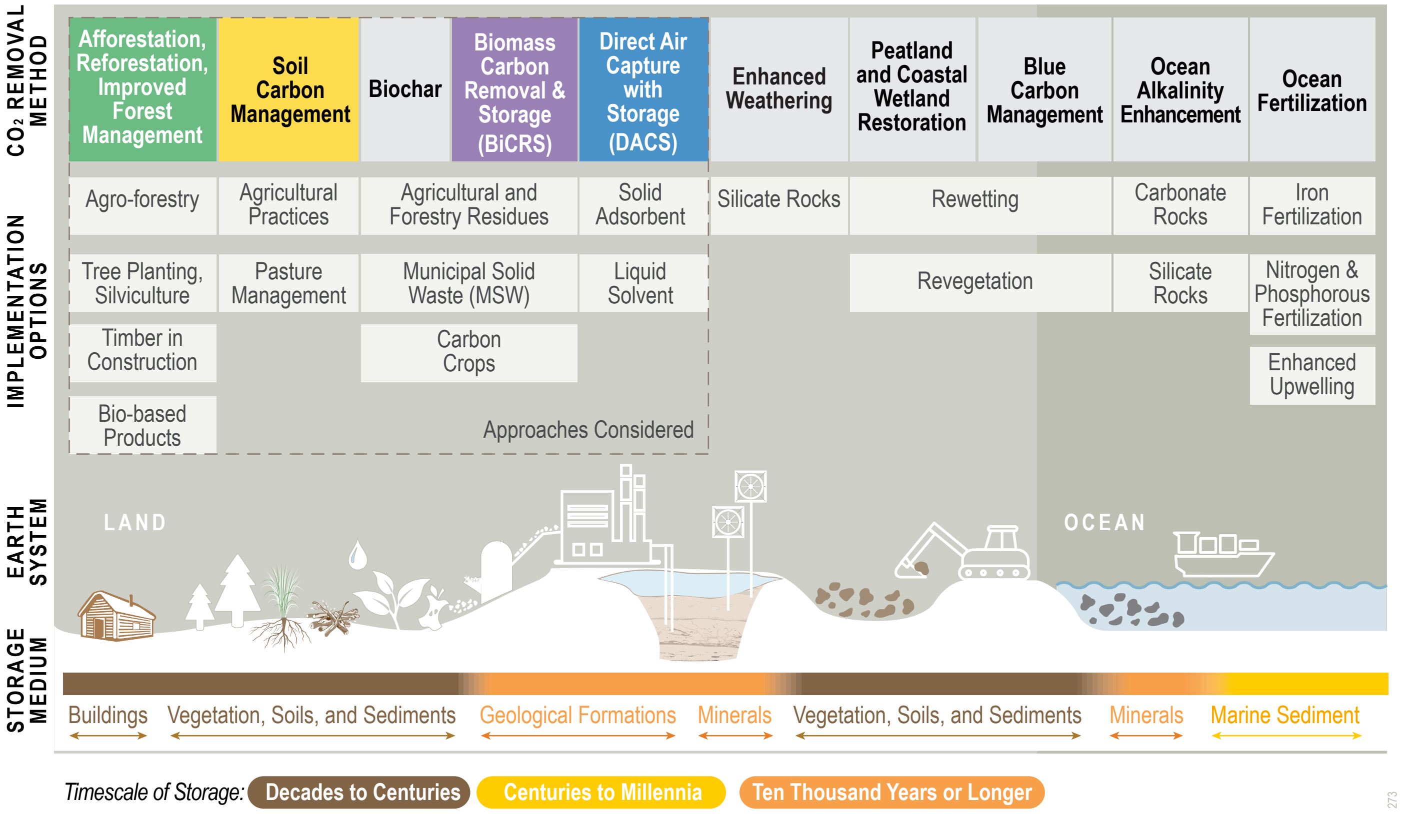


**Figure ES-2.** *Conceptual illustration of options available for $CO_2$ removal, redrawn from Figure 2 in Minx et al. 2018 [5]. $CO_2$ removal methods analyzed in this report are highlighted in color. We considered only $CO_2$-removal strategies with sufficient county-level resolution information (circa 2022) to estimate costs and established an inclusion threshold of at least 10 million tonnes of $CO_2$ removal per year for a $CO_2$-removal strategy to be considered.*

Other promising approaches—such as mineral weathering, $CO_2$ mineralization, grassland and wetland management, coastal blue carbon and ocean-based methods (Figure ES-2)—were not included because of insufficient data on cost, impacts, and necessary resources, but we expect region-specific data on these "roads not travelled" will soon become available.

We acknowledge that forest, soil, and geologic $CO_2$ storage have differing durability. Geologic carbon storage is highly durable while forests and soils store carbon in ecological pools that are more vulnerable to reversal. We frame these combined strategies as a portfolio that will allow our nation to transition from near-term investment in $CO_2$ removal and maintenance of immediately deployable storage (through forest and cropland-soil management) to long-term durable investment in geologic storage once technologies develop and scale.

This report is not intended as a prescriptive plan but rather as an examination of regionally specific opportunities, with careful consideration of local and national needs and constraints.

We evaluated feasibility, capacity, impacts, and costs on a county-level for the entire United States (including Alaska and Hawai`i), considering removal methods that could each be expected to remove at least 10 million tonnes of $CO_2$ equivalents ($CO_2$e) per year and for which we could estimate the costs achievable by 2050. It is vital that $CO_2$ removal must not compete with urgent ongoing efforts to decarbonize US energy, industrial, agricultural and forestry sectors; rather, they must proceed in parallel. Thus, we evaluated the availability of energy that is additional to that needed for 2035 grid-carbon neutrality. We also explicitly considered the amount and type of land required for each approach, as this is the primary physical constraint on the amount of $CO_2$ removal we can employ. Finally, we evaluated environmental and socioeconomic co-benefits and risks, because decarbonization and carbon removal must be designed to minimize risk of negative environmental, economic, and public-health impacts.

## Key Findings

Many locations in the United States can set off on the 'road to $CO_2$ removal' immediately by employing **cropland-soil management and forest-based solutions** that are in addition to current activities (**Figure ES-3**). By 2050, the combined effect of these practices can achieve close to 100 million tonnes of $CO_2$ removals per year (**Figure ES-4**). These approaches have multiple co-benefits for ecosystem productivity, biodiversity, water conservation, environmental quality, and resilience to climate change. Critically, we can deploy them rapidly, and they do not require energy resources that would otherwise go toward decarbonizing the rest of the nation's economy. While carbon storage in trees and soils is potentially reversible (i.e. due to fire, insect outbreaks, and cropland management changes) and is less durable than geologic storage, these approaches still represent an efficient stopgap that keeps carbon out of the atmosphere until more lasting solutions can be implemented.

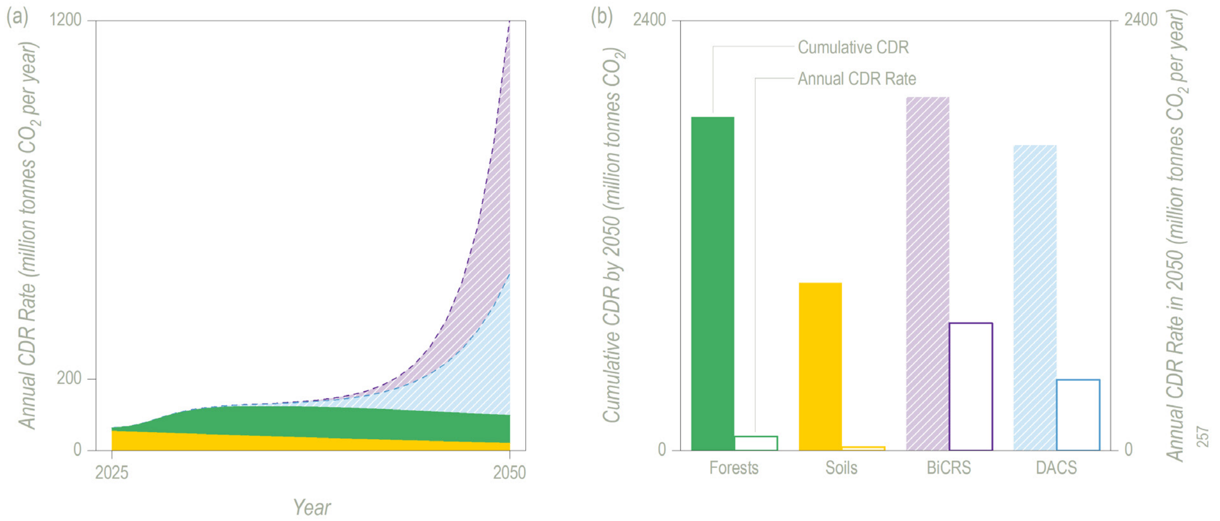


**Figure ES-3.** *The potential $CO_2$ removal by 2050 for four major removal approaches depends strongly on the rate of development. Forest management and soil-based interventions can begin in the near term, resulting in a large cumulative impact by 2050. BiCRS and DACS are likely to develop more slowly due to permitting requirements and the need for capital investments, but by 2050 (Figure ES-4), their annual rates will be large. Shaded areas show the relative amount of cumulative $CO_2$ removed, whereas vertical height indicates the relative annual rates of $CO_2$-removal in a given year See* ***Chapter 8 – Cross-Cutting*** *for additional detail.*

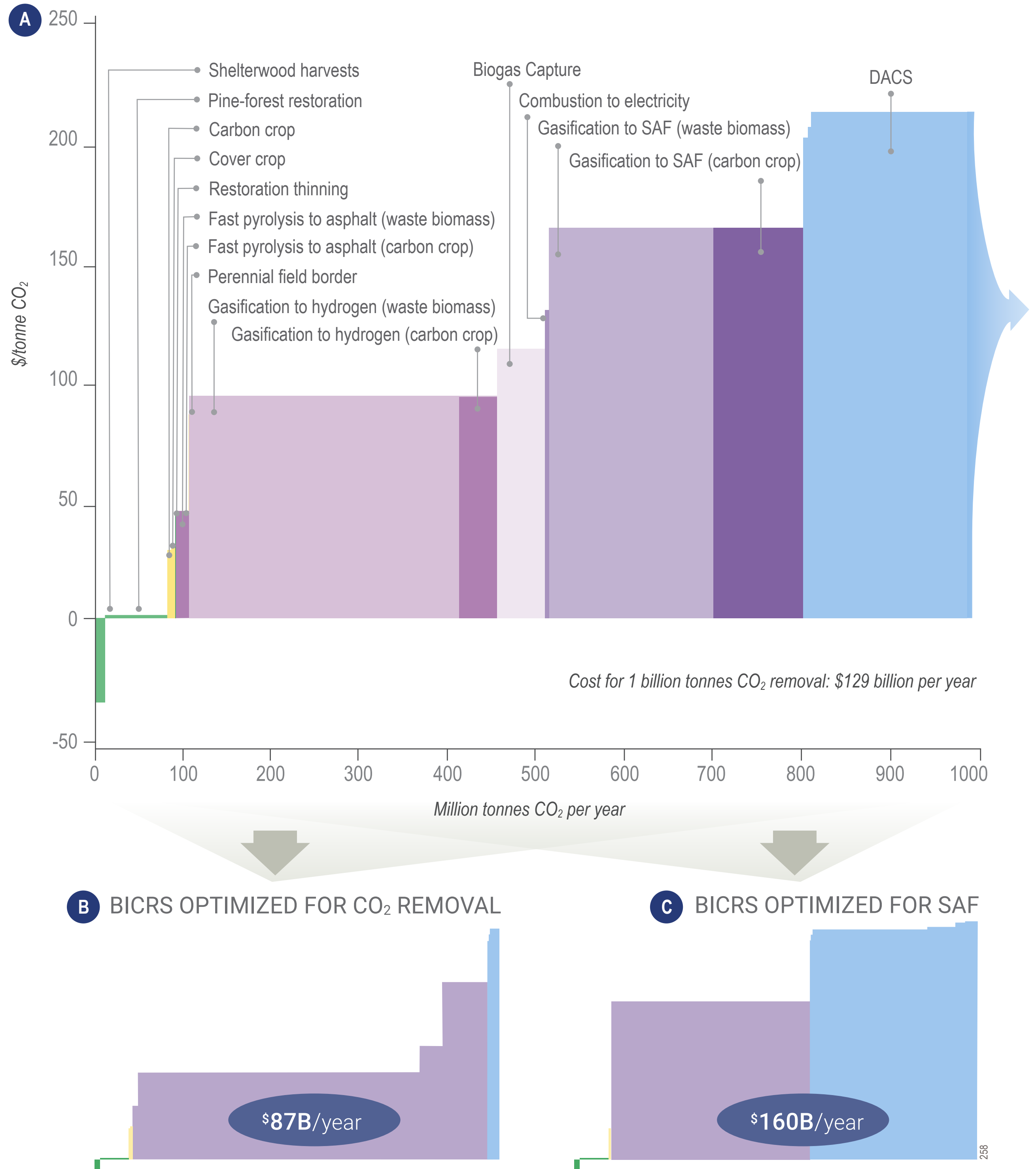


**Figure ES-4.** *Representative 2050 supply curve for 1 billion tonnes of $CO_2$ removal per year in the United States, calculated from a high-resolution, county-level analysis. Amounts are ordered by estimated cost and constrained by resource availability, land use and energy supply. All costs include capital, operation, transportation, life-cycle costs and carbon impacts. Forest management potential (green) is calculated for only 3 regions of the US (northeast, western, southeast). For commodity-cropland soils (yellow), we focused on cover crops, perennial field borders, and perennial carbon crops. For BiCRS (purple), waste and crop biomass could be used for many national priorities—in (A), a subset of the biomass supply is allocated to sustainable aviation fuel (SAF) (17.5 billion gallons per year) and the remainder modeled to minimize carbon-removal cost; in (B) biomass use is optimized for $CO_2$ removal (with no SAF); in (C) we optimized for 28 billion gallons per year of SAF. The capacity for direct air capture with storage (DACS, blue) is larger than displayed; DACS technical potential is nearly 14 billion tonnes of $CO_2$ per year at less than $250/tonne. The integrated area of all bars gives the total cost for 1 billion tonnes of $CO_2$ removal per year.*

$CO_2$ removal approaches that capture carbon by converting waste biomass and purpose-grown carbon crops to long-lived products or geologic storage can have substantial annual capacity by 2050—more than 800 million tonnes of $CO_2$ per year at a cost of less than $100 per tonne (Chapter 6 – BiCRS; Figure 6-2). These removals can occur while carefully maintaining biodiversity, negative life-cycle GHG emissions (e.g. nitrous oxide emissions from fertilizer), foregone soil-carbon accrual, and while avoiding impacts to the nation's food supply and costs.

The nation may prefer to use organic wastes and biomass to make sustainable liquid fuels—this must be balanced with the desire for carbon removal. We analyzed biomass-use options to maximize carbon removal while maintaining sufficient production of sustainable aviation fuel (SAF) and carbon-negative hydrogen. Figure ES-4 illustrates a balanced approach in which 300 million tonnes of biomass is directed to make sustainable fuels, while the remainder is used to minimize $CO_2$-removal cost. In this example, 700 million tonnes of $CO_2$ can be removed from the atmosphere each year at an average cost of $120 per tonne.

If only biomass wastes and forest thinning residues are used for carbon removal, the potential biomass supply (~ 500 million dry tonnes per year) could yield 700 million tonnes of $CO_2$ removal at $80 per tonne (Table 6-18). Thus, even with no land-use change, the United States has significant potential biomass-based $CO_2$-removal capacity.

DACS can provide a significant portion of the $CO_2$ removal needed to achieve net-zero and is a critical backstop if other removal approaches fall short. We analyzed the two best-developed DACS methods to date—solvent-based and absorbent-based systems—both co-located with geologic storage. Because of the limited availability and difficulty of building new electricity transmission, we required that DACS processing facilities be sited in the same counties as new renewable-energy sources (Figure ES-11). Even with these constraints, we found that the United States has large technical potential for DACS, with nearly 14 billion tonnes of $CO_2$-removal per year possible at a cost of less than $250 per tonne. The cumulative $CO_2$ removed by DACS by 2050 is highly dependent on timing of implementation; in Figure ES-3 we present DACS cumulative removals –assuming almost all deployment occurs in the final decade before 2050.

$CO_2$ removed from the air can be stored in ecosystems via soils or trees, in long-lived products, or via geologic storage. BiCRS and DACS rely on geologic storage for long-term durable storage of removed $CO_2$. We evaluated the availability of geologic storage in sedimentary basins and basalt and other mafic rocks, likely storage project costs (land leases, fees, monitoring), and transport costs of moving $CO_2$ to storage sites or of moving biomass to processing sites near prospective geologic storage. More than half the nation's land area is potentially suitable for $CO_2$ storage; the remainder of the country lacks geologic storage resources. Further, storage is available in sedimentary rocks that can accept large volumes of $CO_2$ (greater than 1 million tonnes per year for projects operating for up to 20 years) in 22% of the United States, with average storage costs of less than $20/tonne.

Our findings show four major $CO_2$-removal approaches have the capacity for large-scale carbon removal by the year 2050 but opportunities and costs differ widely by region and land availability (**Figure ES-5**). In the United States, the capacity for $CO_2$ removal through cropland-soil and forest management is largely limited by the amount of appropriate land, and ideal BiCRS and DACS locations are constrained by storage and renewable energy availability.

Cropland-soil and forest-management practices remove carbon from the atmosphere at the highest rates near the beginning of their implementation (Figure ES-3), but for these ecological approaches, carbon removal and storage both depend largely on maintaining practices over time. The timescale for implementing BiCRS and DACS is more difficult to project. We modeled the cumulative impact of BiCRS and DACS by assuming they could be deployed at a rate that yields a total of approximately 1 billion tonnes of $CO_2$ removal per year in 2050 for all the $CO_2$-removal methods together (Figure ES-4), when implementing the methods in order of cost.

Figure ES-4 illustrates one example of many ways $CO_2$-removal methods could be combined to reach the goal of 1 billion tonnes per year. We anticipate that local desires, constraints on resource usage (land area, biomass, and additional carbon-free energy), and policy decisions will have significant effects on the ultimate mix of $CO_2$-removal technologies that are used.

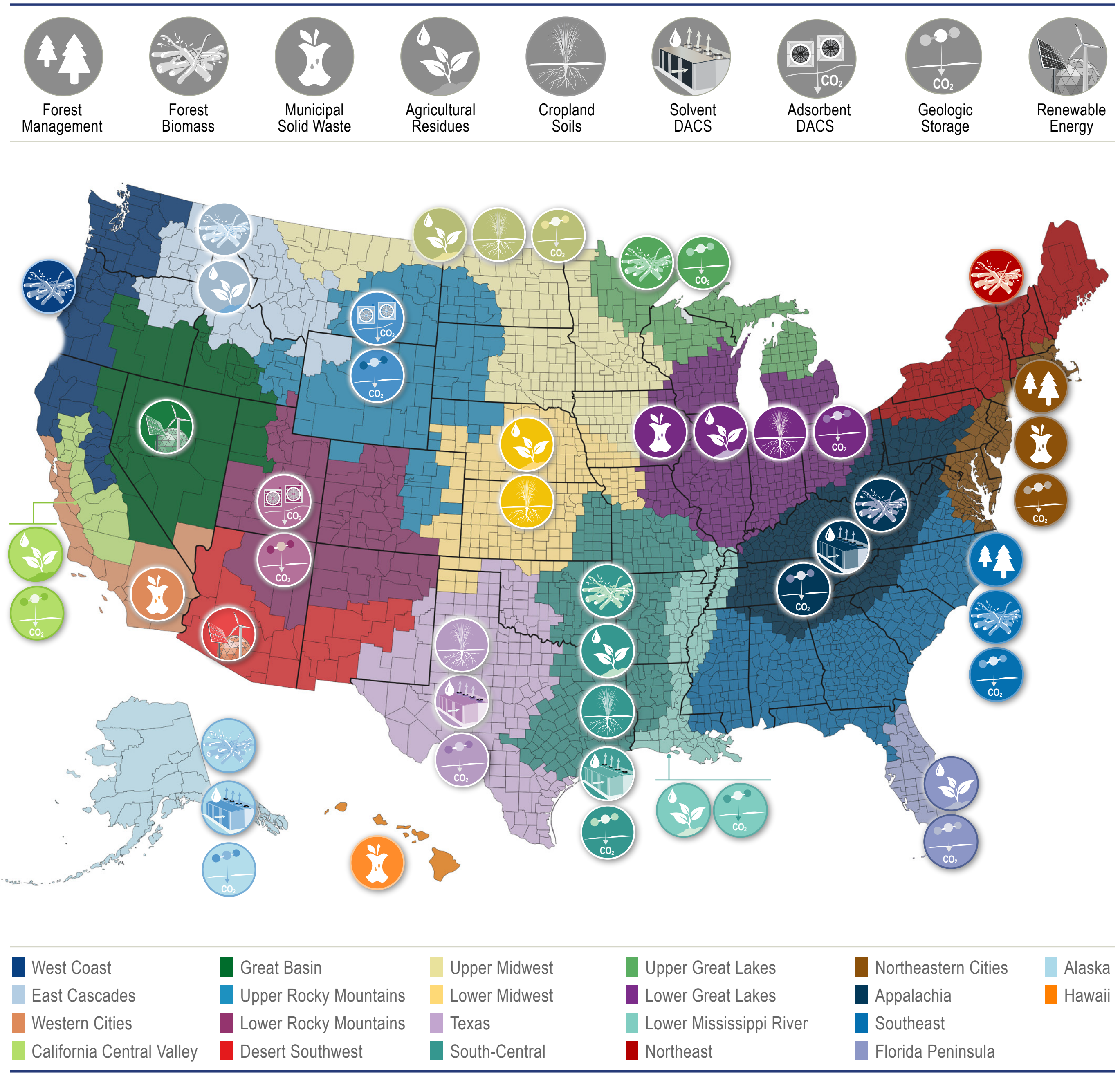


**Figure ES-5.** *Regions map with county grouping defined by primary carbon-removal resources. The icons qualitatively highlight key regional resources that can contribute to $CO_2$ removal. We determined the regional groupings on a quantitative basis with qualitative boundary conditions. First, we assessed the primary above-ground carbon resources at a county level with a coarse boundary between forests, agriculture, urban, and other areas. Second, we evaluated geographic carbon-storage potential in forest biomass, cropland soils, and geologic reservoirs. Third, we analyzed cross-cutting factors, including watersheds, energy-generation capacity, and current and potential transportation resources. Fourth, we considered regional land ownership and environment and population health. Finally, we made judicious decisions about where to merge, divide, stretch, and contract each region based on the cohesive story that could be told, while incorporating boundary conditions (e.g. we required each region to be contiguous, including bodies of water).*

# Our Analysis Process

We began our analyses by determining the resources necessary for each $CO_2$-removal approach—namely land area, energy, biomass, and geologic storage—and then the amount of $CO_2$ removal available in each county in the United States. We assessed the cost, effectiveness, and applicability of available technologies, as well as other needs, such as geologic storage (**Chapter 4**) or transportation. We deconflicted the resulting options to ensure that no land resources were used more than once and land types were appropriate for the designated use (e.g., projected land for renewable energy and DACS could not be placed on land currently designated as parks, urban land, or farmland). We considered environmental impacts (**Chapter 8**) and transportation impacts (**Chapter 5**) for all technologies simultaneously. Finally, we considered the socioeconomic and local environmental implications of every analyzed approach (**Chapter 9**). We used these analyses to provide a set of options for every region of the nation, evaluating the appropriateness, value, and impacts of each of the $CO_2$-removal approaches. Our primary output is a set of supply curves—volumes of available $CO_2$ removal at estimated 2050 prices (**Figure ES-4 and Chapters 2, 3, 6, 7**). These supply curves can inform local, regional, and national decisions.

# Findings
## by the Numbers

As previous model-based $CO_2$-removal studies suggest [4,5,6], we will need all the approaches analyzed in this report as an ensemble to annually supply upwards of a billion tonnes of $CO_2$-removal capacity to the United States. But there are many ways to mix and match these approaches, and certain techniques are more appropriate for specific regions. Soil and forest solutions should, logically, be used to the maximum extent possible due to their co-benefits, rapid scale-up, and ease of implementation. BiCRS and DACS can be widely applied in specific areas of the nation where the resources, land, geologic storage, energy, equity, and environmental conditions are appropriate.

Our Top Ten specific findings include the following:

### ① REFORESTATION AND AFFORESTATION

Reforestation and afforestation in the southeastern United States, fire-resilience forest treatments in the western dry forests, and managing forests to produce wood products and promote regeneration of more climate-resilient forests in southern New England and southeast New York could yield a total removal of 1.5–1.8 billion tonnes of $CO_2e$ (cumulative from 2025 to 2050) at a cost ranging from \$44/tonne to a net revenue of \$37/tonne. On an annual basis, this is equivalent to approximately 72 million tonnes $CO_2e$ per year.

### ② COMMODITY-CROPLAND SOILS

Managing commodity-cropland soils to implement cover crops, perennial field borders, and perennial carbon crops is a low-energy, immediately deployable $CO_2$-removal strategy. After accounting for cumulative county-level costs, foregone income, and payments for $CO_2$ removed, cropland-soil-management practices could profitably remove 130 million tonnes of $CO_2e$ (cumulative from 2025 to 2050) at a price of \$40/tonne or 936 million tonnes at \$100/tonne. On an annual basis, this increases over time to reach 8.9 million tonnes or 37.3 million tonnes $CO_2e$ per year (respectively, for the \$40/tonne and \$100/tonne price points).

### ③ GEOLOGIC $CO_2$ STORAGE

More than half the land area in the United States has potential for geologic $CO_2$ storage (and up to 60% if basalts and other mafic rocks are included) at an estimated average cost of less than \$53 per tonne of $CO_2$. In 22% of the nation's land area, well-studied sedimentary rock sequences can accept large volumes of $CO_2$ at very low cost—\$20/tonne on average—even when including project-maintenance costs. Thus, tradeoffs between high-cost local storage versus pipelines to low-cost remote storage sites are a consideration.

### ④ BiCRS CAPACITY

After considering land use, biomass availability, biomass transportation, 27 biomass conversion pathways, and biorefinery siting, we find that US BiCRS capacity could approach 700 million tonnes of $CO_2$ per year from biomass wastes and residues alone, and nearly 900 million tonnes of $CO_2$ per year with the addition of purpose-grown crops, for a combination of pathways that maximizes removal capacity while minimizing cost. We could reach this capacity without impacting cropland or food prices—albeit with significant up-front capital investment—at a net cost of less than \$100/tonne $CO_2$. Using a large portion of the available biomass for sustainable aviation fuel (SAF) would considerably reduce the volume of achievable $CO_2$ removal but would also contribute substantially to decarbonizing aviation. In Figure 258A, we illustrate a balance of options that produces 17.5 billion gallons of SAF per year (one half of the goal set forth in the US Department of Energy's (DOE's) SAF grand challenge roadmap report [7]), while still providing other negative-emissions bioproducts and fuels.

### ⑤ DACS

The United States has a technical potential of over 9 billion tonnes of $CO_2$ per year for DACS powered by local purpose-built renewable electricity (particularly in the intermountain West and West Texas) and of over 4 billion tonnes of $CO_2$ per year for DACS powered by natural-gas reserves (with carbon capture). Costs for this $CO_2$ removal largely range from \$200 to \$250/tonne $CO_2$. Water constraints will be an important consideration for DACS, as some of the regions with highest DACS potential are expected to experience increasing water scarcity. We would not need to use most of this DACS capacity to achieve US net-zero emissions goals, assuming that we can meet other decarbonization priorities.

### ⑥ LONG-TERM JOBS

The ensemble approach for achieving 1 billion tonnes of $CO_2$ removal can create more than 440,000 long-term jobs—nearly five times the number of jobs lost from the coal industry since 1990 [8].

### ⑦ LAND USE

Reaching 1 billion tonnes of $CO_2$ removal per year will require less than 1% of the total land area in the United States; much of the BiCRS potential leverages agricultural residues and other organic wastes that have no impact on land use.

### ⑧ DISADVANTAGED AND NON-DISADVANTAGED COMMUNITIES

The land area suitable for BiCRS and DACS is roughly equally divided between disadvantaged and non-disadvantaged communities. Even when optimized solely by price and powered by additional renewable energy, DACS facilities are not inequitably distributed in disadvantaged counties. This suitability baseline was important to quantify because, as this nascent industry grows, equitable siting of these projects can only be assessed relative to a baseline.

### ⑨ AIR QUALITY

Large-scale $CO_2$-removal efforts are likely to result in net improvements to air quality, particularly when accounting for wildfire-risk mitigation, but the impacts (positive and negative) may be unevenly shared across regions.

### ⑩ REGION-SPECIFIC $CO_2$-REMOVAL OPPORTUNITIES

Our analysis points to many region-specific $CO_2$-removal opportunities. For example, the Western Cities and Northeastern Cities regions produce large amounts of carbon-rich municipal solid waste (MSW) that can be diverted from landfills to more permanent and economical forms of carbon storage, and the Upper and Lower Rocky Mountains and West Texas regions have remarkably high potential for large-scale deployment of DACS co-located with renewable energy.

## Detailed Evaluations

Each chapter and appendix in this report contains extensive analyses and demonstrates the options and issues we considered in detail. Here we provide a summary of those analyses.

### Energy Equity and Environmental Justice (EEEJ)

Rapidly scaling $CO_2$ removal to the billion-tonne scale by 2050 could stimulate immense EEEJ changes across the United States. With purposeful engagement, design, siting, and management, $CO_2$ removal can be an indirect conduit for environmental justice nationwide, with outsized opportunities for restorative justice in communities currently burdened inequitably with pollution issues, as well as recognition justice for those facing workforce challenges amidst decarbonization. **Chapter 9 – EEEJ** discusses these challenges in detail.

One of our foundational EEEJ findings, summarized in trade-off tables presented in each chapter of the report, is that $CO_2$-removal methods can be divided into two classes that warrant different scale-up strategies: (1) those that already have widespread public support and high restorative-justice potential, but are limited by uptake costs (e.g., soil conservation practices) and (2) those that are perceived as “first-of-their-kind” (e.g., DACS) but have outsized potential to reemploy workforces that have experienced inequitable job losses the past several years—this is a key recognition-justice issue of national decarbonization. In our analysis, we constructed EEEJ indices specific to each $CO_2$-removal method that indicate how poised each county is to benefit from a particular $CO_2$-removal method, within the subset of counties with high, affordable $CO_2$-removal capacity (**Chapter 9 – EEEJ**). We then used a social vulnerability index (SVI) to identify (1) highly vulnerable counties that could be better protected by widely supported $CO_2$-removal methods with outsized restorative-justice opportunities and (2) less vulnerable counties that may have the social infrastructure and bandwidth to collaborate on scaling $CO_2$-removal methods as early adopters (**Figure ES-6**).

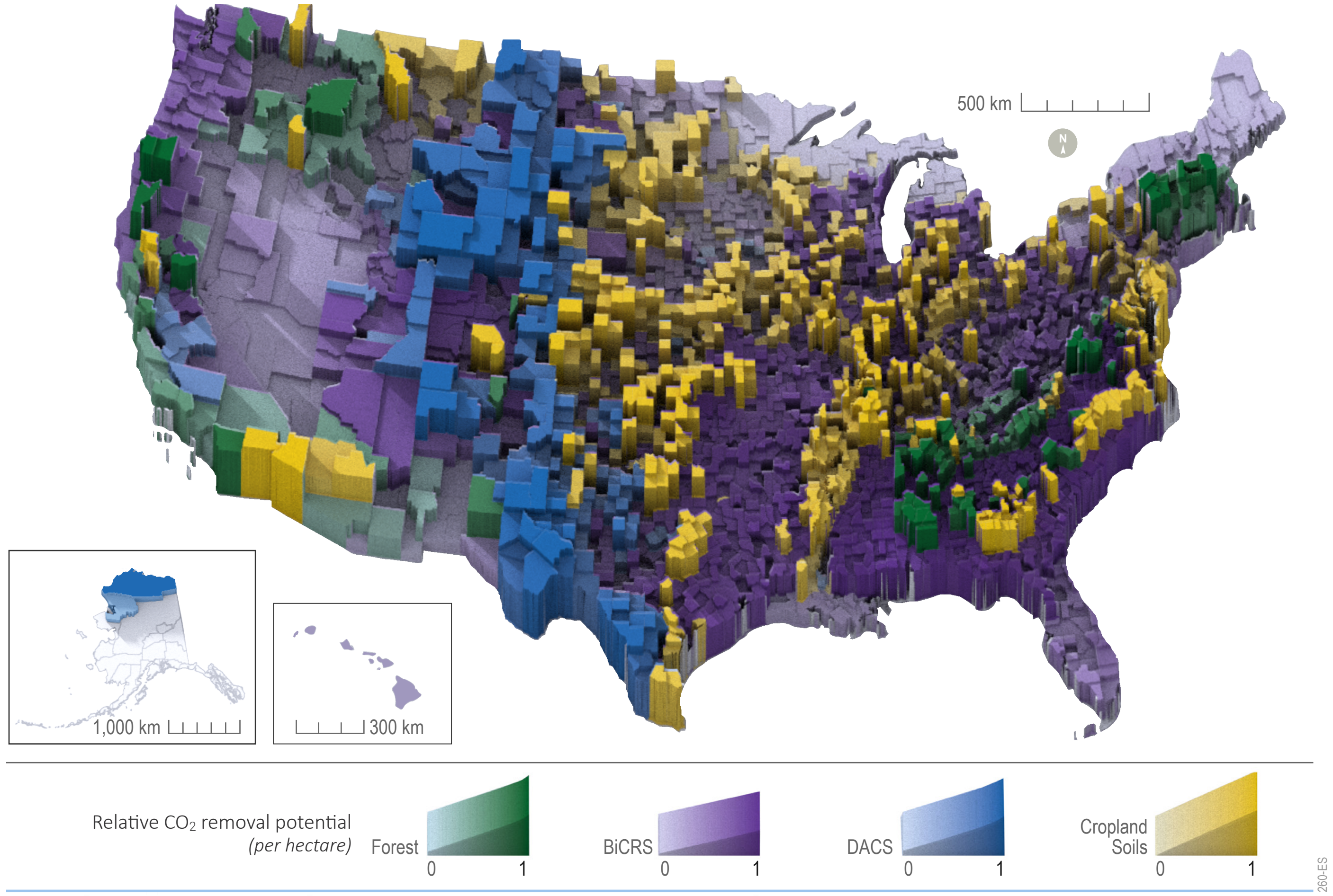


**Figure ES-6.** *Mapped $CO_2$-removal potential across counties, factoring in EEEJ and Social Vulnerability (SVI) indices and categorized by removal method. Northeast forests, western forests, and soils prioritized high-SVI areas; other methods favored low-SVI areas. Method scores calculated by multiplying county $CO_2$-removal potential, EEEJ Index, and SVI or reverse-scaled SVI. County rankings based on method scores, with the highest-scoring method's percentile rank depicted. Higher values signal significant $CO_2$-removal prospects with potential environmental and socioeconomic benefits. This map offers a broad perspective, see **Chapter 9** for details.*

### Geologic Storage

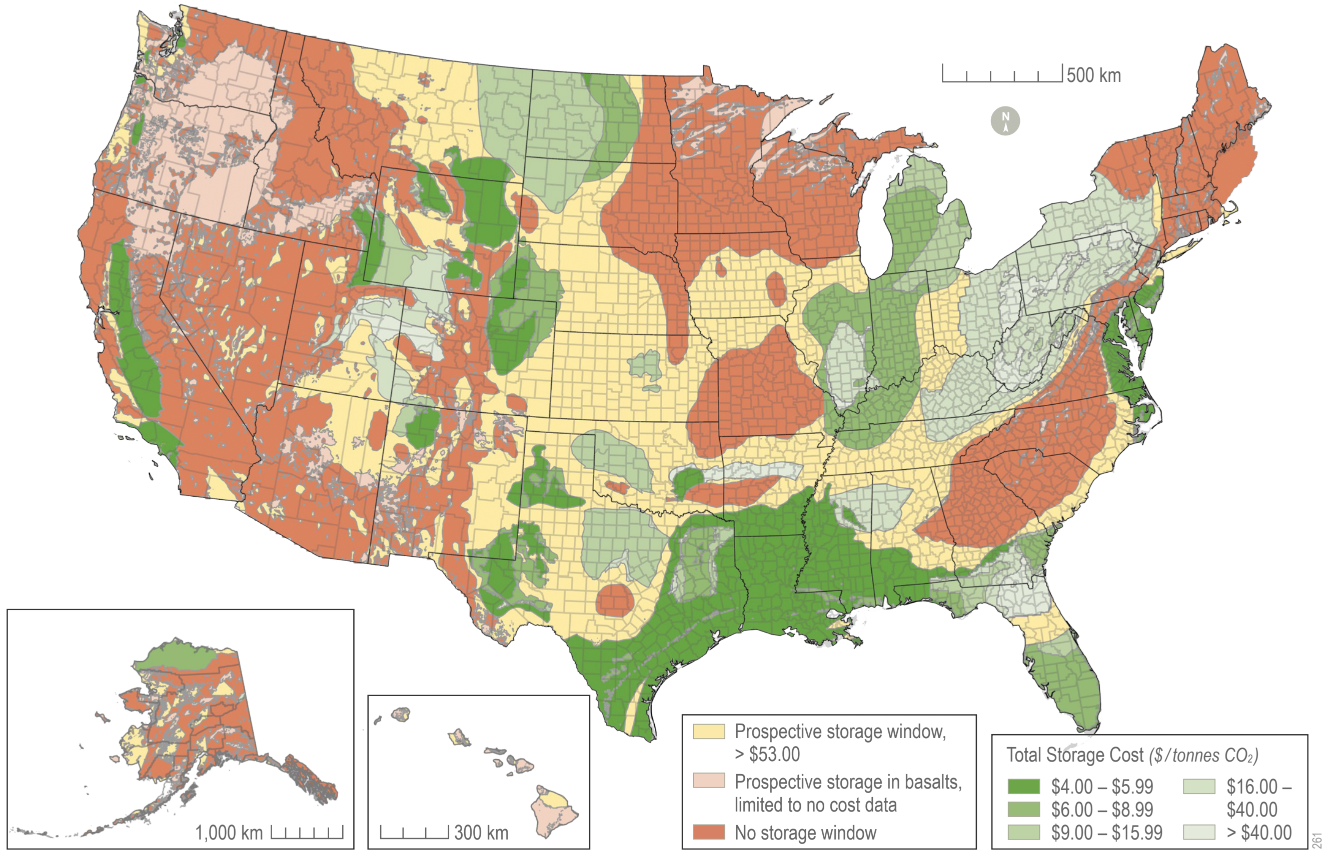


**Figure ES-7.** *Distribution of geologic $CO_2$ storage resources with estimated mean project-based costs. Regions in green are well characterized geologic basins with sufficient data to estimate project costs. Regions in yellow contain geologic formations that fall within the storage window, but where data needed to make detailed cost estimates are not available, therefore we assume a cost of greater than \$53/tonne $CO_2$. Regions in light orange are basalts or other mafic rocks that may be suitable for mineral storage of $CO_2$ but where data are insufficient to make cost estimates. Regions in dark orange do not have storage resources.*

Geologic Storage is an integral component of many major types of carbon removal (e.g. DACS or BiCRS), providing durable storage for $CO_2$ removed from the atmosphere. We conducted a new analysis of the distribution and estimated cost of US geologic storage resources, introducing novel elements that are explored in detail in **Chapter 4 – Geologic Storage:**

1) We explicitly mapped the “storage window”—the subsurface volume where $CO_2$ storage is possible within sedimentary rocks that are below fresh water and deep enough to keep $CO_2$ as a dense fluid, while still above depths where injecting $CO_2$ is logistically difficult.
2) We included new factors that impact the cost of geologic $CO_2$ storage: how land leasing costs are affected by $CO_2$ plume size and pressure, storage fees paid to landowners, costs of characterization and monitoring, and monetary benefits paid to host communities.
3) We estimated costs on a project basis, with a “storage project” defined as one million metric tonnes of $CO_2$ injected annually for 20 years. This approach allows developers to better match removal projects with available storage.

The United States has abundant onshore storage resources; however, plans to use these resources must consider their uneven distribution. By mapping the storage window, we found areas outside of previously assessed basins where exploration could potentially locate new storage options (primarily in the central United States; yellow areas of Figure ES-7). Our estimated project costs, while calculated differently than in previous studies, have roughly the same range and geographic distribution as previous studies.

The best locations in the country for geologic $CO_2$ storage will have very low costs and are likely to see early development of nearby DACS and BiCRS projects since the availability of local storage will minimize needs for transportation and pipelines. Outside of these areas, suitable storage may be available, but storage costs will be higher, with more wells required to inject 1 million tonnes of $CO_2$ per year for 20 years (**Figure ES-7**).

## Forests

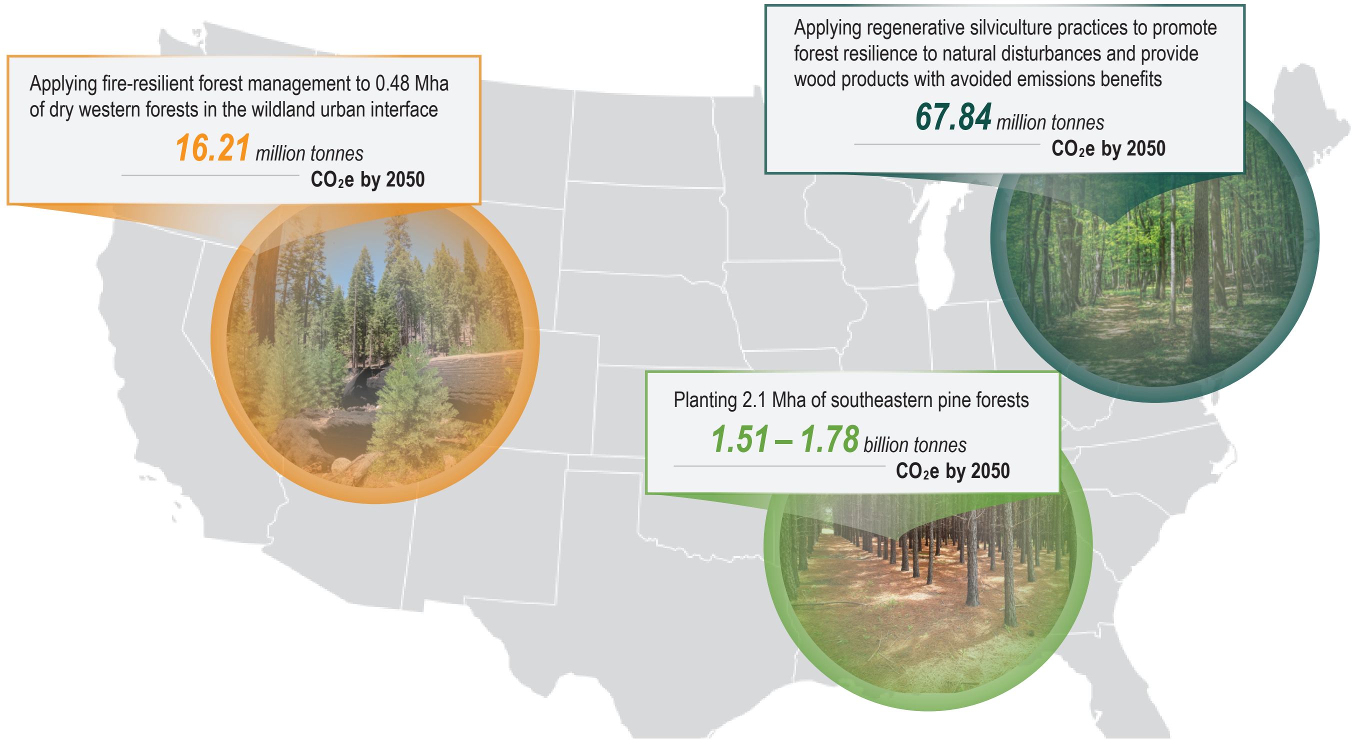
Forests serve two important climate-mitigation services. First, trees and other forest vegetation are living "DAC machines" powered through renewable solar energy. Forest plants have evolved to remove $CO_2$ from the atmosphere and transform it into carbohydrates and other organic molecules. Second, trees and forest vegetation are carbon-storage facilities (holding carbon in living plant tissues) and carbon pipelines (transporting carbon into forest soils). Forest management can directly impact how effectively forests remove atmospheric $CO_2$ and how durable they are as carbon-storage facilities. In this report, we focus on how various forest-management practices may increase long-term carbon storage in forests, while sustaining and ideally promoting provision of the other critical services forests provide for human societies.

Policymakers and forest managers have three primary levers they can use to increase future forest-carbon stocks: increasing the total forested area of the United States, increasing the rate at which forests remove $CO_2$ from the atmosphere, and increasing the durability of forest-carbon storage. Sustainable forest-management practices tailored to specific forest regions can pull these levers in the interest of carbon storage and simultaneously positively influence multiple other services that forests provide. In Chapter 2 – Forests, we demonstrate how regionally specific forest-management practices provide viable roads to $CO_2$ removal—that are both place-based and resistant to disturbance—in three key US forest regional case studies (summarized below):

1) In the southeastern Piedmont and Coastal Plains areas, afforestation or reforestation through loblolly-pine planting can increase the total forested area of the United States. Planting on 2.1 million hectares (5.2 million acres) of available land in these areas in 2025 would lead to total $CO_2$ removals of 1.51–1.78 billion tonnes of $CO_2e$ (cumulative) by 2050. Planting high-density pine forests for restoration can remove 71.14 million tonnes $CO_2e$ per year at a price of $1.22 per tonne $CO_2e$. Alternatively, planting low- density pine forests for commercial plantations on the same land base can remove 67.27 million tonnes $CO_2e$ per year while generating a net revenue of $13.80 per tonne $CO_2e$ (**Figure ES-8**).

2) In the dry forest regions of the western United States, applying forest management techniques designed to promote fire-resilience can increase forest $CO_2$ removal and storage, as well as forest health and resilience. Applying selective fire-resilient management practices to 0.48 million hectares (1.19 million acres) of dry forests in the wildland urban interface of the western United States may remove up to 16.21 million tonnes of $CO_2e$ (cumulative) by 2050 (at an average cost of $44/tonne) and would help abate carbon impacts of wildfire.

3) In southern New England and southeastern New York, managing forests to produce wood products and promote regeneration of more climate-resilient forests on 2.6 million hectares (6.4 million acres) of mixed-hardwood forestlands at a rate of 2% per year could provide up to 2.61 million tonnes of $CO_2e$ removal per year by 2050 (relative to passively managing forests with no harvests). This outcome assumes forests will be disturbed in the future—following the trends of extreme weather and pest and pathogen outbreaks that this region is already experiencing—and estimates net climate benefits from wood product energy and material substitution. This removal rate can be achieved while generating a net revenue of $37.46/tonne $CO_2e$ through timber sales.



Applying fire-resilient forest management to 0.48 Mha of dry western forests in the wildland urban interface
**16.21** *million tonnes*
**$CO_2e$ by 2050**

Applying regenerative silviculture practices to promote forest resilience to natural disturbances and provide wood products with avoided emissions benefits
**67.84** *million tonnes*
**$CO_2e$ by 2050**

Planting 2.1 Mha of southeastern pine forests
**1.51 – 1.78** *billion tonnes*
**$CO_2e$ by 2050**

**Figure ES-8.** *There is growing evidence that 'climate-smart' forest management practices may increase forest carbon durability and reduce forest emissions. Forest management has benefits beyond $CO_2$ removal and storage by providing wildlife and biodiversity habitat, food, fuel, timber and fiber to human communities, air and water pollution reduction, and cultural, aesthetic, recreational, and spiritual value. The variety and importance of the suite of services forests provide creates numerous opportunities, but also numerous challenges, for managing the nation's forests. There is no singular one-size-fits-all climate-smart forest strategy to pursue. Following this ethos, we present three case studies that represent region-specific examples of forest management for carbon removal and storage that are place-based and climate-smart.*

These forest management options also affect the multitude of services forests have always provided to humans, including non-carbon-based climate benefits, such as cooling temperatures and regulating climate; cleaning our air and our water; providing habitat for wildlife and other food, fuel, timber, fiber, and sources of biodiversity for human communities; and offering immense cultural, aesthetic, recreational, and spiritual value.

## Soil Carbon

Accruing organic carbon in cropland soils is a prime target for near-term, soil-based $CO_2$ removal because croplands are already heavily managed and cover a large expanse of the United States. In addition, practices that enhance organic carbon in croplands are established and immediately deployable. Our analysis examines the coupled economic and technical potential for cropland-soil-based $CO_2$ removal at a county-level across the contiguous United States.

In **Chapter 3 – Soils**, we analyzed the spatially explicit responses of commodity-cropland organic carbon and GHG emissions to a suite of management practices (cover crops, perennial field borders, and perennial carbon crops) through the year 2050 using the DayCent and SALUS biogeochemical models. **Table ES-1 and Figure ES-9** show the effects of these practices if they are implemented *when they are more profitable than county-specific baseline management* (commodity corn, wheat, cotton, soybean, oats, barley, sorghum grain, hay, and peanuts) at three carbon prices. While the per-area $CO_2$ removal could expand to a high technical potential over the vast area of cropland in the United States, the economic profitability constraints that we imposed in our analysis limit our estimates of soil-based $CO_2$ removal potential to much smaller values than previous estimates. Given the combination of county-specific technical and economic potential, we found that cover crops contributed more than 75% of the potential 130 million tonnes of cumulative economically viable $CO_2$ removal for a $CO_2$ price of $40 per tonne. Commodity cropland in the Lower Great Lakes, Southeast, and Lower Mississippi River regions contributed particularly high amounts of soil-

**Table ES-1.** *Summary of profitable soil-based carbon removal outcomes for the combination of cover cropping, perennial field borders, and perennial carbon crops on commodity-grain cropland in the contiguous United States across a range of carbon prices.*

| Carbon Price | Economically Viable Land Area | Mean Annual $CO_2$-Removal Rate | Climate Benefit *(incl. avoided emissions)* | Cumulative $CO_2$ Removal 2025–2050 | Cumulative Climate Benefit *(incl. avoided emissions)* 2025–2050 |
|---|---|---|---|---|---|
| *\$/tonnes $CO_2e$* | *million hectares* | *million tonnes $CO_2$ per year* | *million tonnes $CO_2e$ per year* | *million tonnes $CO_2$* | *million tonnes $CO_2e$* |
| 0 | 2 | 4 | 2 | 29 | 65 |
| 40 | 5 | 9 | 6 | 130 | 187 |
| 100 | 23 | 37 | 37 | 854 | 936 |

*** For carbon-crop assessments, costs are more than offset by the income from selling biomass; not included here.

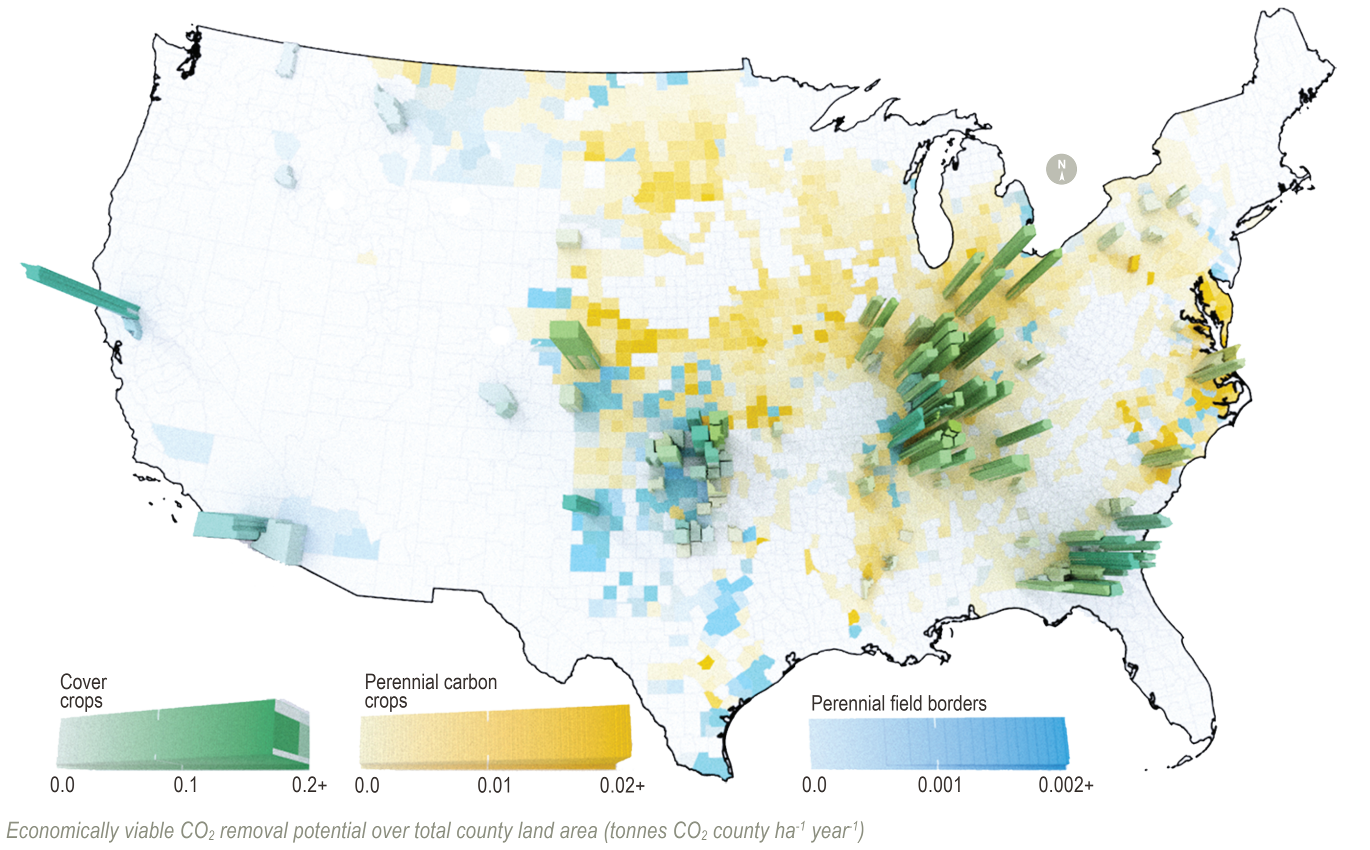


**Figure ES-9.** *County-level potentials for soil-based $CO_2$ removal from planting perennial carbon crops (yellow), cover crops (green), and perennial field borders (blue); boldest colors indicate areas of highest potential within each practice. Counties where multiple practices are possible have multiple colors overlaid. Cover cropping (green) is mapped on a scale that is one order of magnitude greater than perennial carbon crops (yellow), which in turn is mapped on a scale that is one order of magnitude greater than perennial field borders (blue). The vertical height of the county is scaled to the total economically viable $CO_2$-removal potential within the county. Land area under each practice shown here is for a \$40/tonne $CO_2e$ climate-benefit price. Scale bar is in units of tonnes of $CO_2e$ per year per hectare of total county land area.*

based $CO_2$ removal and storage between 2025 and 2050. Soil carbon could be increased throughout much of the cropland in the United States but is limited by appropriate land, profitability to farmers, and the need to continue producing crops the nation relies upon.

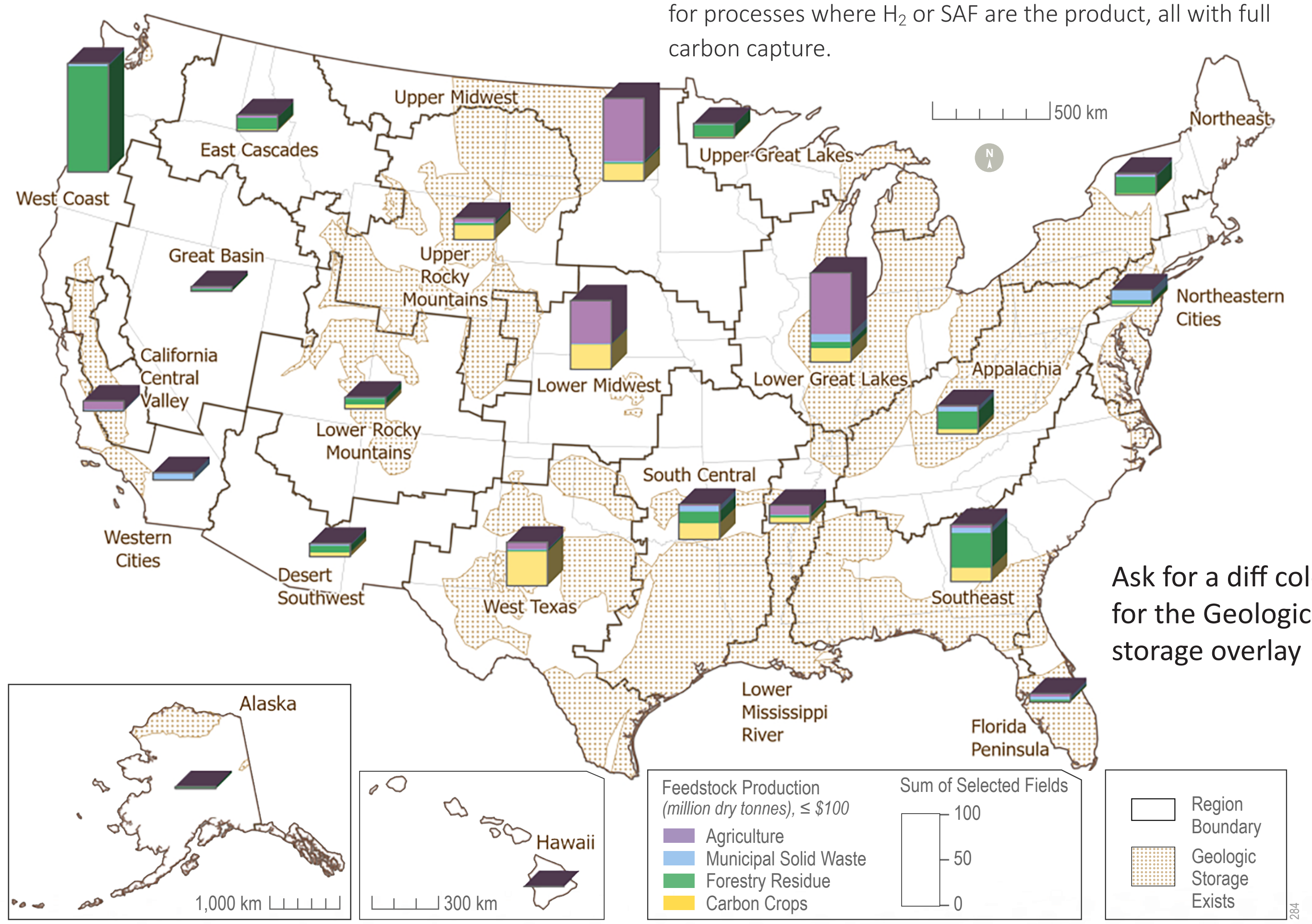
In addition to the quantitative outputs of our analysis, it highlighted three important issues for soil carbon:

- Cropland-management practices that build soil carbon also reduce soil erosion and $N_2O$ emissions, improve water retention, and provide bird and other wildlife habitat.
- While durability of soil-based $CO_2$ storage is uncertain, even short-term storage has climate benefits, especially when spread across space and time. Cropland-soil management should be considered a near-term component of a national strategy that eventually transitions the equivalent $CO_2$ storage to highly durable geologic storage.
- To avoid exacerbating existing extreme inequalities in land ownership, an equitable cropland-soil-based $CO_2$-removal incentive program must carefully consider to whom funds will flow.

## Biomass Carbon Removal and Storage (BiCRS)

All integrated-assessment model projections with a reasonable chance of limiting warming to 1.5 °C by 2100 rely on biomass carbon removal and storage (BiCRS) as a primary approach [9,10]. BiCRS takes advantage of the fact that plants capture and store $CO_2$ from the air and places value on the use of biomass for carbon removal (rather than for energy alone) (**Chapter 6 – BiCRS**). BiCRS processes convert biomass to long-lived products or to chemicals, fuels, or energy, with capture and geologic storage of $CO_2$ emissions from the conversion process. The outsized potential impact of BiCRS (durable carbon removal potential at an intermediate-level cost of <\$100/tonne $CO_2$) lies in part in its ability to generate a wide range of chemical, materials, and energy co-products from biomass, thus generating revenue streams that offset some of the carbon-removal cost. The most prominent BiCRS risks are associated with land-use changes—if they displace natural ecosystems and food production—the latter creating a risk of indirect land-use change and unforeseen adverse climate impacts. Other major risks are associated with the complexity of a carbon-removal pathway that requires collaboration of biomass producers, biorefinery and geologic storage operators, and bioproduct and $CO_2$ distributors. We explicitly consider these risks in Chapter 6 – BiCRS, as well as in chapters focused on transportation, cross-cutting issues, EEEJ, and regional opportunities. Further, we present a comprehensive analysis linking soil-based carbon removal pathways and BiCRS. **Figure ES-10** shows one integrated evaluation of cross-cutting BiCRS requirements, illustrating the available biomass in each region of the country and its proximity to the best geologic storage.

A key tradeoff for biomass use is between the production of SAF, for which biomass may provide a domestic source with a low-carbon footprint, and the production of hydrogen, which maximizes the amount of $CO_2$ removed while minimizing the costs. The nation will have to weigh all the topics considered in this report to manage this tradeoff: there are multiple ways to use our fundamentally limited resources. The choice of how to use resources (biomass, available land, renewable energy) may be more important than cost. To illustrate, **Table 269** compares three different biomass supply options, for processes where $H_2$ or SAF are the product, all with full carbon capture.



Ask for a diff color for the Geologic storage overlay

**Figure ES-10.** *BiCRS biomass supply according to biomass 'feedstock' type for each $CO_2$-removal region in the United States. The biomass assessment shown here is our Zero-Cropland-Change case, which includes wastes and residues in addition to carbon crop potential modeled on non-cropland for 2050. The shaded regions correspond to land areas with known high-quality geologic storage potential.*

Our BiCRS analysis generated several key findings:

- BiCRS' carbon removal rate in the United States can exceed 800 million tonnes of $CO_2$ per year at a net cost less than \$100/tonne of $CO_2$, with no impact on cropland or commodity prices (Zero-Cropland-Change case).
- Every region has a role to play in BiCRS-based carbon removal; interaction between regions is required in most cases for the full value chain. The Lower Great Lakes and Southeast regions stand out for abundant biomass co-located with large land areas with geologic storage potential.
- We found a wide range of biomass availability for BiCRS in a mature market—from 0.5 to nearly 1 billion tonnes per year depending on the approach to land-use.
- BiCRS pathways that produce hydrogen are among the lowest cost (per tonne $CO_2$) because of the high amount of $CO_2$ removed per tonne of biomass and the revenue available from the sale of $H_2$. However, biomass is also vitally needed to produce SAF, which also requires $H_2$. We did not deconflict these uses but give options for carbon-removal aspects of both. A wide range of technologically mature BiCRS pathways exist that can serve social, political, regional, and national goals while reducing the burden of pollution on communities.
- To implement BiCRS-based $CO_2$ removal, hundreds of mid- to large-scale facilities must be built across the United States that link reliable biomass supply, biorefineries, geologic storage, and bioproduct distribution. The complexity and scale of the required implementation, coupled with the potential for significant climate and regional benefit, requires urgent action.
- With purposeful scale-up that assesses the baseline pollution burdens of each feedstock and the people who are inequitably exposed to them, BiCRS can be used as a tool for restorative environmental justice for a number of environmental pollutants (e.g., persistent chemicals and fine particulate matter, odorific gases, and excess nutrients).

**Table ES-2.** *Results overview for three biomass scenarios (at \$73/tonne biomass) considered in this report. The Baseline case includes only wastes, agricultural and forestry residues, and "western-forest restoration" biomass. Zero Cropland Change includes the Baseline (biomass wastes and residues) amount and adds carbon crop cultivation on Conservation Reserve Program (CRP) land, marginal land, and lands made available due to vehicle electrification without impacting other cropland or modeled crop prices. Maximum Economic Potential calculates market driven biomass potential, (with sustainability constraints), following methods of the Billion Ton Report [11]. Annual $CO_2$ removal potential in 2050 includes the sum of BiCRS and soils-based removal. See Chapters 3 and 6 for full details of these cases.*

| Biomass Assessment (2050) | Land Area Change | Carbon Crop Yield | Commodity Price Change | Associated Soil-Based Removal | Annual $CO_2$ Removal Potential (for soil + BiCRS) in 2050 |
|---|---|---|---|---|---|
| | *(million hectares)* | *(million tonnes/year)* | | *(million tonnes/ year in 2050)* | *(million tonnes/year)* |
| Baseline | 0 | 0 | 0 | 0 | 693 |
| Zero Cropland Change | 29 | 133 | 0 | 4 | 903 |
| Maximum Economic Potential | 25 | 297 | +6 % corn,<br>+12 % wheat, +8 % soy | 6 | 1225 |

**Table ES-3.** *Comparison of the maximum carbon removal and product creation for use of low-moisture biomass to make $H_2$ compared with making SAF—with full carbon capture—on the most efficient processes available.*

| Biomass Assessment (2050) | Net $CO_2$ Removal Potential | | $CO_2$ removal cost | | Product Volume | | |
|---|---|---|---|---|---|---|---|
| | *(million tonnes/year)* | | *(\$/tonne $CO_2$)* | | *(million tonnes of $H_2$ or billion gallons of SAF)* | | |
| | $H_2$ | SAF | $H_2$ | SAF | $H_2$ | SAF | SAF Equiv* |
| Baseline | 614 | 364 | 84 | 151 | 27 | 8 | 20 |
| Zero Cropland Change | 820 | 490 | 91 | 146 | 34 | 11 | 28 |
| Maximum Economic Potential | 1140 | 694 | 90 | 149 | 50 | 16 | 39 |

*Multiple types of liquid products can be made in addition to SAF depending on reaction conditions. SAF-equivalent production includes aviation fuels, gasoline, and diesel, all in units of SAF gallons (**Chapter 6 – BiCRS**).

## Direct Air Capture (DAC) with Storage (DACS)

We evaluated the two types of DAC that have been best developed to date: absorbent systems, such as those developed by Climeworks and Global Thermostat, and solvent systems, such as the process used by Carbon Engineering (**Chapter 7 – DACS**). DACS has the potential for billion-tonne-scale atmospheric $CO_2$ removal but will require concurrent buildout of energy resources that go beyond what is required for decarbonizing the electrical grid. For renewable-electricity-powered DACS, the land required for deploying wind or solar photovoltaic electricity generation limits the maximum potential capacity. However, there are several US regions with significant potential to generate renewable electricity beyond what is needed for decarbonizing the electrical grid; some of these regions intersect with the geologic formations required to safely store the $CO_2$ removed from the atmosphere (**Figure ES-11**). Our domestic natural-gas reserves could also enable additional regions to participate in large-scale DACS projects—with capture of the emissions from using natural gas—if we decide as a society to use these resources for this purpose. While the potential for DACS deployment is massive, it will likely remain the most expensive $CO_2$-removal option out of those considered in this report. As such, the ability to reduce the cost of the technology, regulatory mechanisms or incentives, and maturation of a carbon-removal marketplace will likely determine the extent of DACS deployment. Estimating the 2050 costs of DACS is difficult today—we applied standard learning-curve analysis with detailed consideration of specific types of equipment and processes, which have different learning rates. However, of all the costs in this report, DACS should be considered the least constrained and the most likely to show large absolute cost improvements generated by future research and development. Key DACS findings include the following:

- We estimate that the United States has a technical potential capacity of over 9 billion tonnes of $CO_2$ per year for DACS powered by renewable electricity and of over 4 billion tonnes of $CO_2$ per year for DACS powered by natu-

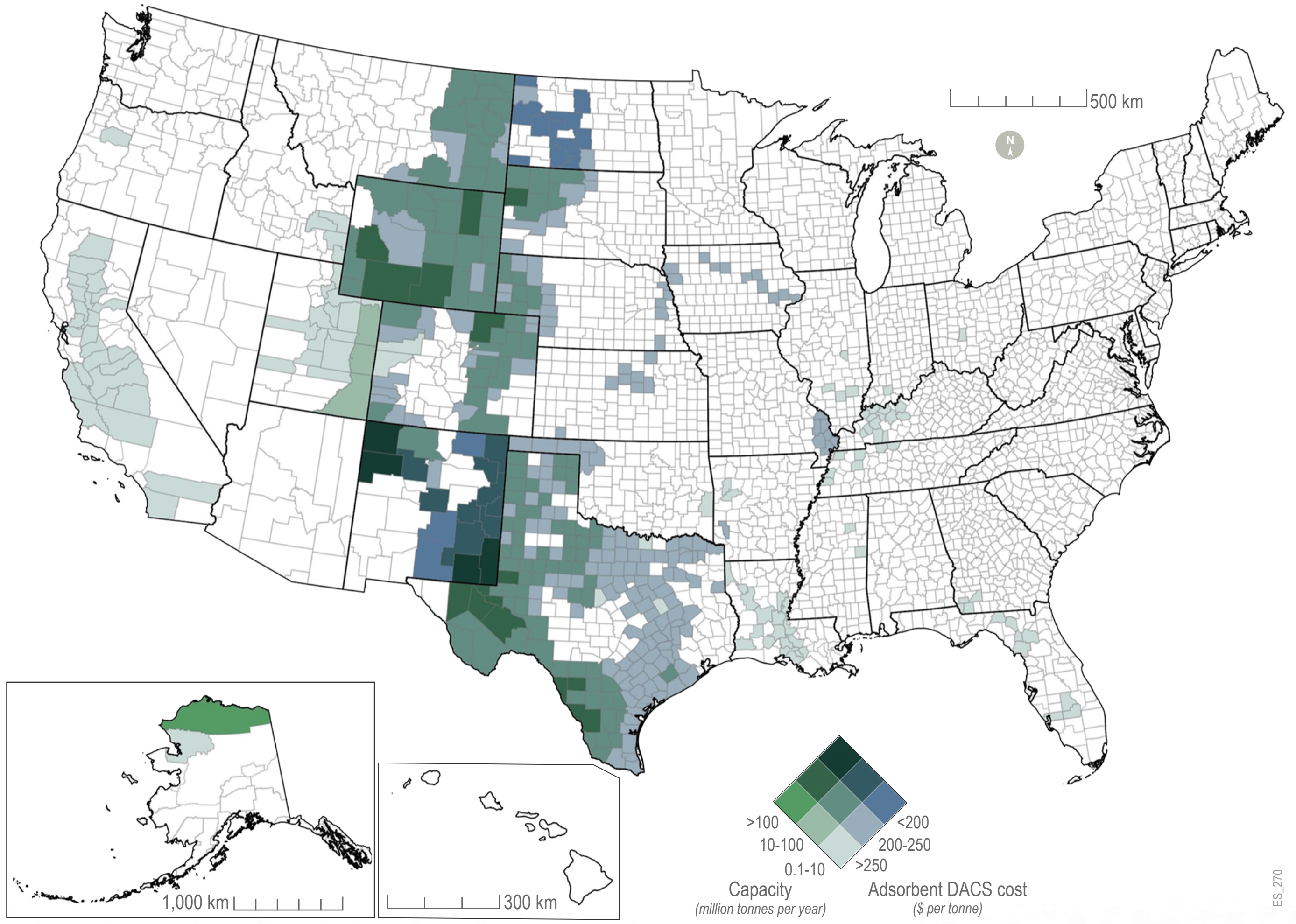


**Figure ES-11.** *County-level assessment of potential capacity of solid-adsorbent DACS powered by renewable electricity and co-located with geologic storage. Costs are based on adsorbent DACS utilizing a heat pump to provide the thermal energy required. Darker shades of green indicate higher county-level capacity, darker shades of blue indicate lower cost for DACS.*

ral-gas reserves, at costs predominantly ranging from \$200 to \$250/tonne $CO_2$.

- The regions of West Texas, Upper and Lower Rocky Mountains, and parts of the Upper and Lower Midwest have the largest potential for billion-tonne-scale DACS deployment with renewable energy, while Appalachia, West Texas, South Central, and Alaska have large potential for DACS deployment with natural gas.
- In the near-term, initial DACS deployment will serve to identify critical areas for technology improvement to more rapidly reduce the cost of DACS-based carbon removal; however, there is a need for improved standards for calculating the net carbon negativity of a DACS process.

## $CO_2$ and Biomass Transportation.

Both BiCRS and DACS are multi-step pathways with activities that may not be co-located. This requires a transportation system for moving $CO_2$ and/or biomass (Figure ES-12). We used a combined cost and transport network analysis to suggest transport modes that would be most economical for a given route. Key transport findings include:

- While pipelines are often the most efficient form of $CO_2$ transportation, they are not a silver bullet; other modes (e.g., rail, trucking, barges) are viable alternatives that have competitive or prevailing economics in certain cases.
- Building a small number of new pipelines would allow movement of BiCRS-produced $CO_2$ from regions of high biomass availability to those with established $CO_2$-storage.
- The infrastructure capacity required to transport biomass and $CO_2$ (for BiCRS) is of a similar magnitude to what the United States currently uses for transporting corn-ethanol plus pulp/paper industry products and hazardous class II liquids, respectively.
- Regions with high opportunity for DACS overlap with areas of the country experiencing persistent job loss in fossil-fuel sectors; prioritizing DACS development in these regions may help maximize socioeconomic co-benefits like economic solvency and infrastructure improvements.

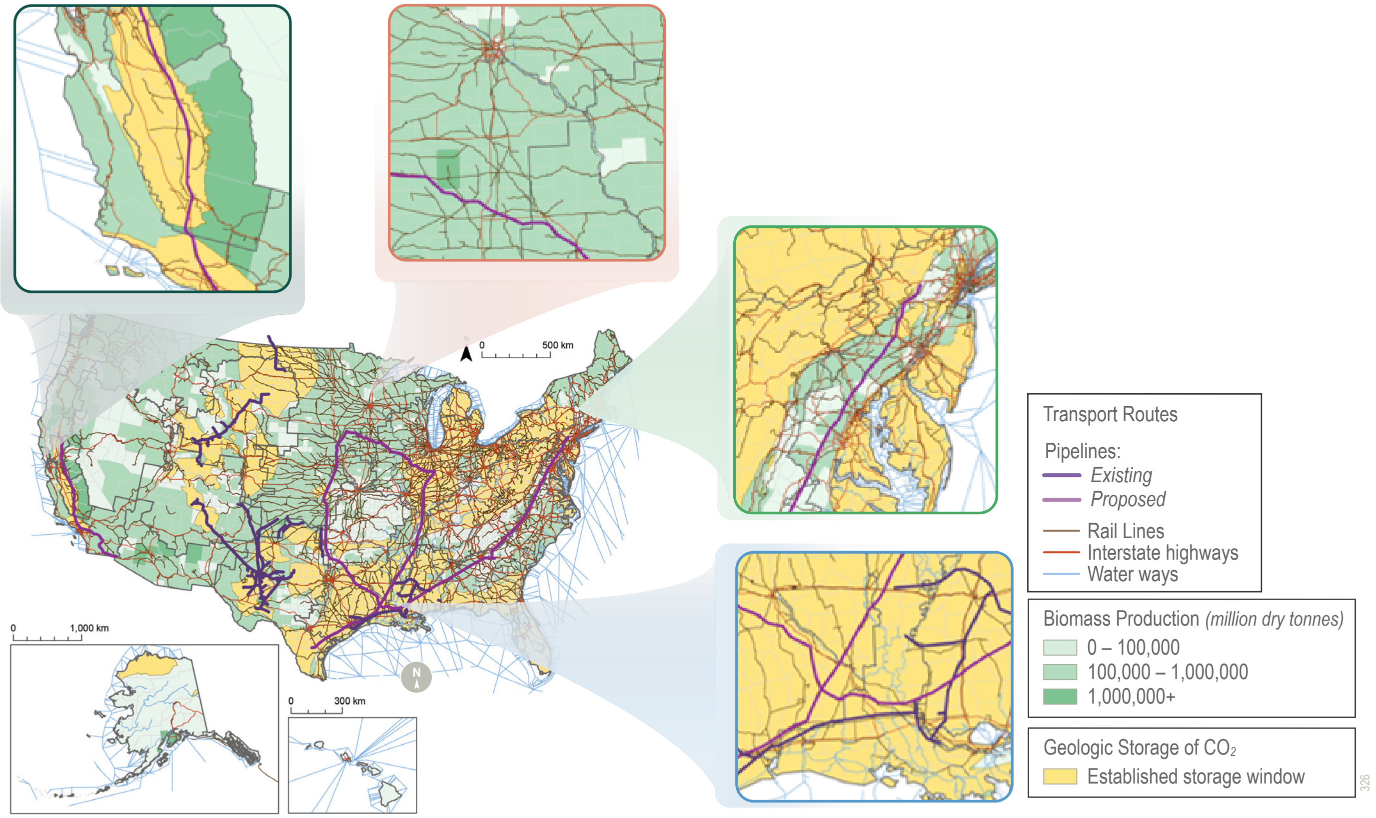


**Figure ES-12.** *Map of networks for transporting biomass and $CO_2$, overlaying geologic $CO_2$ storage and biomass production. The four highlighted regions illustrate (A) CA, where pipelines and rail coincide and coastal shipping could complement; (B) MN, which has large biomass sourcing potential but no viable $CO_2$ storage; (C) the Gulf Coast, with existing and proposed pipelines, viable $CO_2$ storage, and the ability to import $CO_2$ from other regions; and (D) the Northeast, where rail and trucking could be used to transport biomass and $CO_2$ locally, while pipelines would be needed to transport $CO_2$ to other regions. Transportation options are currently limited and will need to scale to implement BiCRS and DACS pathways.*

## Cross-Cutting Resource Requirements and Environmental Impacts.

**Chapter 8 – Cross-Cutting** pulls together scenarios for each $CO_2$-removal strategy to assess land- and water-resource requirements, as well as implications for air quality. We developed a land-suitability and sequential down-selection approach to understand how different constraints affect the area available for land-intensive $CO_2$-removal pathways. For example, **Figure ES-13** shows the process of selecting suitable land both for carbon crops needed to supply BiCRS facilities and for solid-adsorbent DACS co-located with renewable energy. We reserved wind- and solar-resource-rich lands for decarbonization of the electricity grid to ensure that DACS facilities do not compete with these decarbonization efforts. We also evaluated the alignment of water needs for DACS and BiCRS facilities with future drought-risk projections under climate change, highlighting the need to be mindful of local water resources when constructing new DACS facilities. Finally, we discussed the potential for $CO_2$-removal strategies to reduce air-pollution emissions and possibly introduce some new air-pollution sources that could impact fine particulate matter concentrations across the United States. Our analyses generated several key cross-cutting findings:

- Pursuing large-scale $CO_2$ removal at (or exceeding) 1 billion tonnes annually is possible while still reserving land and renewable-energy resources for decarbonization
- Carbon crops require approximately 20 million hectares to remove around 0.9 billion tonnes of $CO_2$ per year, and solid-adsorbent DACS co-located with renewables requires 0.8 million hectares to remove an additional 0.2 billion tonnes of $CO_2$ per year. The area potentially suitable for DACS co-located with renewables and on-site geologic storage is vast: 33 million hectares across the United States. Planting pine forests in the Southeast would add an additional 2.1 million hectares to the total land footprint.
- Water requirements for BiCRS and DACS facilities will likely sum to less than the equivalent of 1% of total US irrigation water demand. However, water consumption for DACS is uncertain, and much of DACS potential exists in regions subject to future drought risk. Local streamflow constraints may be an important limiting factor in where both BiCRS and DACS facilities can be built.
- Large-scale $CO_2$ removal, particularly when pursued in parallel with decarbonization, is likely to result in substantial air-quality improvements across the United States. Improved forest-management practices can reduce

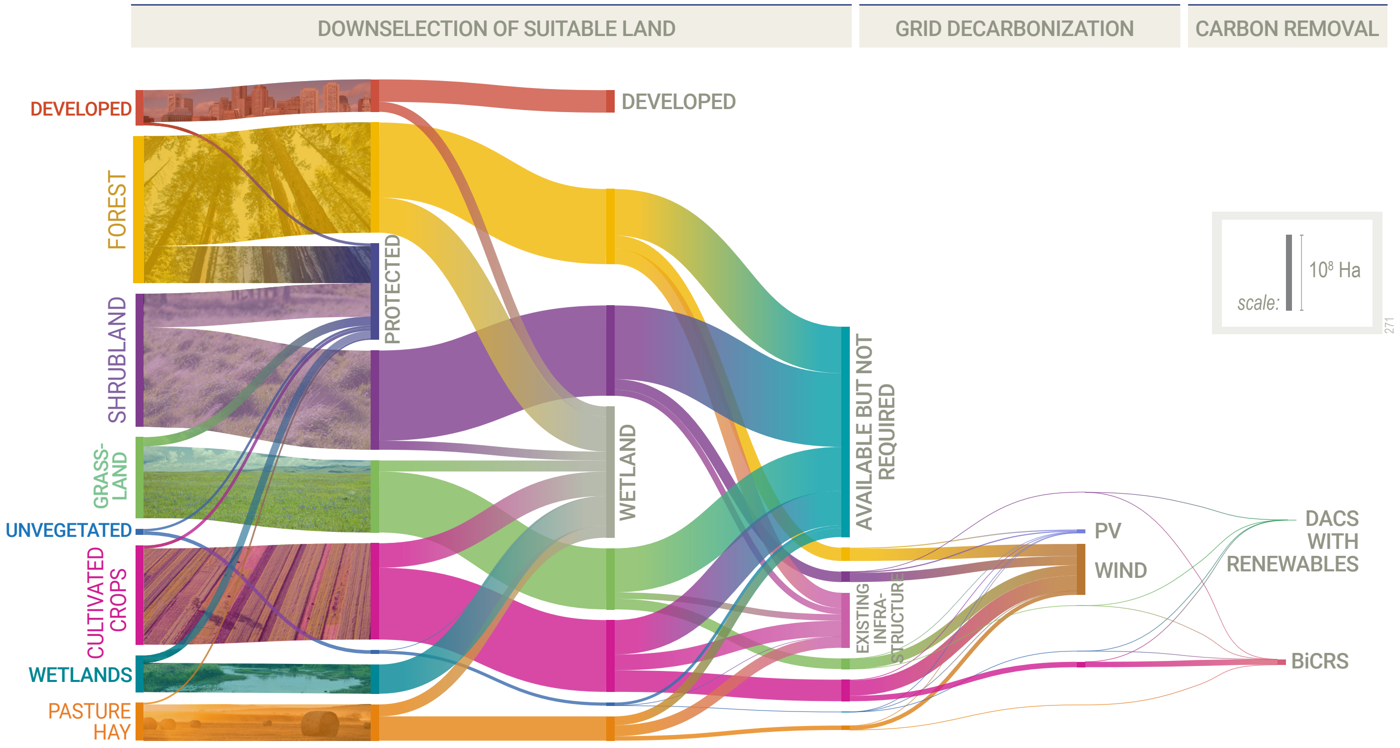


**Figure ES-13.** *Downselection of land resources across the United States for large-scale carbon removal, accounting for grid decarbonization needs. The lefthand side summarizes all land cover types in the United States. We excluded wetlands, protected lands, developed land, forests, and land occupied by existing infrastructure from consideration. Major land requirements to reach at least 1 billion tonnes of $CO_2$ removal are shown on the far righthand side, including land for cultivation of carbon crops and land for adsorbent DACS co-located with renewable energy generation. Original land cover data is from the National Land Cover Database. For clarity, land originally classified as "herbaceous" is labeled here as grassland and land classified as "barren" is labeled unvegetated.*

emissions from large wildfires. Emissions from BiCRS and DACS facilities are uncertain and will depend, in part, on carbon-capture-solvent or-adsorbent thermal decomposition and loss to the atmosphere.

### Regional Opportunities.

Every US region has unique opportunities to play a role in $CO_2$ removal. Cooperation between regions toward national goals is critical for achieving a carbon-neutral future and a higher quality of life throughout the country. We identified 22 $CO_2$-removal-based regions where the diverse geography, geology, climate, biomass, economies, histories, and populations create common opportunities and pose distinct constraints for $CO_2$ removal (Figure 262). To make these geographic delineations, we started by overlaying forestry maps, agriculture charts, and BiCRS-biomass regions, and we then factored in county-level DACS analysis, geologic storage areas, and other variables. Nearby counties with similar $CO_2$-removal narratives were grouped into regions, and we imposed constraints that each region had to be contiguous. **Chapter 10 – Regional Opportunities** provides an assessment of the strengths and challenges for each region in actively pursuing a $CO_2$ removal and highlights the synergies between regions that make collaborative efforts across the nation greater than each region working alone.

## How to Use this Report

The analyses in this report are designed to provide support for decisions on the siting and sizing of $CO_2$-removal approaches. This report is not a plan for those activities. We provide the best estimates available for resource demands, costs, and impacts of $CO_2$-removal approaches so that, at a county-scale or larger, decision-makers have a basis for choosing among the large number of $CO_2$-removal options. Readers can begin with the techniques of interest; these are described in detail in **Chapters 2** – Forests, **3** – Soils, **4** – Geologic Storage, **6** – BiCRS), and **7** – DACS). Alternatively, readers can begin by looking at their region, as described in **Chapter 10** – Regional Opportunities, and consider the primary benefits and limitations described there. Information regarding transportation of $CO_2$ and biomass throughout the country and common cross cutting resources, such as water and energy can be found in **Chapters 5** – Transportation and **8** – Cross-Cutting, respectively. Finally, each chapter that covers a $CO_2$-removal approach includes a brief discussion of the EEEJ issues pertinent to its technology, while **Chapter 9** – EEEJ provides a more detailed discussion of our EEEJ analyses methods and results.

Because this report is a supply analysis built up from the highest-resolution data available, it may provide different overall $CO_2$-removal capacities than previous integrated-assessment models or top-down economic models. For specific projects and regional decisions, we believe our analysis will be distinctly useful for weighing alternatives and local benefits.

# REFERENCES

1. The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050. Published by the United States Department of State and the United States Executive Office of the President, Washington DC. November 2021. https://unfccc.int/documents/308100
2. 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-carbonpollution-air)
3. Office of Fossil Energy and Carbon Management Carbon Negative Shot Summit, https://www.energy.gov/fecm/carbon-negative-shot and https://www.energy.gov/fecm/carbon-negative-shot-summit
4. Chloé Fauvel et al., Regional implications of carbon dioxide removal in meeting net zero targets for the United States. Environmental Research Letters, 2023. 18(9): p. 094019, https://iopscience.iop.org/article/10.1088/1748-9326/aced18/meta
5. Jan C. Minx et al., Negative emissions—Part 1: Research landscape and synthesis, 2018. Environmental Research Letters 13(6): p. 063001, https://iopscience.iop.org/article/10.1088/1748-9326/aabf9b/meta
6. Sabine Fuss et al., Negative emissions—Part 2: Costs, potentials and side effects. Environmental Research Letters, 2018. 13(6): p. 063002, https://iopscience.iop.org/article/10.1088/1748-9326/aabf9f/meta
7. DOE Sustainable Aviation Fuel Grand Challenge Roadmap, https://www.energy.gov/eere/bioenergy/articles/sustainable-aviation-fuel-grand-challenge-roadmap-flight-plan-sustainable
8. Charles D. Kolstad, What Is Killing the US Coal Industry? Stanford Institute for Economic Policy Research, 2017. https://siepr.stanford.edu/publications/policy-brief/what-killing-us-coal-industry
9. Intergovernmental Panel on Climate Change (IPCC). Global Warming of 1.5 °C (IPCC Special Report on Impacts of Global Warming of 1.5 °C above Pre-industrial Levels in Context of Strengthening Response to Climate Change, Sustainable Development, and Efforts to Eradicate Poverty). 2022. Cambridge University Press, Cambridge; DOI: 10.1017/9781009157940. https://www.ipcc.ch/sr15/
10. Joeri Rogelj, et al., Scenarios towards limiting global mean temperature increase below 1.5 °C. Nature Climate Change, 2018. 8(4): p. 325-332, https://doi.org/10.1038/s41558-018-0091-3
11. Matthew H. Langholtz, B. J. Stokes, and L. M. Eaton. 2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy. 2016. United States; 10.2172/1271651. https://www.osti.gov/biblio/1271651