CHAPTER 10

Regional Opportunities

SUMMARY

We identified 22 regions where differences in geography, geology, climate, forest type, biomass, economies, histories, and populations create distinct opportunities and challenges for carbon removal. In this chapter, we illustrate these unique attributes of each region, explore how they shape local opportunities for CO_2 removal, and highlight the synergies that exist between regions. Readers can approach this chapter as an overview of the key opportunities and considerations for the places they call home to participate in CO_2 capture, conversion, and storage; they can then explore each CO_2-removal pathway in depth within the other chapters of this report. The goal of this chapter is to illuminate the nuances in CO_2 removal capacity and costs across the country; as our analysis makes clear, every region of the United States has a CO_2 removal opportunity and a unique story to tell.

Key Findings

We quantitatively defined 22 regions based on the geographic distribution of primary carbon resources—namely forest residue, agricultural feedstocks, and municipal solid waste (MSW)—and carbon-storage potential, including geologic storage, cropland soils, and forest type. Some of the key findings include:

- Most regions may have excellent biomass sources or geologic storage potential but will likely need to interact with one another to complete the entire pathway
- There are wide varieties of forests and agriculture across the country, but concentrated in the Midwest and Southeast there are biomass residues that could more than cover the 1 gigatonne per year US carbon-removal goal
- Beneath our feet, the capacity for CO_2 storage is vast, particularly in West Texas and the Upper Rocky Mountain regions, but in some regions, notably the Northwest and Hawai'i, additional studies are needed to improve our understanding of geologic storage potential
- Western Cities and Northeastern Cities regions produce large amounts of carbon-rich MSW that can be diverted from landfills to more permanent and economical forms of carbon storage

CHAPTER SCOPE

This chapter explores regional aspects of the many resources and pathways for CO_2 removal in the United States.

- Biomass carbon removal and storage (BiCRS)
- Forest carbon reservoirs
- Cropland soils and agriculture health
- Direct air capture (DAC)
- Geologic storage
- Transportation infrastructure
- Ecosystem and human wellbeing
- Electricity consumption, water use, and fire prevention

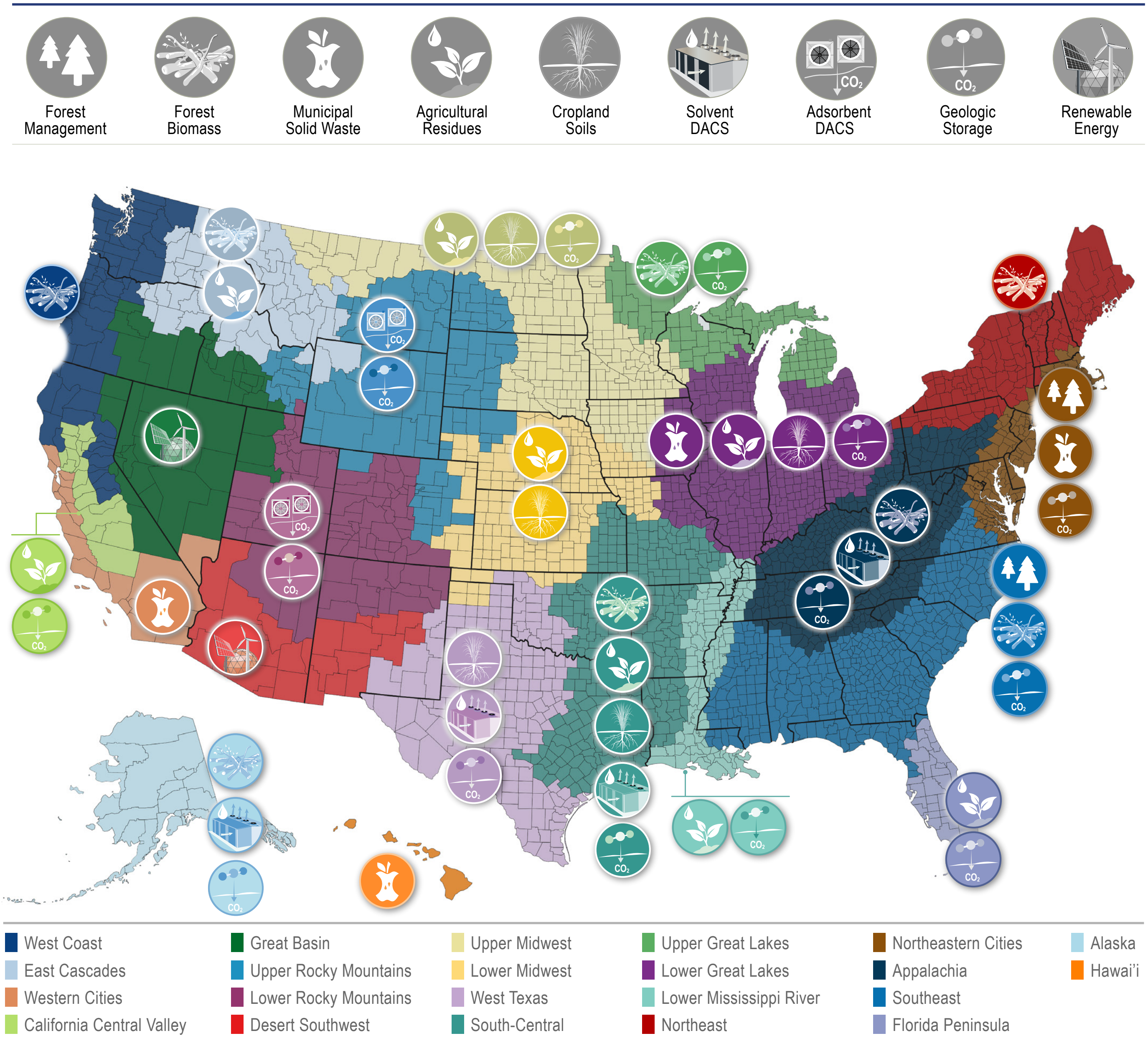


Figure 10-1. *Regions map with county delineation and primary carbon-removal resources. Regional boundaries are delineated based on quantitative assessments of carbon-removal resources with boundary conditions such as requiring each region to be contiguous, including bodies of water. The icons qualitatively highlight key regional resource contributions to CO_2 removal.*

We also note key externalities of CO_2 removal that impact both human and environmental health and wellbeing, including the following:

- Improved forestry management in the West can improve air quality in the Midwest
- Soil conservation practices can help prevent soil erosion around the Ohio and Mississippi River Basins
- Direct air capture with storage (DACS) and carbon-management projects can provide valuable jobs throughout the Rocky Mountains

Collectively, these findings indicate that cooperation between every region is important for achieving not only a carbon-neutral future but also a higher quality of life throughout the United States.

Overview

The United States is made up of geographically diverse and distinct regions, each of which contains an array of resources that can contribute toward carbon-removal targets. Here, we have assigned each of the more than 3000 US counties to one of 22 regions, prioritizing the carbon-resource availability in each region while also accounting for energy equity and environmental justice (EEEJ) considerations in addition to other resources such as geologic CO_2-storage capacity, energy sources, and water availability. We determined the regional delineations 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 the geographic carbon-storage potentials in forest biomass, cropland soils, and geologic sites. Third, we analyzed the cross-cutting factors, including watersheds, energy-generation capacity, and current and potential transportation resources. Fourth, we considered regional land ownership and factors to 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 for each region. We acknowledge that, in some cases, the county granularity may not be sufficient to strictly distinguish between region boundaries, particularly near the Continental Divide where individual counties cover very large areas of land. Where necessary, we describe blurred boundaries between regions where multiple considerations required decisive prioritization, such as the overlaps between farm and forestlands in the Midwest. Included in that decision was the choice to make each region contiguous (including bodies of water) for clarity, a nontrivial task when parsing through densely urban and biomass-rich regions that are intertwined along the Eastern seaboard. Because of these nuances, thoughtful consideration of nearby regions, in addition to analyses of the particular region of interest, can improve outcomes.

Table 10-1. *Regional comparison of carbon resources and carbon-removal strategies on an annual quantity basis. The forest growth potential represents an annual baseline projected growth of existing forests with no management changes. The Cropland Soils potential assumes a carbon price of \$40/tonne CO_2. Biomass and transportation data assume 2050 zero-cropland-change which addresses the concern of losing agricultural land for food production by imposing a constraint that only marginal lands and non-cropland areas can be used for the production carbon crops—plants specifically grown to remove CO_2 from the atmosphere.*

	Alaska	Appalachia	California Central Valley	Desert Southwest	East Cascades	Florida Peninsula	Great Basin	Hawai'i	Lower Great Lakes	Lower Midwest	Lower Mississippi River	Lower Rocky Mountains	Northeast	Northeastern Cities	South Central	Southeast	Upper Great Lakes	Upper Midwest	Upper Rocky Mountains	West Coast	West Texas	Western Cities	TOTAL
BIOMASS *(million tonnes per year)*																							
Agriculture residues	0. 0	1.4	8.3	1.3	2.6	3.0	1.8	0.0	58.4	40.9	8.9	0.4	1.9	0.8	1.8	3.2	1.1	59.8	4.1	0.9	6.7	1.1	**208.4**
Forest Biomass	2.0	16.9	0.1	6.4	11.2	1.4	2.1	0.0	5.7	0.3	2.0	5.6	15.7	4.1	11.1	33.0	11.1	1.2	1.8	100.4	1.2	0.3	**233.5**
Municipal Solid Waste	0.1	4.3	1.2	1.1	0.4	2.9	0.4	0.1	7.5	0.7	0.9	1.0	1.7	9.0	5.2	5.0	0.4	1.3	0.8	1.9	1.1	5.7	**52.4**
Carbon Crop	0.0	4.6	0.1	3.9	1.5	0.9	0.4	0.0	13.4	23.6	5.4	4.2	1.3	1.7	15.3	13.2	1.2	16.4	13.8	0.4	32.6	0.1	**153.9**
Transportation *(million tonnes per year)*																							
Truck	-	21.8	5.5	5.6	5.7	2.7	5.6	-	42.6	28.7	2.6	2.6	8.2	16.1	42.2	34.8	5.4	28.3	18.5	41.4	23.2	2.8	**344.5**
Rail + Truck	-	0.0	0.0	4.4	4.3	0.0	2.7	-	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.0	5.0	0.0	0.0	0.0	0.0	**21.3**
Pipeline	-	0.0	0.0	2.7	0.0	0.0	0.0	-	19.2	13.2	0.0	2.8	0.0	0.0	7.9	10.8	0.0	10.6	2.8	0.0	15.4	0.4	**85.9**
Direct Air Capture *(million tonnes CO_2 per year)*																							
Adsorbent CO_2 Removal Rate	206	6	75	34	38	1	6	-	8	253	18	700	-	-	104	4	-	169	2825	5	4837	3	**9293**
Solvent CO_2 Removal Rate	686	1300	3	-	-	-	-	-	-	-	-	198	294	-	984	58	20	58	268	4	1230	-	**5103**
Bio-Carbon Storage *(million tonnes CO_2e per year)*																							
Forest Growth	0.8	119.0	-0.1	-0.6	6.8	9.7	0.6	-	0.3	1.2	29.1	-5.1	63.9	22.4	156.6	333.2	41.7	1.7	0.1	81.6	0.8	0.1	**863.7**
Cropland Soils	-	0.5	0.3	0.1	0.2	-	0.0	-	0.9	1.7	0.6	0.6	0.1	0.2	0.3	0.7	0.6	0.17	0.1	0.2	0.1	0.0	**8.8**
Geo-Carbon Storage Area *(million hectares)*																							
Conventional *(at <\$40/tonne CO_2)*	22.0	24.0	5.4	0.0	0.7	7.6	0.1	0.0	30.1	4.3	11.6	8.1	9.9	6.5	24.7	25.1	5.6	11.6	37.2	1.3	52.5	2.0	**290.4**
Prospective	35.3	13.2	0.4	5.1	2.0	1.7	3.5	0.8	14.9	36.4	5.8	16.4	0.6	1.3	15.1	11.8	0.0	15.6	17.6	3.0	1.9	2.6	**205.2**
Basalt	14.3	0.4	0.2	3.0	11.5	0.0	16.6	2.0	0.0	0.0	0.0	3.5	1.0	0.9	0.0	0.4	6.5	1.7	1.2	11.6	0.3	0.4	**75.3**

Energy Equity and Environmental Justice (EEEJ)

The wellbeing of both people and the ecosystem within the United States is a critical first consideration for any infrastructure, industry, or activity, particularly with the goal of achieving net-zero CO_2 emissions by 2050. Collected under the umbrella of EEEJ, this regional analysis is intended to provide some key metrics for measuring wellbeing, including job creation/losses from different industries, soil erosion, air pollution (specifically particulate matter under 2.5 micrometers (PM2.5)), inclusion of tribal nations' land and economic activity, and water eutrophication from fertilizer runoff. The pathways for CO_2 capture and storage proposed throughout this report can both exacerbate inequality and provide important co-benefits depending on where and how these activities take place. Seeking out the co-benefits for enhancing place-based wellbeing while aggressively pursuing a net-zero economy can augment any carbon-removal activity.

Forests

The regions across the United States support a wide variety of forests in a diversity of climates (**Figure 10-2**), resulting in differing carbon-storage potential and risks to permanence. The overarching trends described in this regional analysis are multivariate and necessarily require nuanced local analysis. In general, forests with higher carbon-storage potential comprise trees that grow naturally at higher densities and in warmer, wetter, or more favorable climate for growth. Forests that have slower decomposition processes tend to have higher stocks of soil organic matter and carbon; this phenomenon can be a function of both weather and species-type with cooler weather slowing down decomposition and conifers shedding leaves, twigs, and other carbon-rich plant tissues that, broadly speaking, can take longer to decompose than broadleaf trees. Though not a comprehensive list, this regional analysis calls out several key tree species that are unique to certain parts of the United States. Coniferous trees include spruce, hemlock, pinyon, juniper, cypress, fir, and a wide variety of pine trees, notably the lodgepole pines of the north and the loblolly pines of the southeast. Broadleaf tree species include birch, hickory, beech, gum, elm, ash, cottonwood, laurel, aspen, oak, and maple, which is important to the ecology and economy of the northeast.

One of the drawbacks of high carbon-density forests is the risk of quickly losing that carbon from both natural and anthropogenic influences. Forests can lose carbon when trees are damaged from high winds, hurricanes, tornadoes, droughts, and ice storms. However, the impacts of wildfires in the West and deforestation leading to land conversion—which creates new agricultural lands or opens space for human development—are two of the most prominent ways forests in the United States emit carbon into the atmosphere. This permanence issue presents concerns for all ecological carbon-storage reservoirs and will benefit from further analysis, particularly as it pertains to short- and long-term land management and local job creation. Chapter 2 – Forests explores three regionally specific opportunities for forest management that are likely to promote forest resilience and protect carbon stocks from disturbances, such as wildfires, pests, pathogens, droughts, and windstorms. Across the United States, regionally specific forest-management practices could be adopted that would likely promote the resilience of both forests and their carbon stocks to future climate disturbances, thus producing forests that have high carbon-sequestration rates and are more reliable for carbon storage.

There are many important considerations for using woody biomass and forest residues for biomass carbon removal and storage (BiCRS) to balance long-term forest health with production/extraction of wood. Forest management for biomass production could consider the impact of management on biodiversity, regeneration, soil health, and other forest uses, and these considerations may create management trade-offs or be areas of management synergy, achieving multiple goals with a singular management activity [1, 2].

Cropland Soils

Soils are one of the largest terrestrial carbon reservoirs and could contribute to CO_2-removal efforts, particularly in the near-term while the development of geologic carbon-storage projects is underway. This report focuses on three soil-carbon storage and conservation practices specific to commodity croplands, explained in depth in Chapter 3 – Soils. (1) Cover cropping is a practice of planting vegetation, often rye grasses, during fallow periods between harvesting and the next planting of crops; this practice reduces soil erosion and accrues additional soil organic carbon (SOC) in the form of both aboveground and belowground biomass (i.e., roots). (2) Perennial field borders refers to the practice of planting native grasses or trees along the edges of fields to act as a wind and water runoff buffer and provides a habitat for pollinator species; field borders also reduce erosion and store carbon in plant roots but are limited in area to only the edges of crop fields, requiring crop field-area reduction of about 1%. (3) Perennial carbon crops refer to the practice of converting land from annual crops (e.g., corn used to produce ethanol) to perennial carbon-biomass crops, such as switchgrass; this practice assumes that the potential electrification of transportation, particularly the electrification of light duty

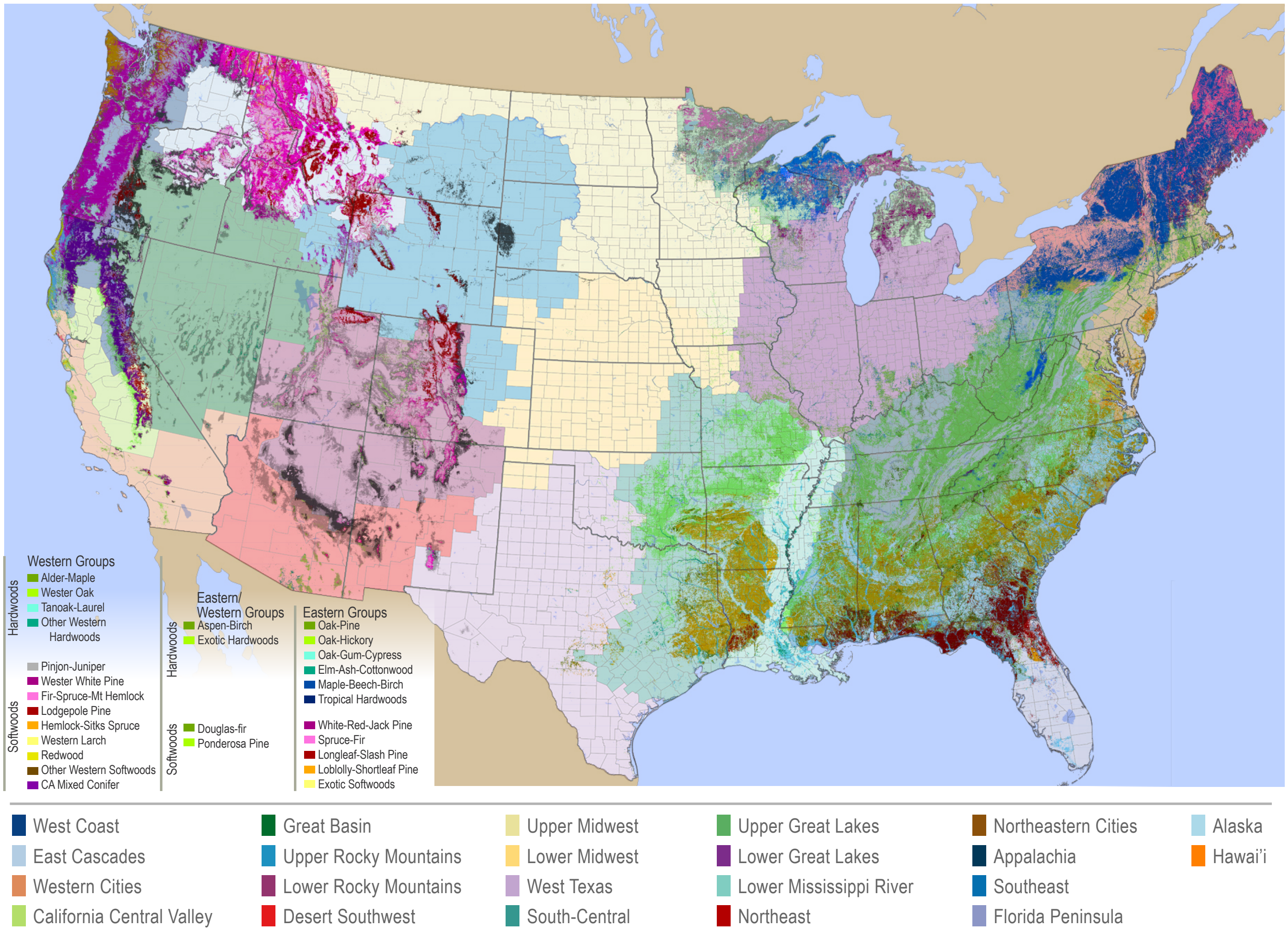


Figure 10-2. *US forest-region overlay. Many regional boundaries are delineated by the borders between forested and non-forested regions and by the transitions between different forest-majority tree species. Forest-type group data are from the US Department of Agriculture (USDA) Forest Service National Forest Type Dataset [3]. Several regions are defined by the geographic forest extent, including the West Coast and the Upper Great Lakes regions. Others are delineated by forest types, such as the boundaries between the Northeast, Appalachia, and Southeast regions.*

vehicles by 2050, can reduce the demand for bioenergy crops and that the available land can be used for CO_2 removal and soil storage without competing with food crops. In this report, we limited analysis to cropland under common annual commodity crops and did not include practices that might apply to perennial crops (i.e., orchards) or rangelands.

Biomass Carbon Removal and Storage (BiCRS)

BiCRS, described in detail in Chapter 6 – BiCRS, is the process of converting biologically produced carbon into a long-lived form out of the atmosphere. Carbon sources can include plant matter, such as forest and agricultural residues or carbon crops; manures from livestock operations; and sorted MSW, such as paper, cardboard, and food scraps.

Carbon-conversion pathways vary widely but can include combustion, fermentation, pyrolysis, and gasification, each of which is better suited to different types of biomass carbon. In particular, the moisture content, ash content, and presence of contaminants or molecular inhibitors must be considered for pairing the carbon feedstock with the conversion technology. The final products can be gaseous (e.g., CO_2), liquid (e.g., bio-oil), or solid (e.g., polyethylene or bio-asphalt), and the final storage locations can include geologic storage or storage in long-lived carbon products, such as bio-oil-based asphalt or lumber for construction. Additionally, many of the conversion pathways produce by-products that also have commercial value, such as methane (from fermentation) and hydrogen (from gasification), which greatly impacts the economics of each pathway.

Chapter 6 provides comprehensive analysis of a BiCRS optimization. In this regional analysis, we discuss only the biomass-carbon feedstocks (**Figure 10-3**) and cost breakdown from the primary analysis of different pathways on a regional basis (**Figure 10-4**). We performed the cost breakdown wholistically across the continental United States and then divided into each regional component. Also, because of the interdependency of BiCRS on carbon sources, transportation, and storage locations, we have woven these aspects into the content of each regional story.

Geologic Storage

The conventional geologic CO_2 storage described in our regional analysis includes only two categories of subsurface emplacement (the process of storing CO_2 underground). The first is CO_2 emplacement in porous sedimentary rocks within the storage-window depth range (750–4000 m)—this is sufficiently deep so that the CO_2 can be stored at high-pressures and as a dense fluid. The second is dissolved CO_2 emplacement in basaltic rocks, which may be considered *in situ* mineral trapping. We did not consider other uses of geologic and earth materials (e.g., mined minerals or waste, reactive fluids, coals and lignites, shales and unconventional hydrocarbon resources, soils, etc.). Geologic CO_2 units—volumes of rock suitable for storage—are considered "favorable" if they are low cost (<$30/tonne CO_2), which is driven both by using few wells that require leasing and by monitoring a small surface footprint. Geology that is "prospective" is not well characterized and requires additional tests to assess its storage capacity and injectivity (the allowable rate of CO_2 injection). Throughout our regional analysis, the age of the storage-target formation is given by its geologic era or period (**Figure 10-5**), with younger, stratigraphically broad, porous rock contributing to favorable geologic CO_2 storage whereas older, structurally complex

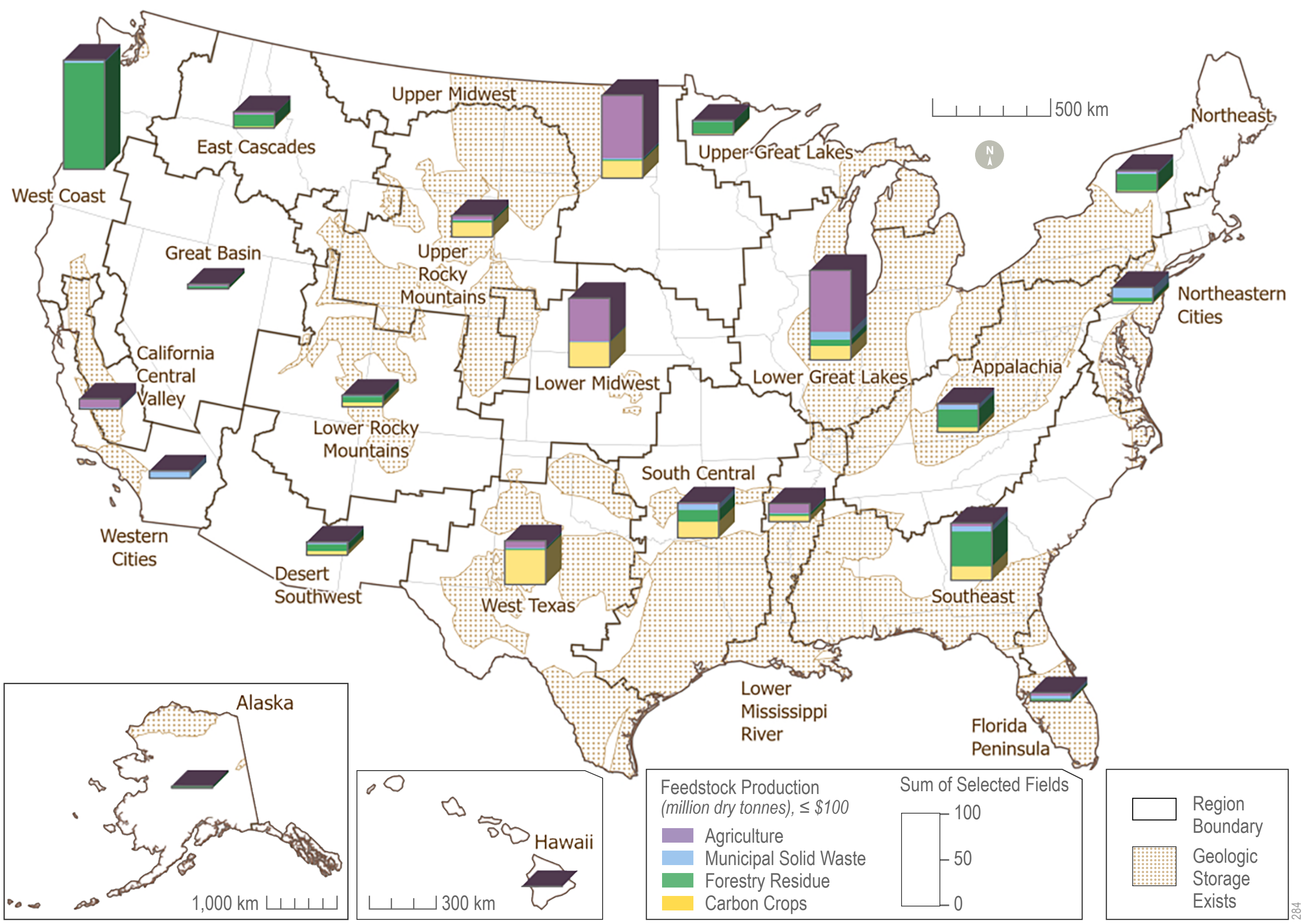


Figure 10-3. *Biomass-carbon resources in each US region with geologic storage overlay. Several regions are defined largely by feedstock production, such as agriculture in the Upper and Lower Midwest regions, whereas others contain key geologic storage windows including the West Texas and California Central Valley regions.*

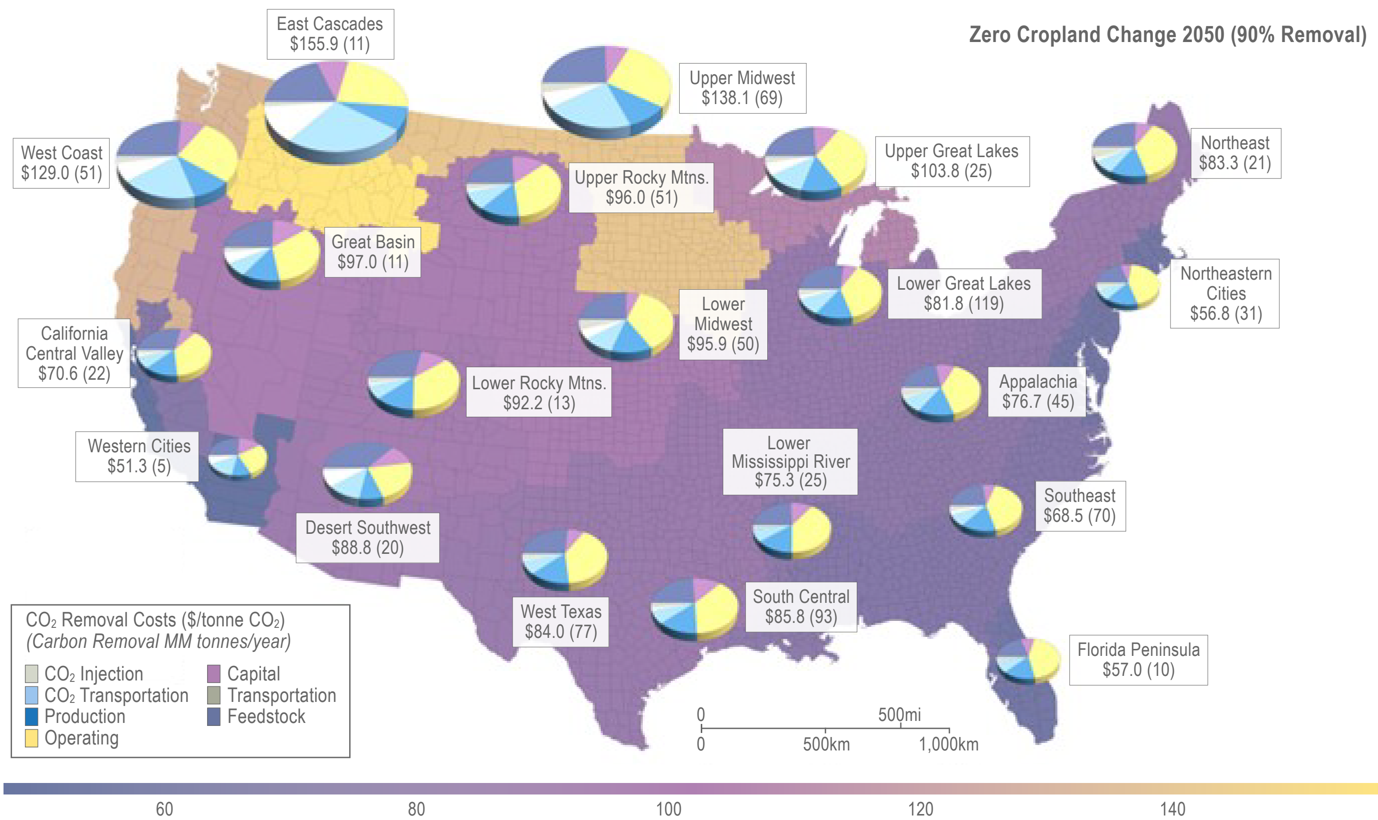


Figure 10-4. *Biomass carbon removal and storage (BiCRS)-optimized pathway costs on a regional basis.*

or non-porous (e.g., basement) rock presents challenges and limits to CO_2 storage. Because of the three-dimensional variation in a given storage unit across large areas, constraints to CO_2 storage often need to be assessed in conjunction with the local permeability and injectivity of the rock.

Transport

Transportation of carbon in this section encompasses the movement of biomass (e.g., felled trees or agricultural residue) and CO_2 from a place of origin to a permanent sink, such as a geologic CO_2-storage unit. Modes of transportation include trucks on existing roadways, trains on railways, barges on waterways, and pipelines for CO_2 transport as a dense fluid; biomass can be transported by all these modes except pipelines. Trucking is often the most ubiquitous option for transportation and the least expensive for shorter distances and smaller capacities because rail and barges have loading and unloading costs and pipelines benefit from economies of scale; trucking is particularly valuable for multimodal configurations as the “first mile” and “last mile” of a transportation sequence. Rail transport is divided into three classes based on annual revenue [4] and is the most cost-effective terrestrial mode of solid-carbon transport. Class I railroads (>\$940M revenue) comprise the 6 largest carriers, which focus primarily on transporting freight and cargo and employ a large majority (>80%) of the rail-industry workforce. Class II (revenue between \$42M and \$940M) and Class III (<\$42M revenue) operate shorter lines, often providing the additional tracks to connect the origin and/or destination of the freight trip to the main rail network.

Barge transportation encompasses all shipping but is limited by accessible waterways and requires port infrastructure for conditioning and reconditioning—the process of modifying the phase, temperature, and pressure of compressed CO_2—to provide safe transportation. Merchant CO_2 shipping has been demonstrated on a small scale (<2000 tonnes), but large-scale shipping has not yet been demonstrated [5]. Shipping in Europe is being developed for transporting CO_2 for storage below the North Sea. However, developing CO_2 shipping in the United States has been limited by the Merchant Marine Act of 1920 (Jones Act), which requires seafaring cargo between US ports to be on American-owned ships—built in the United States—and to use a majority crew (>75%) of US citizens or permanent residents.

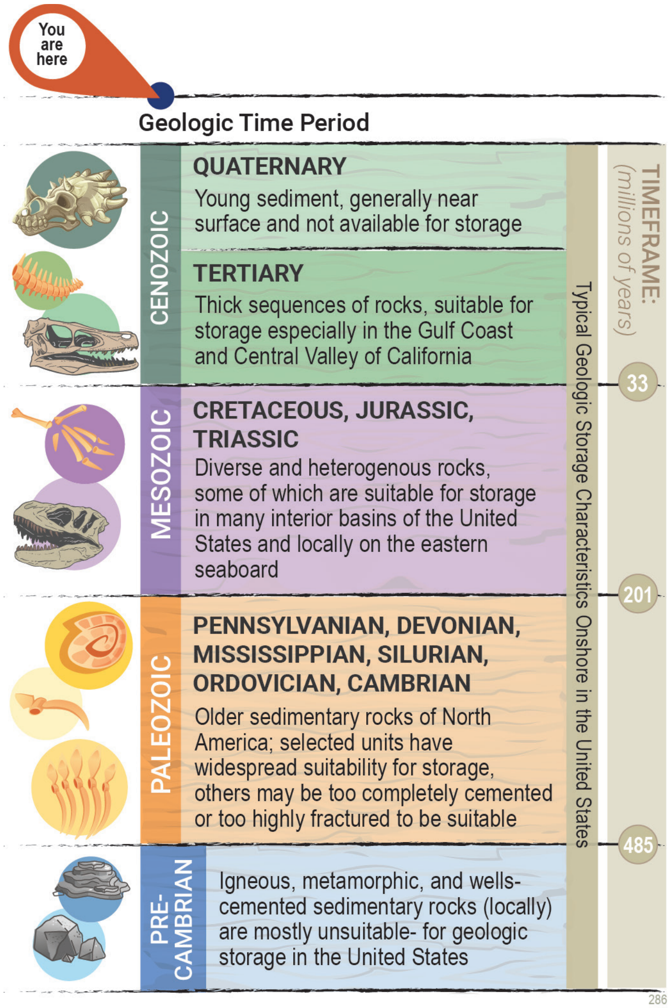


Figure 10-5. *Time chart of geologic eras.The subsurface geology under the United States varies substantially in rock type and age, both of which signficantly impact the CO_2-storage potential and are critical features to future carbon-storage sites.*

Pipelines are the least operationally expensive method to transport large volumes of CO_2 but require extensive infrastructure expansion—beyond the existing 8500 kilometers (5300 miles) scattered throughout the center of the United States—that is both capital intensive and requires community buy-in. Pipeline transport also requires CO_2 conditioning and reconditioning but different from that required for shipping [5].

Direct Air Capture with Storage (DACS)

DACS is the process of removing CO_2 that has already diffused into the atmosphere, currently at 420 parts per million. DACS has numerous pathways, many of which are still in development or in early-stage demonstrations. These pathways include solvent-based capture with liquids, such as aqueous solutions of hydroxides, and solid-adsorbent-based capture with high-surface-area materials based on amines. Different technologies have various input requirements including water, electricity, and heat, and some are influenced by temperature and humidity and are thus more advantageous in particular climates. The analysis in this report considers both solvent-based and adsorbent-based DAC, and this regional analysis focuses primarily on siting constraints, electricity prices, and proximity to suitable geologic storage sites for these two classes of DACS. Electricity and heat availability from low-carbon sources is also imperative, requiring co-location with wind, solar, and geothermal energy sources.

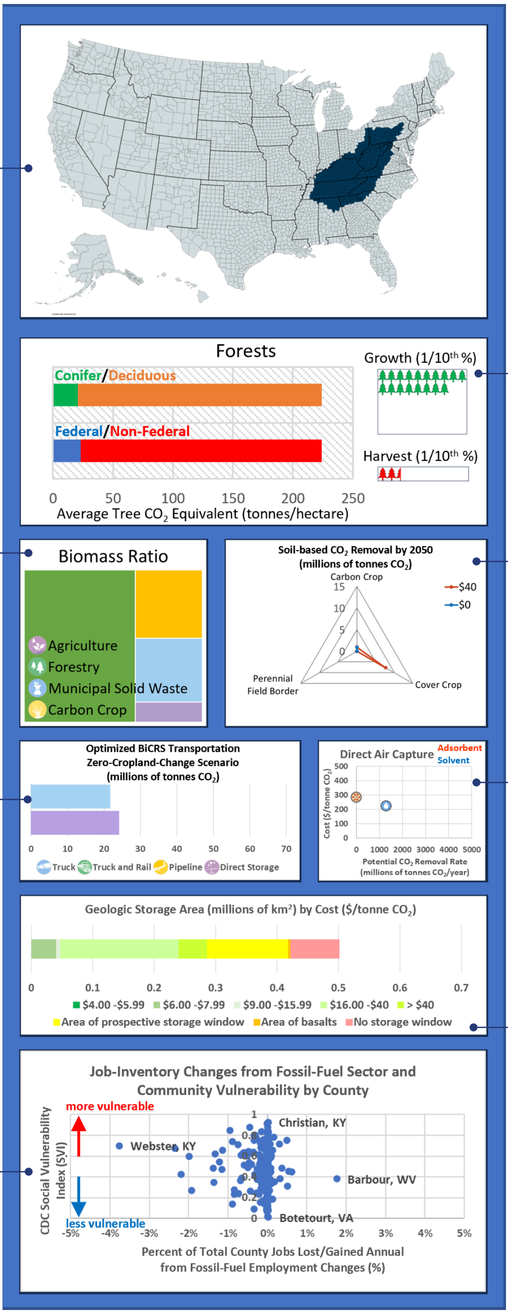
Cross-Cutting Considerations

While each region is diverse and the pathways to CO_2 removal and storage are intertwined, several factors cut across every region and pathway, which we explore as additional considerations. These factors include land use, water use, and air quality. The two major land uses in this report are (1) dedicated crop production for both soil organic carbon (SOC) sequestration and BiCRS feedstock production and (2) renewable energy generation, including solar photovoltaic and wind, used to power DACS facilities. Additionally, the land-use analysis conveys the extent of forest-thinning activities. Water use is driven by both DACS and BiCRS facilities, as all new agricultural production included in this report is exclusively rain fed. Air-quality impacts are dependent on the location and configuration of BiCRS facilities, which combust a variety of solid and gaseous fuels, directing most flue gases to solvent-based carbon capture and sequestration systems. Because most flue gases can be treated with CO_2-capture solvents, the air-quality implications are entirely dependent on the fraction of pollutants that escape to the atmosphere and the portion of solvent that thermally decomposes to ammonia or other known pollutants.

Data Presentations

For each US region, we have created a montage of figures that graphically describes the region's range of resources applicable for CO_2 removal. All the graphs and charts in these side bars are identically scaled on linear axes so the entire contents can be compared between regions. The descriptions in the call-out key on the following page are intended to provide context for each of the graphs and charts and are drawn from the detailed analyses found in the other chapters of this report.

Call-Out Key



Highlighted Region Map:

Depicts the counties included within the region described.

Forests:

Average aboveground tree-carbon density divided between (top) conifer and deciduous varieties and (bottom) location (on federal vs. non-federal land) for management. Growth: Chart shows the net percentage of annual aboveground growth, including mortality, but excluding harvest. Harvest: Chart shows percentage of forests harvested annually on all land. Green indicates net growth, red indicates net mortality/harvest. Each tree icon represents 1/10th of a percent (each line of trees represents 1%).

Biomass Ratio:

Percentage of annual biomass produced assuming a 2050 zero-cropland-change scenario.

Cropland Soils:

Cumulative soil-based CO_2-removal potential by 2050 assuming modified cropland practices priced at $0 and $40/tonne CO_2.

Carbon Transportation:

A transportation strategy optimized for transportation costs in 2050 under the zero-cropland-change scenario. Biomass and CO_2 transportation volumes across all transportation modes shown in the top bar and direct storage from BiCRS facility (no transportation required) shown in the bottom bar.

Direct Air Capture: (DAC)

Weighted average costs and potential removal rate of CO_2 from the air by 2050, assuming (1) amine-based solid adsorbents or (2) liquid solvents.

Geologic Carbon Storage:

Topographic area for conventional geologic CO_2 storage binned at projected costs per tonne. Areas of prospective storage and of basalt require further study, and "no storage window" indicates land void of reasonable storage potential. The sum of the area approximates the total size of each region.

Jobs and Social Vulnerability:

Average job changes from 2015–2021 from the fossil-fuel sector vs. the Social Vulnerability Index (SVI) reported by the CDC (1 is more vulnerable; 0 is less vulnerable). Each point represents a specific county in the region; about 50% of the counties are not reported due to lack of available data on one or both indices.

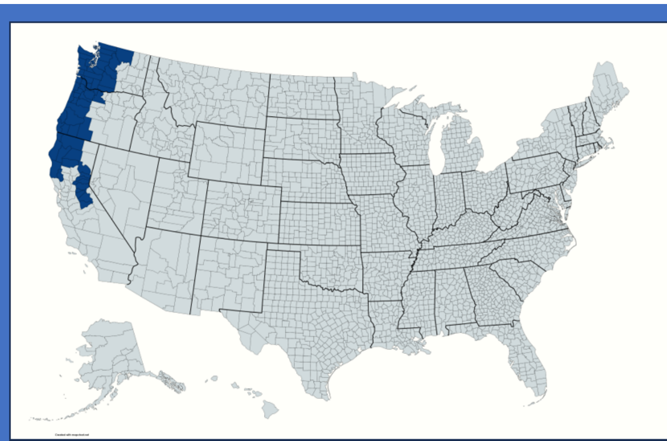
West Coast

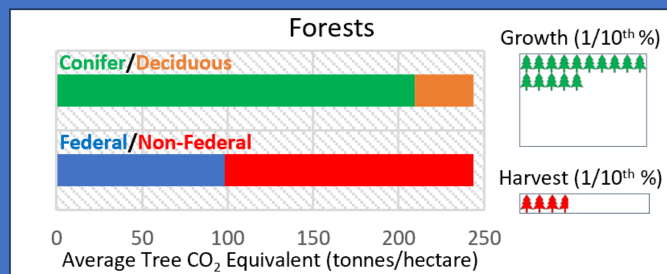
Delineation, Forests, Cropland Soils, and Biomass Carbon Removal and Storage (BiCRS)

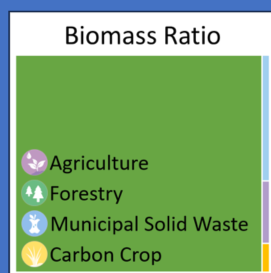
The West Coast is a densely forested region, stretching from the Washington border with Canada, along the Pacific Coast and Cascade Mountain Range, to Northern California. The Pacific Northwest hosts a coastal temperate rainforest, characterized by Douglas-fir along the Cascade and Pacific Coast Mountain Ranges and hemlock-Sitka spruce forests in the Washington Peninsula; the forests in Northern California are predominantly mixed-conifer. The cool, wet climate and conifer-dominated forests are carbon-rich, in part due to the accumulation and slow decomposition of organic matter and downed woody materials on the forest floor. The commercial logging industry has a long history in this region and is a major producer of softwood products, including a growing production of engineered wood. BiCRS feedstock is dominated by forestry supply—the second largest after the Southeast region—from thinning operations to reduce wildfire risks. Challenges include accessibility and cost of forest biomass coupled with limited, well-characterized geologic-storage sites potentially requiring transportation. However, biomass feedstock, capital, and operating costs are markedly higher than transportation costs. The West Coast region has a relatively low proportion of area used as annual-commodity cropland and relatively little potential for expansion of the soil-based CO_2-removal practices analyzed in this study.

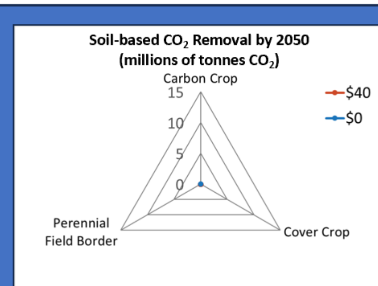
Geologic Storage

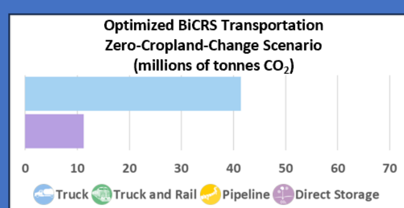
Young sedimentary rocks in parts of the Puget Trough (Willamette Basin between Salem, Oregon and Bellingham, Washington) and local sedimentary basins associated with the Pacific Coast Ranges (west Olympic, Willapa Hills, Astoria-Nehalem, Tyee-Umpqua, and Coos) have good prospective for favorable geologic CO_2 storage [6]. The storage potential of the intermediate composition volcanic rocks of the Cascade Range have not been assessed, and the remainder of this region, which includes northern Washington, the Olympic Peninsula, and southwest Oregon, contains basement rocks with no conventional CO_2 storage potential.

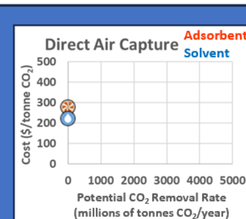


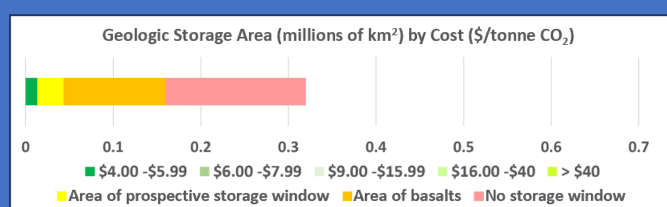


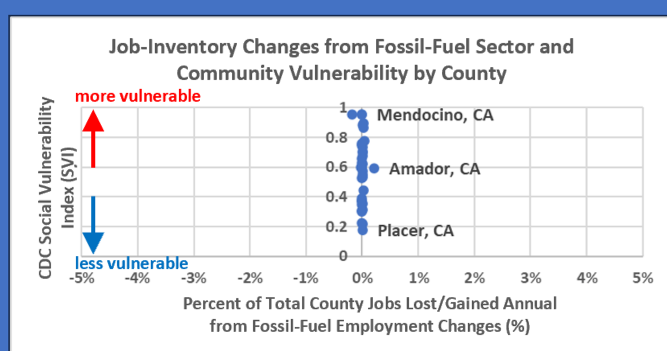












Cross-Cutting Factors

Renewably powered DACS potential in the West Coast region is limited due to the lack of local geologic storage and the highly forested areas that are unsuitable for large solar or wind installations. In the near-term, the abundance of hydropower makes the local electrical grid relatively clean compared to the rest of the country, potentially making this region interesting for testing new grid-connected technologies. When more is understood about the potential and cost for CO_2 storage in basalts, this region could become more important for DACS.

Transportation

Because these geologic storage areas are underexplored, expanded infrastructure may be required for transporting biomass or carbon to the California Central Valley or, more challengingly, to the Upper Rocky Mountains. This region is well connected with the Central Valley and the East Cascades with a rail network running north-south and mostly owned by the Burlington Northern and Santa Fe Railway and the Union Pacific Railroad. Pipelines are proposed with various extensions from the Central Valley toward the north or isolated in Washington state. Connections via rail are more limited toward the Great Basin, with also very limited proposed pipelines toward that region. Barges could also be used; they would require specific CO_2 terminals to ensure that CO_2 remains well conditioned and is reconditioned between transport modes if needed.

Energy Equity and Environmental Justice (EEEJ)

Despite the frequent rain throughout most of the year, hot, dry summers and increasing extreme weather events make the dense forests of the West Coast susceptible to wildfire, particularly in Northern California. Wildfires produce large amounts of PM2.5 (airborne particles in smoke), which presents respiratory health risks for people in the wake of the prevailing westerly winds. While these consequences of wildfire occasionally present issues for the major urban centers along the Pacific seaboard, the impacts are experienced acutely throughout the northern third of the United States and deep into the Upper and Lower Midwest and South-Central regions, contributing to increased mortality from respiratory complications. However, management of these dense forests presents an opportunity for carbon-negative fuel production, wildfire mitigation, and job creation for the underemployed, skilled forestry workforce, particularly in Oregon and Washington. Long-term forest planning impacts many people and is particularly important because the majority of forestlands are owned and managed by private commercial timber industry, with large areas of land held by tribal nations.

Constraints

Forest-thinning operations may produce the most visible changes to the landscape in the West Coast region. More than half of the land cover in the region is forest, and forest-management activities may produce residues that can support local BiCRS facilities.

This region encompasses most of the leeward side of the Cascades but is separated from the East Cascades and Great Basin regions by substantial changes in climate—particularly precipitation—and biomass type.

East Cascades

Delineation, Forests, Cropland Soils, and Biomass Carbon Removal and Storage (BiCRS)

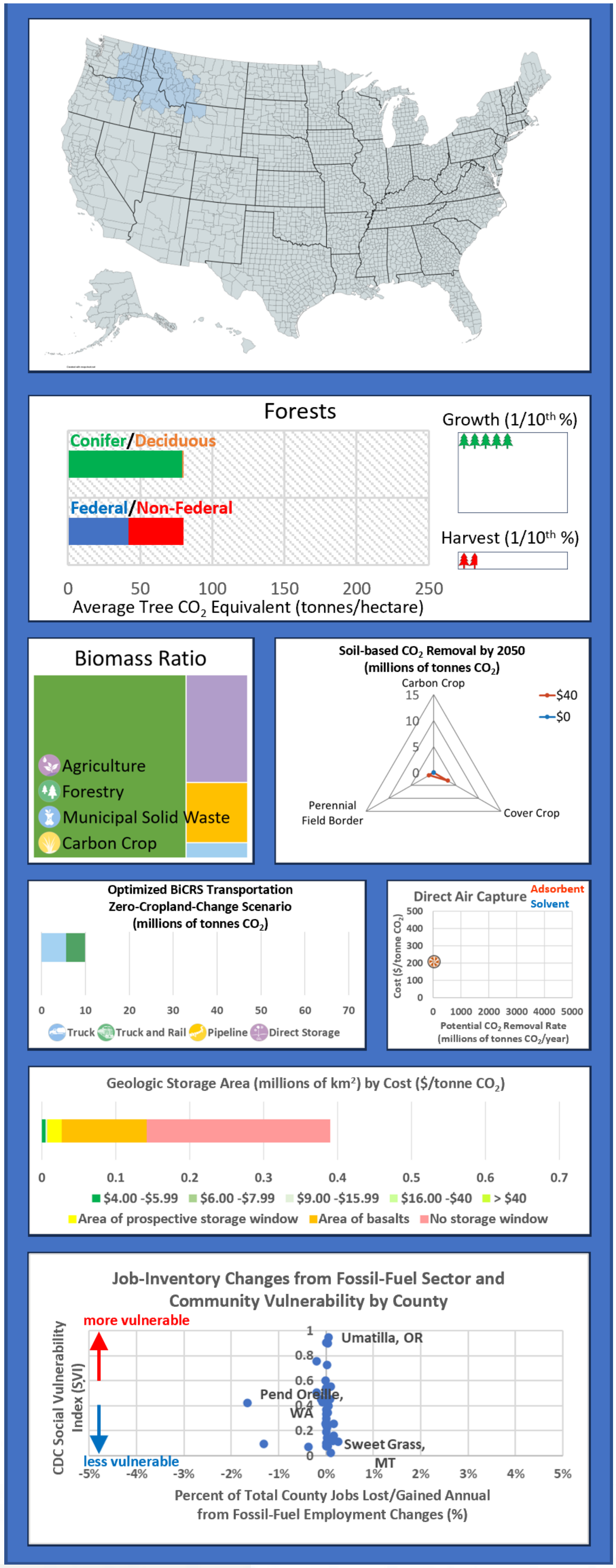
The East Cascades region extends from Western Washington to the Missouri River Basin and includes Yellowstone and Teton national parks to the far southeast. Though largely characterized by the carbon-dense forests in the northern stretches of the Rocky Mountains—notably high-elevation Douglas-fir, fir-spruce-mountain hemlock, and lodgepole pine—this region also includes the Columbia River Basin agriculture of Washington and northeastern Oregon. Timber has been a major economic commodity in this region since the late 1900s, mostly for ponderosa pine. BiCRS feedstock mainly comprises commercial forestry and wheat grass from agricultural operations. Planting perennial field borders has a moderately high CO_2-removal potential in the East Cascades region, with greater incentives leading to greater CO_2 removal in soils. This region also has moderate potential for soil-based CO_2 removal from cover-crop implementation, but this potential may be limited by water availability.

Transportation and Geologic Storage

Although this region contains large amounts of biomass and plentiful water resources, due to the topography and the low population density of the region, only a few major rail lines service the region. The Burlington Northern and Santa Fe Railway and the Union Pacific Railroad own half of them.

The only major geologic CO_2-storage resources in this area are the basaltic volcanic rocks of the Columbia Plateau, which covers much of northern Oregon and southern Washington; several studies of mineral trapping in this area have had positive results (Chapter 4 – Geologic Storage). Several prospective areas of sedimentary rocks in the Ochoco and Harney Basins in central Oregon (beneath the basalts) are poorly assessed [6], and most of Idaho and western Montana lack conventional carbon-storage resources.

With limited assessed geologic CO_2-storage potential, CO_2-transportation infrastructure may be required. Studies proposing more extensive pipeline networks envision connecting the region with either the West Coast or the Lower and Upper Rocky Mountains.



East Cascades, *continued*

Cross-Cutting Factors

Renewably powered DACS potential in the East Cascades region is limited due to the lack of local geologic storage, as well as the highly forested areas that are unsuitable for large solar or wind installations and cultivated croplands that are unsuitable for solar installations. In the near-term, the abundance of hydropower makes the local electrical grid relatively clean compared to the rest of the country, potentially making this region interesting for testing new grid-connected technologies. Importantly, most of the electricity generated in this region is from hydroelectric production along the Columbia River but is largely sent westward to the Seattle and Portland urban centers. When more is understood about the potential and cost for CO_2 storage in basalts, this region could become more important for DACS.

Energy Equity and Environmental Justice (EEEJ)

Though distinct in biomass type from the dense forests of the neighboring West Coast region, the East Cascades region is particularly susceptible to fires due to lower precipitation. Given that the majority of forests in this region are owned and managed by federal agencies, with large amounts of lands held by large tribal nations, this risk can be similarly addressed by equipping the underemployed, skilled forestry workforce concentrated in eastern Washington and northern Idaho with jobs in forestry management and fire prevention.

Constraints

The southern border of the East Cascades is marked by a transition to the more arid climate of southeastern Oregon and southern Idaho, though no county line clearly describes this delineation. The border of the East Cascades with the Upper Rocky Mountains attempts to encompass as much woody biomass in the former while containing the substantial geologic storage capacity for CO_2 in the latter.

Western Cities

Delineation and Biomass Carbon Removal and Storage (BiCRS)

The Western Cities region is characterized by the urban areas stretching from the California Bay Area along the Pacific Coast to the border with Mexico, and also includes Clark County, Nevada to encompass Las Vegas. This region contains large populations with a large production of municipal solid waste (MSW) comprising substantial carbon content. BiCRS feedstock in this region—largely from MSW, including paper and paperboard diverted from landfills and the biogenic portion of construction and demolition waste—is among the lowest cost in the United States on average. Organic-waste diversion from landfills is already part of California's emissions-reduction goals through Senate Bill 1383. BiCRS offers another path for this organic, biogenic waste beyond composting.

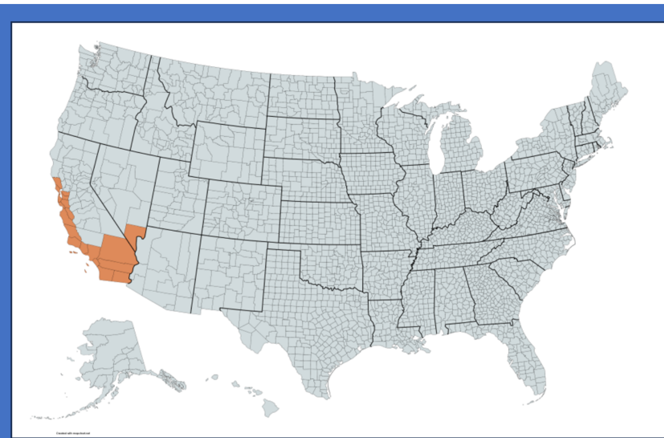
Forests and Cropland Soils

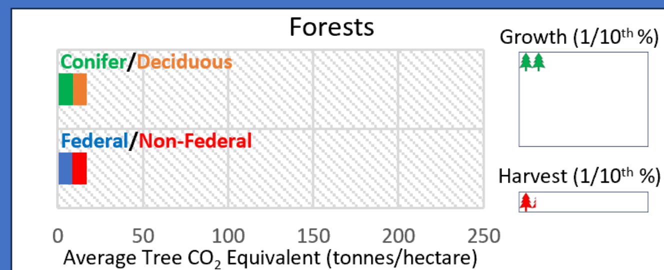
The forests of the northern portion of this region are iconic coastal redwood and coniferous forests, while the southern portions are hardwood forests comprising western oak and tanoak-laurel forest-remnant patches; most forests in this region are non-corporate, privately owned.

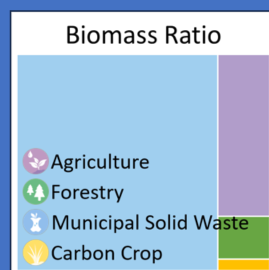
The Western Cities region has low-moderate potential for CO_2 removal through both cover cropping and planting perennial field borders. However, cover cropping may not be feasible in this region in drier years as irrigation is common and the climate is quite warm and dry in the southern counties of this region. The northern counties of this region are more likely to grow specialty fruit and vegetable crops, which we did not analyze in this report. However, conservation practices are likely to have erosion and soil-structure benefits in these croplands.

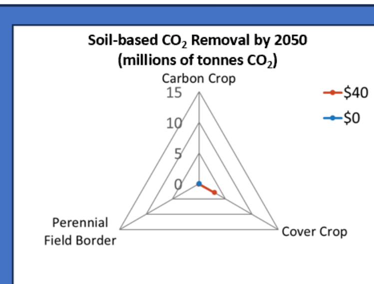
Geologic Storage and Transportation

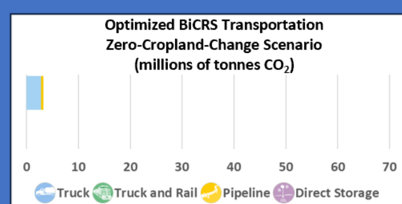
This structurally complex geologic area is mostly classified as metamorphic and basement rocks and lacks conventional geologic CO_2 storage, with the exception of the Ventura and Los Angeles Basins. These basins contain both well-characterized, structurally complex sedimentary geologic-storage capacity and prospective storage that requires further characterization [6-8]. Small prospective basins include Salinas, La Honda,

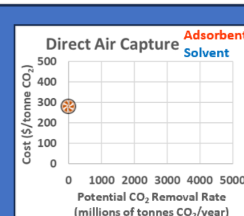


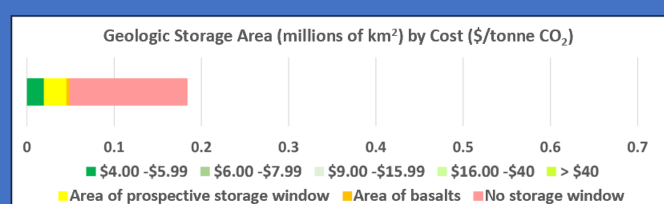


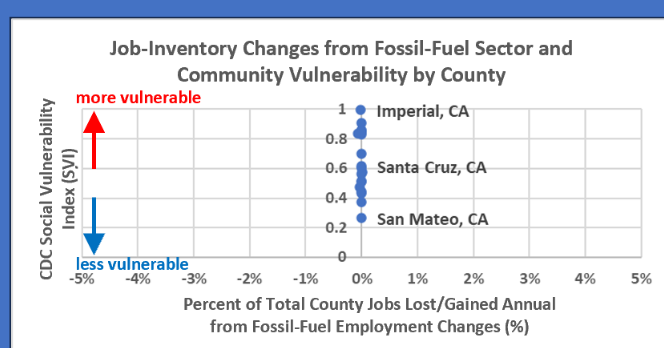












Cuyama, Orinda, and Livermore [6]. How pressure change resulting from a large-volume injection in this region might impact active faulting will have to be considered carefully.

The rail network, dominated by the Union Pacific Railroad and the Burlington Northern and Santa Fe Railway, connects the northern (San Francisco Bay Area) and southern (Los Angeles) extents of the Western Cities region through the Central Valley due to the topography of the region. The proposed pipeline networks show similar routes. The rail and proposed pipeline networks are also connecting the region to the Desert Southwest with the more far-reaching options connecting to the Lower Rocky Mountains. For transport to storage locations near waterways, barges could also be used.

Cross-Cutting Factors

In the Western Cities region, high population densities, requiring large amounts of renewable electricity, make it difficult to envision large-scale facilities for DACS. The exception might be in Southern California near the Salton Sea, which has abundant geothermal resources; DACS facilities that are integrated with geothermal electricity facilities, possibly pulling heat from the geothermal fluid before it is injected back underground, could effectively utilize this “waste” energy, though the CO_2 may need to be transported for geologic storage (e.g., via the proposed pipeline to the nearby San Joaquin Basin in the California Central Valley region). The Western Cities region is also water stressed, fire prone, and already vulnerable to earthquakes along the San Andreas Fault, challenging large infrastructure projects for carbon capture and storage, particularly near San Francisco, California.

Energy Equity and Environmental Justice (EEEJ)

The arid climate of the Western Cities region makes it prone to high PM2.5 from a combination of fuel burning for transportation, wildfires, and crop burning, particularly in Southern California. Additionally, the high drawdown of water and close proximity of agricultural activity in the California Central Valley presents an outsized risk of eutrophication in the waterways and near-coastal areas, with an increased impact again along the southern coast. Additionally, policy and economic activity have led to substantial fossil-fuel job losses in several counties, which presents an opportunity to employ a skilled workforce in carbon-management infrastructure.

Constraints

The Western Cities region encompasses large counties in southeastern California (particularly San Bernardino County), which contain expansive tracts of land that could be categorized in one of the neighboring regions but were defined within this region to maintain connectivity up to southern Nevada. Some metrics would also include Washington County, Utah as a part of Western Cities, but, again, we excluded this county to preserve connectivity. The most notable delineation for this region is along the Southern Coast Ranges, which separate the urban Western Cities region from the agricultural California Central Valley.

California Central Valley

Delineation, Cropland Soils, and Biomass Carbon Removal and Storage (BiCRS)

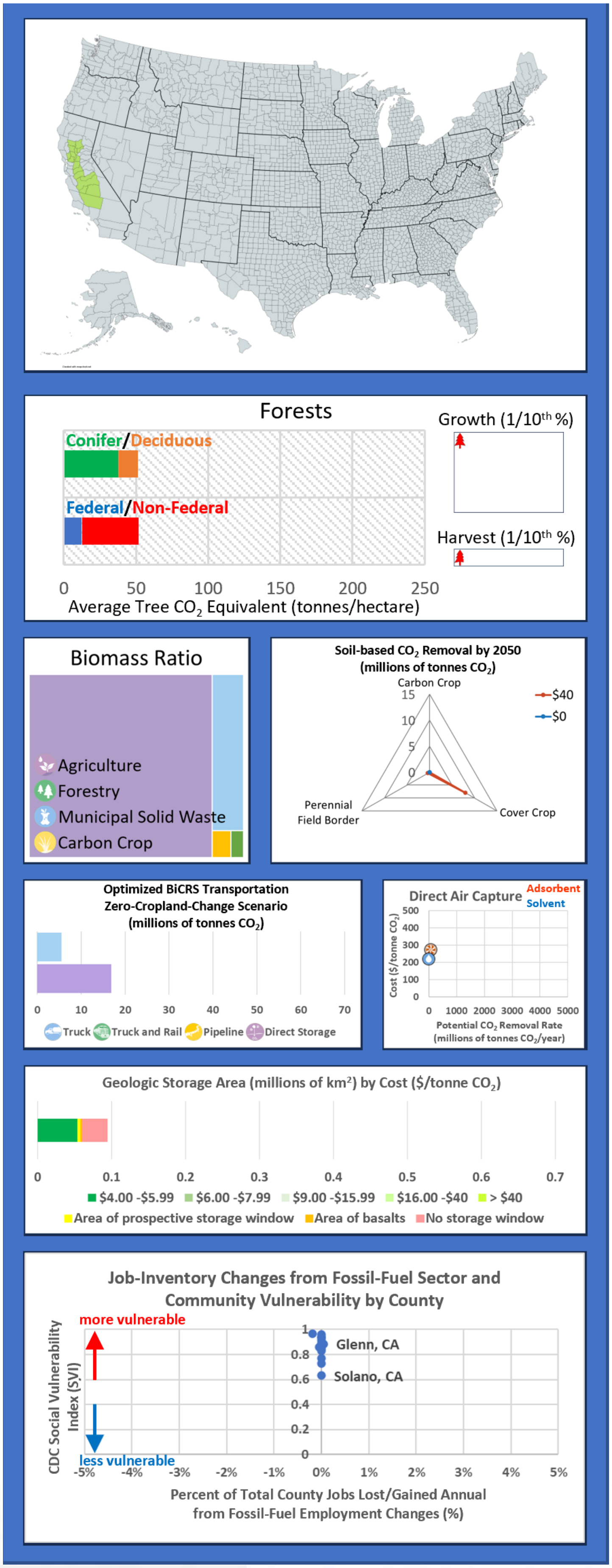
The California Central Valley region is a unique plains region situated between the Klamath Mountains, Coast Ranges, and Sierra Nevada Mountains. Characterized by water-intensive agriculture, including pasture feed, alfalfa, almonds, pistachios, and citrus and subtropical fruits, this region contains the breadbasket of California and produces large quantities of agricultural biomass. The California Central Valley region has a high concentration of cropland, though much of it is in perennial orchards. CO_2 removal through cover cropping and perennial carbon crops does not apply to orchards because they are already planted with perennials; however, the tree trimmings can be used as BiCRS feedstocks. Despite the limited area, cover cropping and perennial field borders have moderate potential for soil-carbon storage, driven by annual cropland in Yolo County. BiCRS feedstock resources in the California Central Valley are dominated by agricultural activities—chiefly dairy operations—and cultivation of tree nuts and rice. Using these wastes beneficially for carbon removal and storage has the potential to increase air quality by reducing pile burning of the low-moisture residues, as well as by decreasing methane emissions from unmanaged manure.

Geologic Storage

Thick sections of young sedimentary rocks of the Great Valley Sequence and associated units fill the Sacramento and San Joaquin Basins. Studies and tests of these rocks have found good geologic CO_2-storage potential, namely surrounding Solano and Kern Counties. The geologic structures are generally broad, but stratigraphic complexity is fairly high in many areas, raising storage costs.

Transportation

Given the presence of storage basins, the California Central Valley region does not necessarily need to transport CO_2 out of the region. The intersection of ample agricultural waste and geologic storage make this a promising region for BiCRS. Transport networks in this region are constrained by the topography of the mountains surrounding it and show a northwest-



southeast orientation, with connections to other regions toward the ends of the valley. This region is a major transport corridor for rail, dominated by the Union Pacific Railroad and the Burlington Northern and Santa Fe Railway Class I carriers. It is also a major corridor for proposed CO_2 pipelines that connect with the West Coast, Western Cities, Great Basin, and Desert Southwest regions. The California Central Valley region already contains a large transportation network and electricity infrastructure and is ringed by regions with substantial renewable energy capacity. However, this area is known for its historic water stresses, which is an important consideration for future infrastructure.

Direct Air Capture with Storage (DACS) and Cross-Cutting Factors

Despite the high electricity prices, the California Central Valley is also the only region west of the Rocky Mountain Range that contains even a moderate potential capacity for DACS. This region has good options for geologic storage paired with DACS powered by wind and solar. However, the expected cost for DACS is relatively high in this region due to the projected cost of electricity in California and the high demand from the high-population-density centers near the coast. This region has a high amount of agricultural land, and siting of DACS facilities and renewable-energy resources must take this into account. In addition, the region already has high water demand due to agricultural production; this may result in preference for DACS technologies that do not consume large amounts of water or some emerging DACS processes that even co-produce water from the atmosphere (albeit with larger cost and energy required).

Energy Equity and Environmental Justice (EEEJ)

Despite recent seasons of substantial precipitation, the California Central Valley region remains susceptible to high PM2.5 concentrations from cropland burning, an issue that is likely to increase in severity as climate change continues to impact long-term water availability in these counties. Relatedly, the substantial agricultural density exposes this region to high eutrophication risk of local waters from fertilizer and manure runoff. The California Central Valley has also experienced outsized crop-production job losses, which has exposed the people of this region to greater economic and corresponding health risks.

Constraints

The line along the Sierra Nevada Mountains is not well delineated by all counties, so the intersection between the West Coast, California Central Valley, and Great Basin regions may need to be thoughtfully considered when accounting for biomass types and future infrastructure planning.

Great Basin

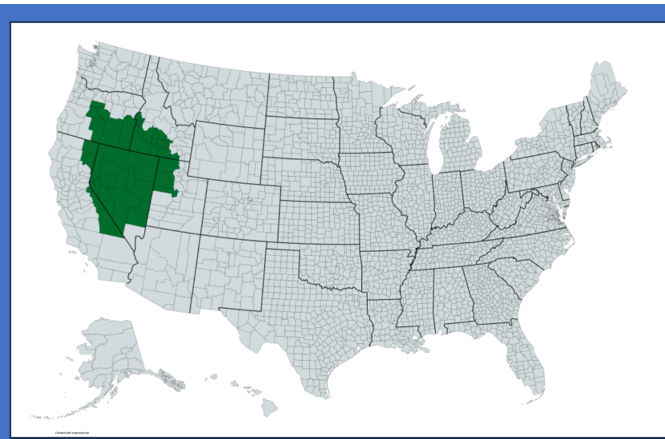
Delineation, Forests, and Cropland Soils

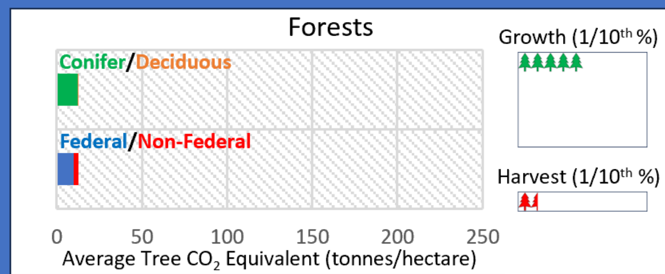
The Great Basin region defined in this report expands beyond the Great Basin watershed detailed in other maps. This region is characterized by very low annual rainfall and nonflowing bodies of water, making it sparse in natural or anthropogenic carbon sources. The sparse forested areas at higher elevations include fir-spruce, lodgepole pine, and ponderosa pine; the dispersed woodlands in southern Nevada are pinyon-juniper. Drought, climate warming, and pest outbreaks are reducing the resiliency of these forests, and the low-value wood products of this region are driving the economic value of these forests largely toward supporting the outdoor-recreation industry. The low concentration of common-commodity cropland in the Great Basin (due to the dry climate) means there is relatively little potential for cropland-based CO_2 removal through the practices analyzed in this report. However, hay and wheat production in Oneida county allow for some expansion of perennial field borders and cover cropping in this region.

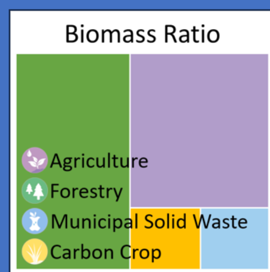
Geologic Storage, Transportation, and Cross-Cutting Factors

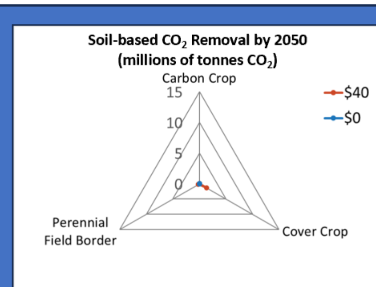
Prospective geologic CO_2 storage in the Great Basin region is very limited, with potential sites occurring only between mountain ranges of the Basin and Range Province; however, the subsurface of these areas is poorly known. If they were locally sufficiently permeable, storage might use shallow, young deposits or consider deeper, old, and structurally complex formations, but having minimal anticipated geologic-storage capacity limits the value of transporting carbon from elsewhere. Contamination of protected freshwater that migrates deep in the Great Basin region is a risk that would have to be assessed to locate permittable CO_2 storage.

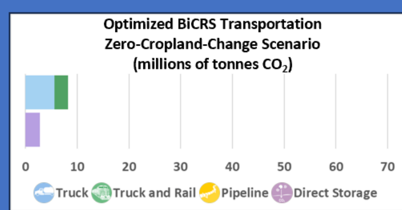
Compounding these challenges, the transportation network is scarce in this region, with only a few rail lines—owned mainly by the Union Pacific Railroad and the Burlington Northern and Santa Fe Railway—that cross the region and connect it to the California Central Valley and the Lower and Upper Rocky Mountains.

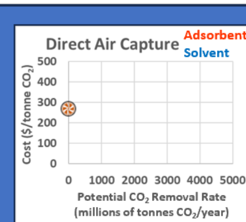


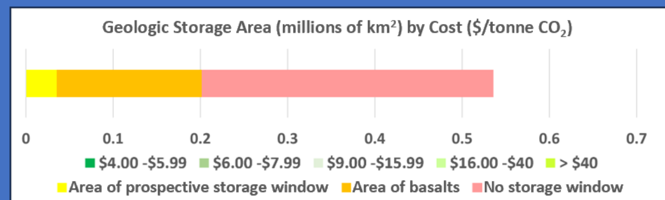


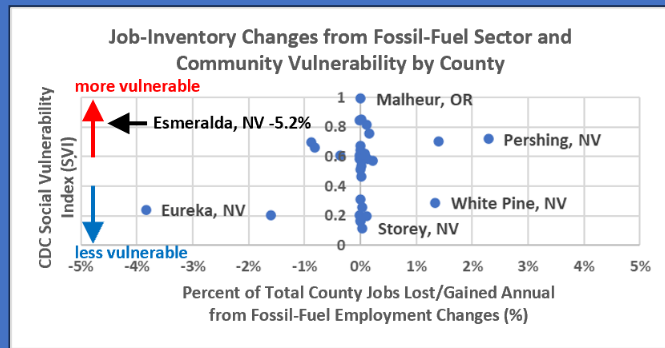












No existing CO_2 pipelines currently service the area, and proposed CO_2 pipelines would only reach the edges of the region.

Though the Great Basin region is predominantly shrub/scrubland, suitable for large solar and wind installations that could be used to power DACS, the lack of local geologic storage options makes this region less desirable for large-scale DACS unless the CO_2 can be inexpensively moved to a nearby region with suitable storage. However, this region is plentiful in hydrothermal and solar resources and could play a large role in future expanded energy generation. Deconflicting this generation capacity with fragile ecosystems may provide long-term benefits to the area.

Energy Equity and Environmental Justice (EEEJ)

Water stress is of primary concern in this region, making the sparse, high-elevation forests critical for watershed protection and erosion control around populations centers. Most of these forests are owned and managed by federal agencies. Where livestock operations are prevalent, particularly in southern Oregon and Idaho, the largely landlocked watershed increases the likelihood of nutrient runoff driving high eutrophication of standing bodies of water. Due to climate change, water deficits are expected to grow in severity, notably in Nevada and western Utah. These factors are of particular concern for the tribal nations dotted throughout this region but spread widely across northern Nevada, in particular.

Constraints

While the border along the Cascades and Sierra Nevada Mountains is fairly distinct, the encroachment of the Great Basin region into Oregon and Idaho to the north and Utah to the east is relatively undefined. Central Oregon contains notable geothermal resources, which can be included in the Great Basin region, and the counties in Utah west of the Great Salt Lake do not have sufficient forest resources to warrant inclusion in the Lower Rocky Mountains.

Upper Rocky Mountains

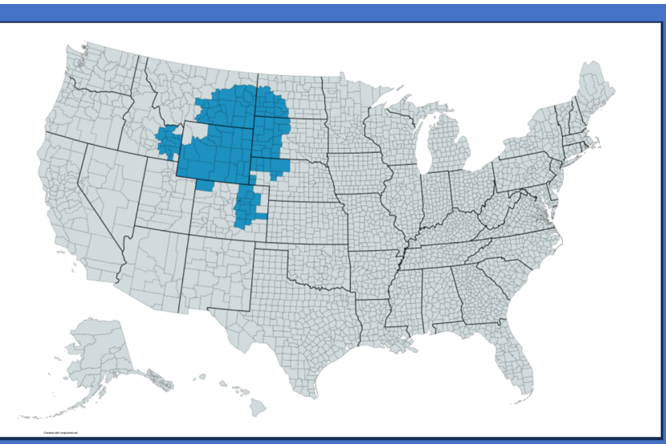
Delineation, Forests, Cropland Soils, and Biomass Carbon Removal and Storage (BiCRS)

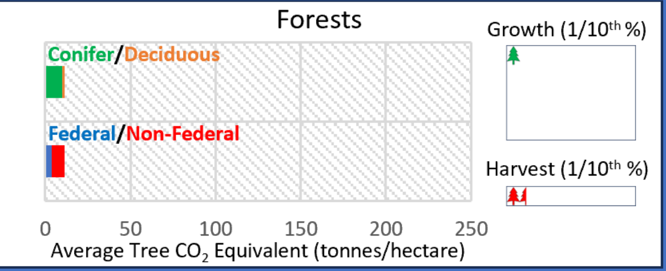
The Upper Rocky Mountains region contains the southeastern corner of Montana, nearly the whole of Wyoming, and portions of Idaho, Colorado, Nebraska, and the Dakotas. Though contained within the Missouri River Basin, this region has minimal agricultural activity, and the sparse forests provide only low-density woody biomass. Ponderosa pine forests are most common, but these coniferous forests are isolated into islands within the greater grassland and prairie landscape of this region; the majority of forests in this region are owned and managed by federal agencies. BiCRS feedstock in this region is dominated by agricultural residue, primarily wheat straw.

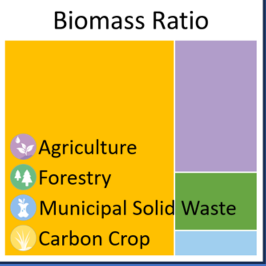
The Upper Rocky Mountain region has moderate potential for soil-based CO_2 storage by implementing perennial field borders and low-moderate potential for the expansion of carbon crops. Commodity cropland in this region is less productive than croplands in the midwestern regions of the United States and thus has a lower opportunity cost for conversion of a small percentage of annual cropland to perennial field borders. This region has relatively low potential for CO_2 removal from cover cropping.

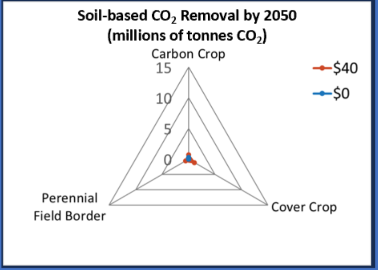
Geologic Storage and Transportation

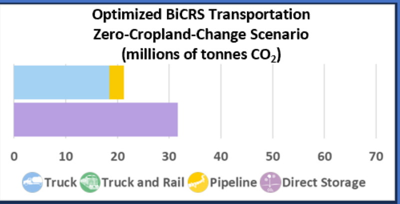
This region is well known for its rich coal deposits, which also account for its large geologic CO_2-storage capacity, concentrated in Wyoming. Parts of the Williston Basin Paleozoic-age rocks have now started accepting CO_2; more locations are in the permitting process throughout North Dakota and are included in this region. Deep intermountain basins, including the Denver-Julesburg, Powder River, Big Horn, Green River, Great Divide, and Hanna Basins, contain relatively well-known storage prospects in late Mesozoic- to early Tertiary-age sandstone [9]. In this region, only areas of basement-cored mountains lack storage resources. Protected freshwater that migrates deep in the basin is a risk that would have to be assessed to locate permittable storage.

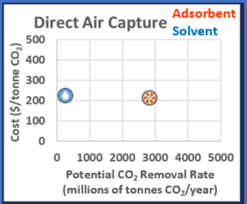


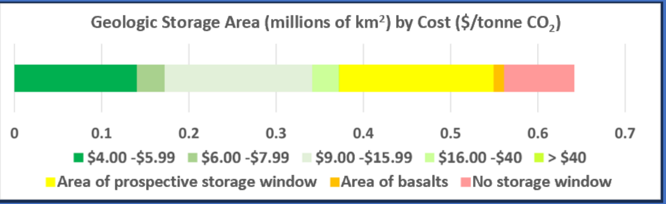


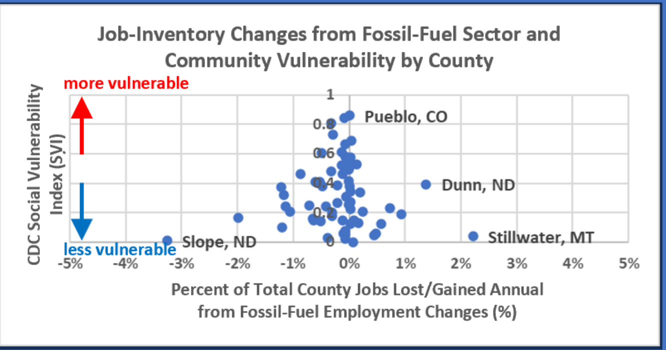












Due to the region's topography and low population density, few rail lines service the region; those that do are owned by the Burlington Northern and Santa Fe Railway and the Union Pacific Railroad. However, CO_2 might not have to be transported far in this region due to the presence of storage basins. An existing pipeline already runs through the region, and previous analysis proposes to densify the network of pipelines in the area [10].

Direct Air Capture with Storage (DACS)

The Upper Rocky Mountains region presents excellent options for renewably powered DACS in the long-term due to the abundance of renewable wind electricity and identified low-cost, high-injectivity geologic storage, particularly in southern and eastern Wyoming and eastern Colorado. Electricity is forecasted to be relatively inexpensive in this region, leading to relatively low DACS cost. An existing CO_2-pipeline connects the geologic-storage resources within the region, and commercial carbon-storage projects are currently ongoing through the CarbonSAFE initiative.

Cross-Cutting Factors

The high-topography areas of this region (e.g., northwestern Wyoming) are not suitable for large installations of renewable energy and may also have issues with public acceptance. Additionally, due to the largely coal-powered electrical grid, care must be taken in the near-term when considering electricity options for powering DACS to avoid emitting more carbon than is captured. This does not mean that this region is unsuitable for DACS but rather that the energy source must be carefully considered.

Energy Equity and Environmental Justice (EEEJ)

Because of the large coal resources, this region has experienced and may continue to experience outsized fossil-fuel job losses, many of which could be returned with a repurposing of the rich geologic features in the area. Thoughtful consideration with respect to the large tribal nations, particularly in southern Montana and central Wyoming can improve outcomes. Though not as inherently at risk of increased wildfires itself, the Upper Rocky Mountains are particularly exposed to PM2.5 from wildfires to the west.

Constraints

The delineation between the Upper and Lower Rocky Mountains regions is fluid, depending on the southern extent of carbon-storage capacity and the northern extent of forest biomass. The lines between the Upper Rocky Mountains and Midwest regions are defined by the westward extent of agriculture within the latter, some of which involves high aquifer-water extraction rates to accommodate the changes in geography and precipitation.

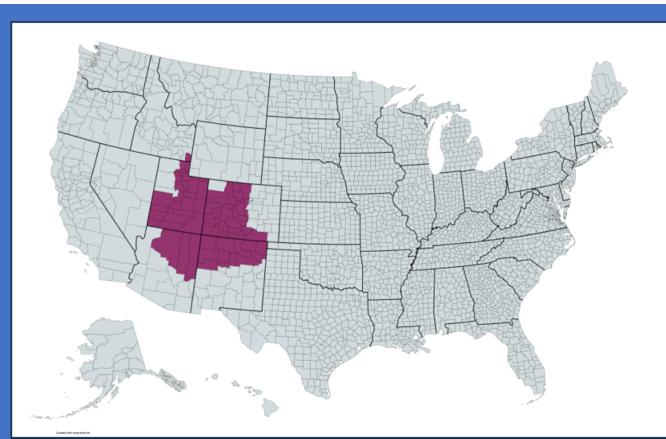
Lower Rocky Mountains

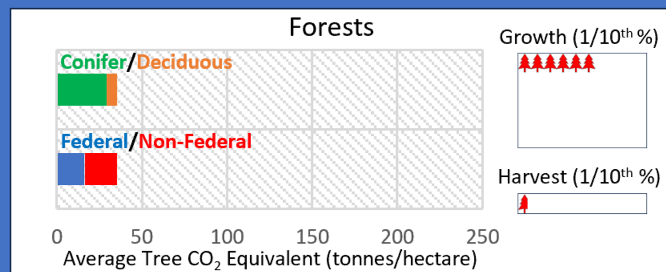
Delineation, Forests, and Cropland Soils

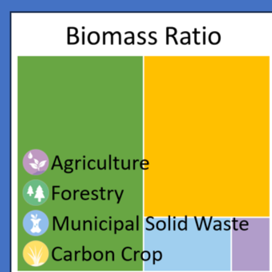
The Lower Rocky Mountains region is characterized by the national forests in western Colorado, which extend south into northern New Mexico and west to the Uinta and Tushar Mountains across the Colorado Plateau in Utah. This region is characterized by pinyon-juniper woodlands with more diverse forest types in western Colorado, including spruce-fir and ponderosa pines at higher elevations. The majority of these forests are owned and managed by federal agencies, with large amounts of lands held by tribal nations. The connection of the southwestern United States to the surrounding regions by major rail lines in the mid-19th century expanded the timber industry, which resulted in large deforestation. Today, forests are recovering, but many are overstocked with dense stands as a result of fire suppression policies for half of the 20th century. The low concentration of common-commodity cropland in the Lower Rocky Mountains, partially due to the dry climate, means that it has relatively little potential for cropland-based CO_2 removal through the practices analyzed in this report.

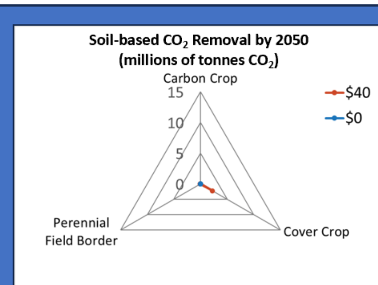
Transportation, Geologic Storage, and Cross-Cutting Factors

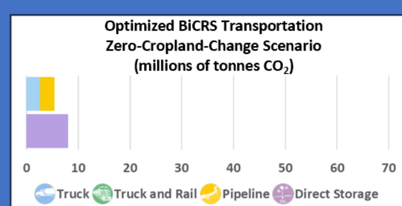
Due to this region's topography and low population density, few major rail lines service the region; those that do are mostly owned by the Union Pacific Railroad and the Burlington Northern and Santa Fe Railway. CO_2 might not have to be transported far in this region due to the presence of storage basins, and it could be a destination for CO_2 coming from nearby regions that have limited storage options, such as the Great Basin. Some pipelines are already operating and connecting the region to West Texas and the Upper Rocky Mountains, and some proposed pipelines would also connect the region with the East Cascades and the Desert Southwest. The most favorable storage area in this region is the San Juan Basin in northwest New Mexico, where some storage testing has been done, focusing on coal. Compared to the Upper Rocky Mountain region, the Lower Rocky Mountain region has more areas of thin or missing sedimentary rocks and more prospective areas beneath which the subsurface is relatively poorly known. Several areas, including

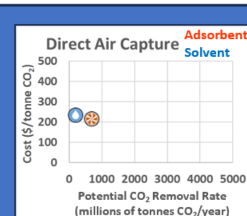


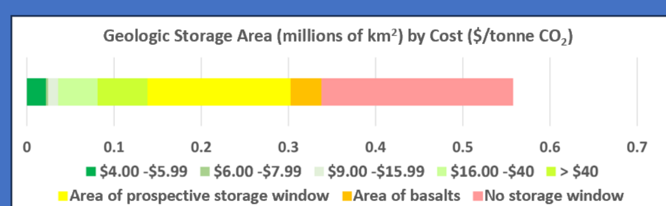


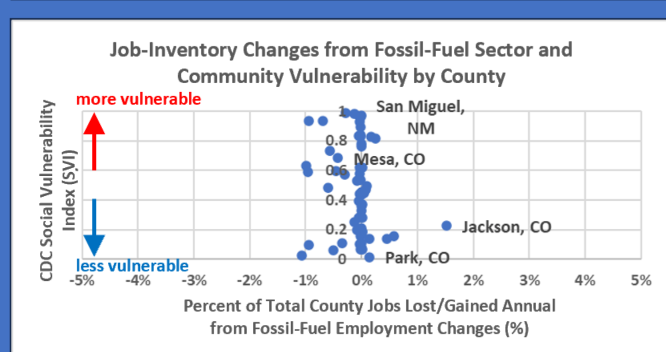












the Uinta and Piceance Creek Basins spanning Utah and Colorado, have been partially assessed by the US Geological Survey (USGS) but so far are of poor injectivity. Nonetheless, the region has some potential for DACS, particularly along the Utah-Colorado-New Mexico borders, due to abundant solar and wind electricity and geologic storage in this area. Generally, much of the Lower Rocky Mountains region is unsuitable for large renewable energy and DACS installations due to the high topography (e.g., western Colorado), but some pockets of identified low-cost, high-injectivity geologic storage exist in the San Juan Basin in northwestern New Mexico that also house large commercial carbon-storage projects through the CarbonSAFE initiative. This basin is also connected by an existing CO_2 pipeline to geologic storage in West Texas. Much of the Lower Rocky Mountains region is also sparsely populated with major cities, which are located only at the outer extents of the region.

Energy Equity and Environmental Justice (EEEJ)

Any potential considerations of this unique geographic territory for contributing to the US' net-zero emissions goals may achieve better outcomes by engaging the many tribal nations in this region. In particular, consideration of direct tribal leadership in matters of land-use—to address any potential conflicts with reservation lands and traditional practices early on—can improve outcomes. This region has limited economic opportunity for wood production due to limited sawmills and has already experienced fossil-fuel job losses, which is likely to be further exacerbated with the retirement of the Navajo Generation Station at Four Corners, impacting Coconino County in particular.

Constraints

As the name suggests, the Lower Rocky Mountains region is bounded to the east by the leeward side of the Rocky Mountain range and by the thinning forests in the Desert Southwest region to the south. Due to the expansive geologic CO_2-storage capacity and existing CO_2 pipelines crossing through northeastern New Mexico and southern Colorado into Texas, there is no precise delineation between this region and the West Texas region.

Desert Southwest

Delineation and Cropland Soils

The Desert Southwest region encompasses the lower two thirds of Arizona up through the middle of New Mexico and, as the name implies, is characterized by arid desert with minimal harvestable biomass. The Desert Southwest, with its hot and arid climate, has low potential for soil-based CO_2 removal in croplands through the practices analyzed in this report, due largely to limited water resources.

Biomass Carbon Removal and Storage (BiCRS), Geologic Storage, and Transportation

While the fragile ecosystem is not ideal for biomass production or storage, this region is the most abundant location for solar-energy generation with interconnects to Las Vegas and Southern California. Much of the Desert Southwest region is a geologic continuation of the Basin, Range, and Front Range Provinces, and the best CO_2-storage potential for sedimentary rocks within the storage window is in small, isolated basins between ranges [11]. Basaltic rocks are found in this area but have not been assessed for storage potential.

Due to the limited storage options in the region, transport is essential. Even with only limited rail lines—mainly owned by the Union Pacific Railroad and the Burlington Northern and Santa Fe Railway—and a short section of existing CO_2 pipeline in the East, the region is connected to the Permian Basin, the California Central Valley, and the Lower Rocky Mountains regions by rail and proposed pipelines.

Cross-Cutting Factors and Direct Air Capture with Storage (DACS)

While there is ample opportunity for solar and wind production to power DACS in the Desert Southwest region, it has no local geologic storage options. Expanded electricity transmission from this region to nearby regions could be an option for using this source of renewable energy to power DACS. Alternatively, a CO_2 pipeline through this region could move CO_2 to

these nearby basins instead of requiring expanded electricity transmission, though both options present challenges for realization.

Energy Equity and Environmental Justice (EEEJ)

Similar to the Lower Rocky Mountain region, the Desert Southwest contains a high density of tribal nations. Their input, coupled with consideration of the fragile desert ecosystem, may provide helpful insights, particularly as expansive solar-energy projects are being proposed. Also, this region is prone to water deficits and high wildfire risks due to the hot, arid climate, which is anticipated to be exacerbated by climate change. The sparse high-elevation forests are critical for dense population centers in the state, providing watershed protection and erosion control; the majority of the forests are owned and managed by federal agencies and held by tribal nations.

Constraints

Because of their size, many of the counties in and bordering this region may benefit from subdivision to account for their geographic variation. Also, the border with the Texas region is fluid with no explicit landmark to differentiate between these two regions.

Upper Midwest

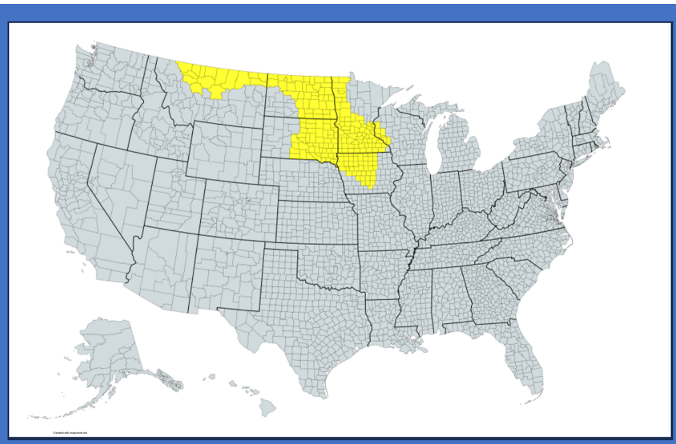
Delineation, Cropland Soils, and Biomass Carbon Removal and Storage (BiCRS)

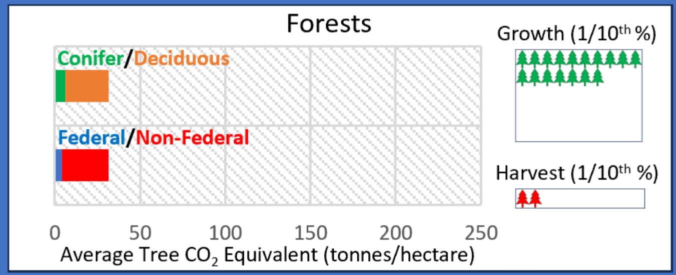
The Upper Midwest region spans much of the Missouri River Watershed from northern Montana, through the eastern side of the Dakotas and into Minnesota, Iowa, and the western reaches of Wisconsin. This region is characterized by rich agriculture and rich water resources, both surface (through the Missouri River watershed) and subsurface (through the High Plaines Aquifer). This region also has excellent wind-energy resources. The Upper Midwest has high potential for soil-based CO_2 removal through perennial field borders and perennial carbon crops as it is a productive commodity-grain-crop region and has available land and relatively amenable climate for perennial plantings. At almost 80 million tons per year, this region has one of the highest amount of biomass for carbon removal and storage of all US regions. The predominant form of biomass is corn stover, followed by modeled switchgrass growth on marginal and abandoned lands.

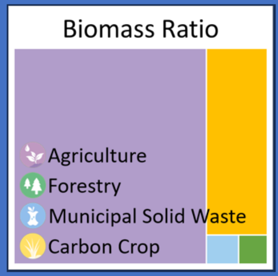
Geologic Storage and Transportation

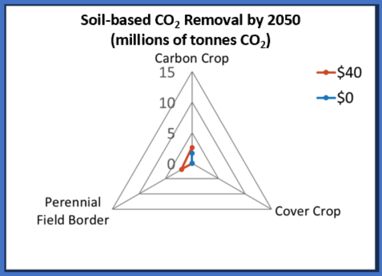
This region's most substantial and well-known geologic CO_2-storage capacity is along its interface with the Upper Rocky Mountains region. The northern part of the Williston Basin also continues into the Upper Rocky Mountain region where structurally simple but stratigraphically complex, Paleozoic-age sediments hosts an extensive well-known storage resource. Prospective sedimentary rocks needing more assessment are found at the west end of the region, but the east end lacks sedimentary rocks. Precambrian-age basalts mapped in the eastern part of the region have not been assessed but, because of their considerable age, they are likely to have lost the permeability needed to assist mineral trapping.

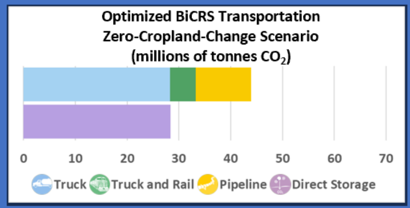
The Upper Midwest region contains a dense rail network. The Canadian Pacific Kansas City Railway, the Union Pacific Railroad, and the Canadian National Railway Company dominate the eastern part of the region, but dwindle toward the West, where the Burlington Northern and Santa Fe Railway dominates. An existing pipeline connects the region to the Upper

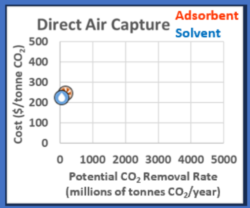


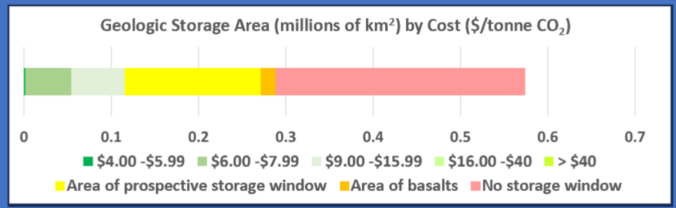


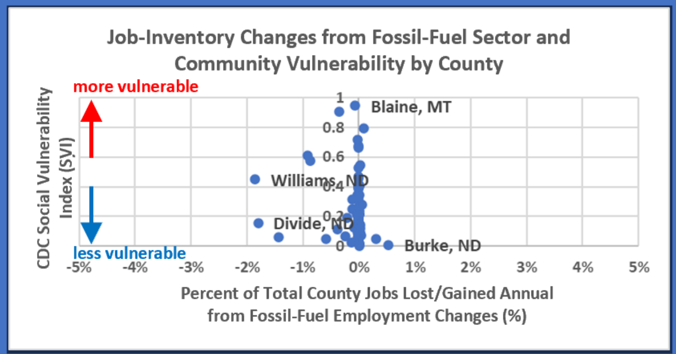












Rocky Mountains region and Canada, with proposed expansions (notably the proposed Midwest Carbon Express Pipeline, reaching toward the Lower Midwest and the Great Lakes, and toward the existing pipeline running through the Upper Rocky Mountains). Optimized models for BiCRS indicate that transportation through the Lower Midwest region to the Gulf Coast would be advantageous.

Direct Air Capture with Storage (DACS) and Cross-Cutting Factors

This region's minimal topography makes it suitable for DACS; however, DACS may conflict in places with land-use considerations for farming. The Midwest region generally has good wind-based renewable-energy production that could be co-located with the cultivated cropland that predominantly covers this region. However, without good local geologic-storage options, expanded electricity transmission for renewable wind energy is needed, possibly to the Upper Rocky Mountain region which has good storage. Substantial infrastructure expansion, including transportation of biomass, CO_2, and electricity, may benefit the carbon economy of the Upper Midwest region.

Energy Equity and Environmental Justice (EEEJ)

The Upper Midwest region is particularly prone to PM2.5 exposure from forest fires in the west and from local crop- and rangeland burning. Though currently rich in natural water resources, high drawdown of the slowly regenerating aquifer coupled with changes in precipitation patterns from climate change expose this region to substantial water shortages, particularly the western extents. Due to the large amount of agricultural activity, including crop and animal production, eutrophication along the Missouri River poses high risks to both wildlife and population centers downstream. Land-use changes or infrastructure projects in this region may benefit from voices from the many tribal nations that live in these areas, particularly the high concentration throughout Montana, Minnesota, and the Dakotas.

Constraints

The boundary dividing the Upper and Lower Midwest regions along the South Dakota–Nebraska border and through southeast Iowa is primarily due to a change in soil type that shifts the agricultural abundance between these regions. However, the overall characteristics of these regions are sufficiently similar that they could have been combined into one discussion. The boundary with the Upper Great Lakes region closely follows the forest-agriculture lines, but the boundary with the Lower Great Lakes region to the west is less definitive and may benefit from incorporating county-level nuances.

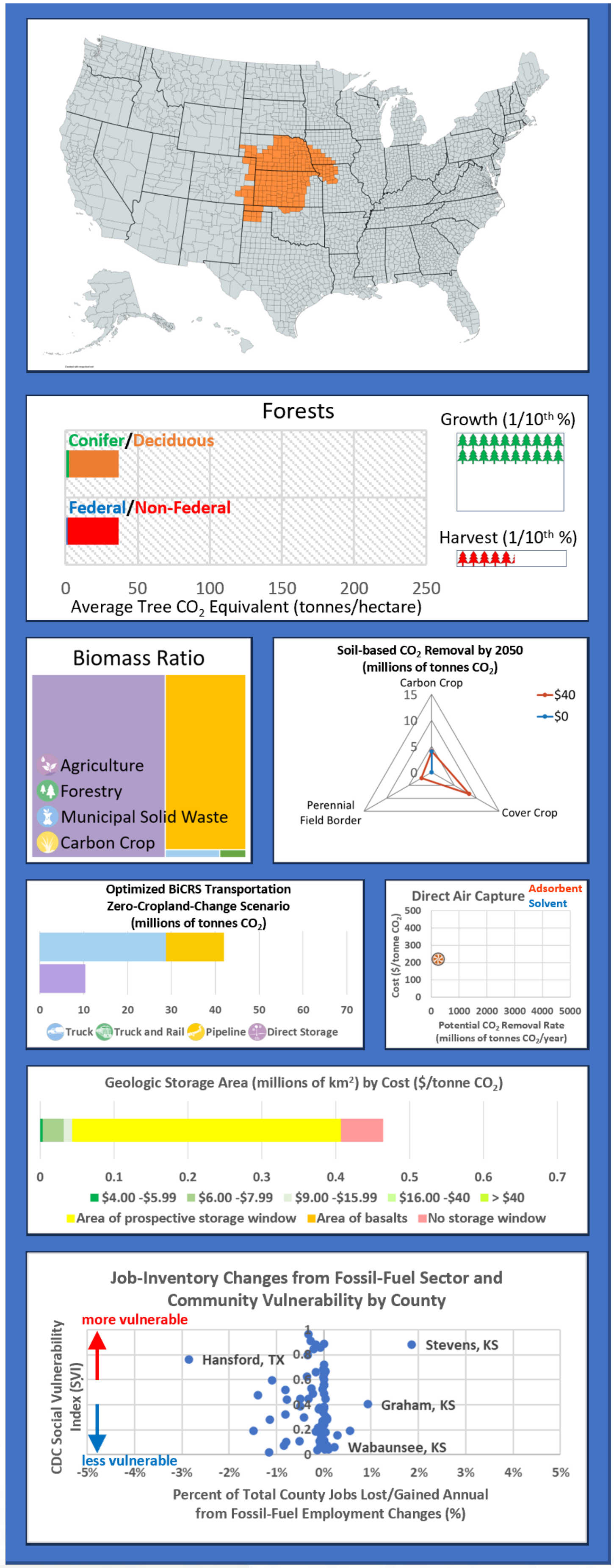
Lower Midwest

Delineation, Cropland Soils, and Biomass Carbon Removal and Storage (BiCRS)

The Lower Midwest region follows along the eastern edge of the Rocky Mountains through Nebraska, Kansas, and into the upper reaches of Oklahoma and Texas. This region is characterized by rich agriculture and rich water resources, both surface (through the Missouri River Watershed) and subsurface (through the High Plaines Aquifer), as well as excellent wind-energy resources. The Lower Midwest region has a high density of commodity-grain cropland and has the highest potential for soil-based CO_2 removal from both perennial carbon crops and perennial field border implementation. This region also has moderately high potential for CO_2 removal through cover cropping. In particular, Kay County in Oklahoma stands out as having the largest economically viable land area for implementing these practices. The Lower Midwest contains among the highest density of corn stover among all regions, and also has high CO_2 removal potential through projected availability of carbon crops on marginal and abandoned lands, the USDA's Conservation Reserve Program (CRP) lands, and bioenergy conversion lands, which can all contribute to BiCRS capacity.

Geologic Storage

The most substantial and well-known geologic CO_2 storage capacity in the Lower Midwest region is along its interface with the Upper Rocky Mountains region. Most of this region contains older sedimentary rocks within the storage window, which need further assessment of permeability to determine where they can serve as a storage resource for large-scale injection. A number of oil field tests show that local injectivity is available; data are still needed on the extent to which these local data points can be interpolated and how many injection wells would be needed to get to scale. Thicker sediments in the western areas of the region have been considered most attractive.



Transportation, Direct Air Capture with Storage (DACS), and Cross-Cutting Factors

Due to the varied quality of geologic-storage resources in the Lower Midwest, CO_2 from this region might have to be transported to neighboring regions. With most Class I carriers present in the region, rail connects well to all neighboring regions, and the historic abundance of agricultural activity has made processing and transportation of biomass routine. Existing pipelines connect the south part of the region to storage. Proposed pipelines show varying levels of density, with connections mostly toward the West Texas and South-Central regions. This region's minimal topography makes it suitable for DACS; however, requirements for DACS may need to be deconflicted with land-use considerations for farming. The Lower Midwest region generally has good wind-based renewable-energy production that could be co-located with the cultivated cropland that predominantly covers this region. However, without good local geologic-storage options, expanded electricity transmission for renewable wind energy is needed, possibly to the Upper Rocky Mountain region, which has good storage. Substantial infrastructure expansion, including transportation of biomass, CO_2, and electricity, may provide additional benefits to the Lower Midwest region.

Energy Equity and Environmental Justice (EEEJ)

The Lower Midwest region is particularly prone to PM2.5 exposure from forest fires in the west and from local crop- and rangeland burning. Though currently rich in natural water resources, high drawdown of the slowly regenerating aquifer coupled with changes in precipitation patterns from climate change expose these regions to substantial water shortages, particularly the western extents. Due to the large amount of agricultural activity, including crop and animal production, eutrophication along the Missouri River (particularly at the lower extents of this region) poses high risks to both wildlife and population centers downstream. Any land-use changes or infrastructure projects in this region may benefit from including voices from the many tribal nations that live in these areas.

Constraints

The boundary dividing the Upper and Lower Midwest regions along the South Dakota–Nebraska border and through southeast Iowa is primarily due to a change in soil type that shifts the agricultural abundance between these regions; however, the overall characteristics of these two regions are sufficiently similar that they could have been combined into one discussion. This region's boundary with the South-Central regions closely follows the forest-agriculture lines, but its boundary with the West Texas region to the south is less definitive and may require accounting for nuances at the county level.

West Texas

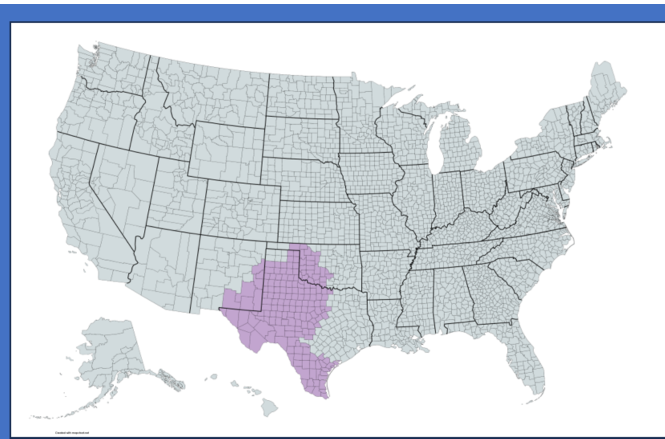
Delineation, Forests, and Cropland Soils

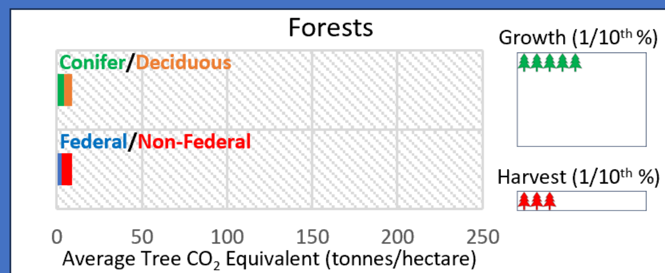
The West Texas region spans most of central and west Texas and parts of Oklahoma and southeastern Arizona. Large amounts of carbon feedstock are present in this region but are an amalgam of woody biomass in the form of oak-pine and loblolly-shortleaf pine, agricultural residues, and secondary wastes that encompass wastes from waste treatment, including composting residue or ash from incinerators. The West Texas region of the southern Great Plains is one of the most promising areas for implementing perennial field borders on croplands, and many hectares of cropland in the region could profit from implementing borders under higher-incentive prices. This region also has high potential for soil-based CO_2 removal in planting cover crops on its expansive wheat fields.

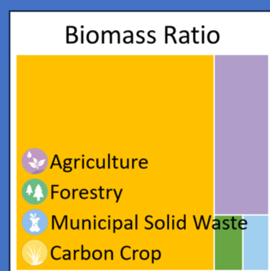
Geologic Storage and Transportation

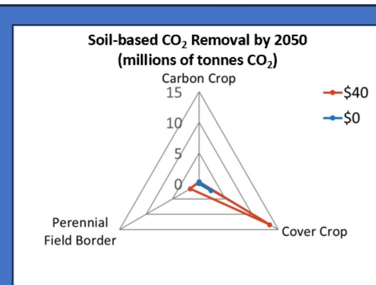
This region is broadly characterized by its tested geologic CO_2-storage capacity, corresponding to the large oil and gas reserves in west and south Texas. It also has substantial networks of existing CO_2 pipelines, large renewable solar- and wind-energy generation capacity, and geography amenable to a large capacity for DAC. The Permian Basin of West Texas has accepted large volumes of CO_2 for enhanced oil recovery (EOR) and has the potential to accept CO_2 for saline storage in Paleozoic-age rocks. Additionally, well-known favorable storage potential is found in the Palo Duro Basin, the Midland Basin–Eastern shelf area, and the Anadarko Basin; with additional characterization, favorable storage prospects can be mapped over most of this region. Risk of induced seismic activity will need to be assessed in these areas, but experience has shown that seismic-risk management techniques are effective. The highly favorable Mesozoic- and Tertiary-age storage areas of the southern Texas coastal plain and coast are already being developed as storage resources.

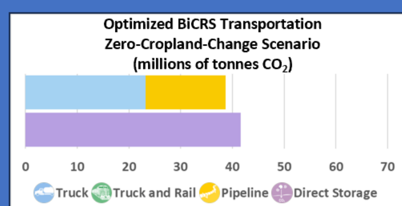
The West Texas region has one of the most extensive existing CO_2 pipeline networks around the Permian basin and is connected with the Lower Rocky Mountains and the Lower Midwest regions. Proposed pipelines would connect this network with the network running along the Gulf Coast. The region has fewer rail lines than the eastern part of Texas, but the lines it has—owned by the Union Pacific Railroad, the Burlington Northern

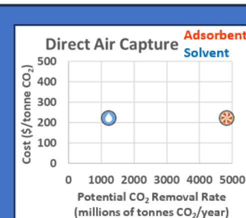


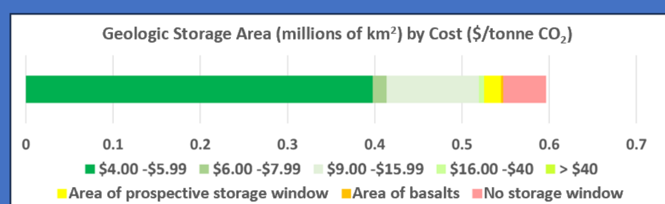


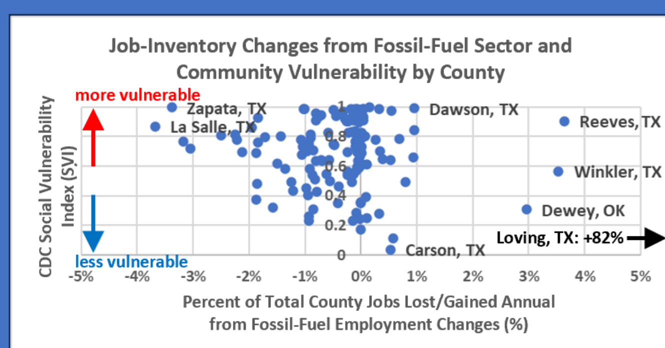












and Santa Fe Railway, and the Canadian Pacific Kansas City Railway—connect West Texas to all surrounding regions. Barges could also be used to import CO_2 from regions with limited storage sites.

Direct Air Capture with Storage (DACS) and Cross-Cutting Factors

West Texas is already a hotbed of activity for DACS due to co-location with existing fossil-energy production, excellent geologic storage, and abundant wind energy, though some of the wind energy is already accounted for in decarbonizing the electrical grid. Forecasts anticipate that electricity will be relatively inexpensive in this region, leading to relatively low DACS cost. Existing CO_2 pipeline connects the geologic storage resources within the region.

Locating natural-gas-powered, high-temperature, solvent-based DACS and capturing the emissions from natural-gas use in this area can be an important near-term strategy that will allow rapid deployment of facilities while not conflicting with electrical grid decarbonization. In the future, natural-gas reserves in this region may allow for a large quantity of low-cost DACS deployment while avoiding long-distance transport of natural gas.

Energy Equity and Environmental Justice (EEEJ)

The already hot climate of the West Texas region is prone to increasing temperatures due to climate change and extreme water deficits, which can particularly impact farmers and ranchers. Expansions into carbon capture and geologic carbon storage may provide increased job opportunities, particularly for unemployed workers skilled in oil- and gas-infrastructure projects. Agriculture, including industrial animal production, poses eutrophication risks for waters in this arid region, specifically along the New Mexico–Texas boundary.

Constraints

The northwest extent of the West Texas region is an approximate boundary that may have overlapping resources and considerations with the neighboring regions. The eastern edge of the West Texas region in contrast is more clearly defined along the forest boundary in the eastern portion of the state and allows for the major urban centers to be within the South-Central region. Even still, decision-makers may gain greater insights by weighing the needs, opportunities, and resources of individual counties near the regional boundaries with those described in neighboring regions.

South-Central

Delineation, Forests, Cropland Soils, and Biomass Carbon Removal and Storage (BiCRS)

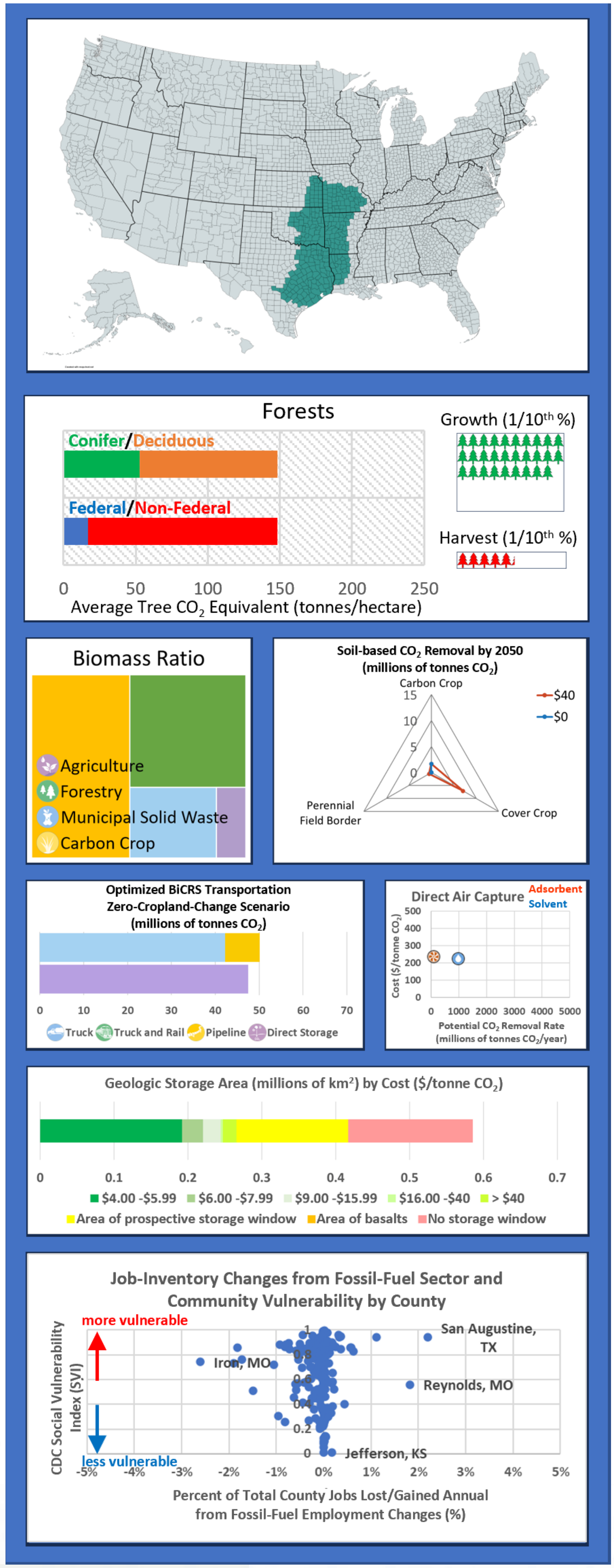
The South-Central region extends from the eastern edges of Texas, Oklahoma, and Kansas toward the Mississippi River. Encompassing the major urban centers in these states, this region is characterized by substantial forest biomass and contains solid carbon in the form of municipal solid waste (MSW). The forests are dominated by economically important loblolly-shortleaf pinelands, with loblolly-slash pinelands in the south largely under corporate ownership, and upland oak-hickory hardwoods in the north, which are largely non-industrial private forestlands. The South-Central region has moderately high potential for soil-based CO_2 removal through converting annual cropland to perennial carbon crops, and moderate potential for implementing perennial field borders, especially on expansive wheat fields in Oklahoma. Additionally, this region has a high carbon-crop potential on marginal lands, which does not conflict with food production.

Transportation and Geologic Storage

The South-Central region sits on top of large potential reservoirs of geologic CO_2 storage, which extend from the mainland into the Gulf of Mexico. In the southern half of the South-Central region, storage potential in Mesozoic and Tertiary-rock is large and well known, with dozens of announced storage projects in development focused near the Gulf Coast and continuing across Louisiana. Good storage is also known in the East Texas Basin. Storage potential in the middle of the region is moderate and poorly known, and two areas of highly deformed and basement rocks in the Ouachita and Ozark Uplifts lack sedimentary rocks in the storage window.

This region also holds some of the densest networks of oil and gas pipelines in the United States and contains major ports for importing and exporting carbon materials. This, along with its large potential reservoirs of geologic CO_2 storage, corresponds to a moderate projected capacity for DACS, albeit at a higher cost than for the neighboring West Texas region.

Rail, owned mainly by the Union Pacific Railroad, the Burlington Northern and Santa Fe Railway, and the Canadian Pacific Kansas City Railway, connects



South-Central, *continued*

this region to all surrounding regions. We found that the South-Central region is a prime location for siting biomass-based biorefineries, and our logistics and transportation optimization model suggested that transporting corn stover from the Midwest to the South-Central region is a good option for maximizing carbon removal and minimizing carbon-removal costs.

CO_2 pipelines are already servicing the coast and the western edge of the region. Proposed pipelines would run through the region and connect it to all surrounding regions, with higher densification of the network in the east and the south of the region. With the extensive port infrastructure on the coast, barges could also be used to import CO_2 from regions with limited storage sites.

Cross-Cutting Factors

The South-Central region predominantly comprises a mixture of pasture lands and mixed forests, with some wetlands along the coast. These categories of land are not suitable for building large-scale solar and wind installations. However, this region contains some of the best resources in the country for geologic storage of CO_2 as well as existing CO_2 pipeline infrastructure. Locating natural gas-powered, high-temperature solvent DACS, and capturing the emissions from natural gas use, in this area may be an important near-term strategy by allowing rapid deployment of facilities while not conflicting with decarbonizing the electrical grid.

Energy Equity and Environmental Justice (EEEJ)

The South-Central region has an outsized PM2.5-pollution risk from both wildfires and local crop- and rangeland burning. This risk may be further compounded by the loss of forestry and logging jobs in Louisiana and Arkansas; urbanization is leading to forest fragmentation, and increasing land values may lead to more forest conversion to human development. Also, plentiful agricultural activity makes this region prone to waterway eutrophication. Additionally, this region contains a high density of abandoned oil wells, particularly in central Oklahoma and eastern Kansas; plans for remediating or repurposing these abandoned wells for geologic CO_2 sequestration may benefit from evaluating the environmental risks to both ecosystems and people—notably the high density of tribal nations in the surrounding area—that may be impacted by industrial activity in the area.

Constraints

The lateral boundaries for the South-Central region are fairly well defined by the major urban areas and forests to the west and the Mississippi River Floodplain to the east. Nuances of individual counties along the borders with the Lower Midwest and Great Lakes regions to the north, particularly the interlocking forest and agriculture feedstocks in Kansas and Missouri, may require detailed local knowledge to assess the best resources for CO_2 removal.

Upper Great Lakes

Delineation, Forests, and Cropland Soils

The Upper Great Lakes region contains the densely forested areas of northwestern Minnesota and the northern extents of Wisconsin and Michigan, including the Upper Peninsula. The region is characterized by its forest biomass, with moderately carbon-dense forests comprising maple-beech-birch, aspen-birch, and white-red-jack pines. These forests are at risk from non-native pests and pathogens and occasional wildfires. The Upper Great Lakes region has relatively low potential for cropland soil-based CO_2 removal due largely to the low area of amenable cropland.

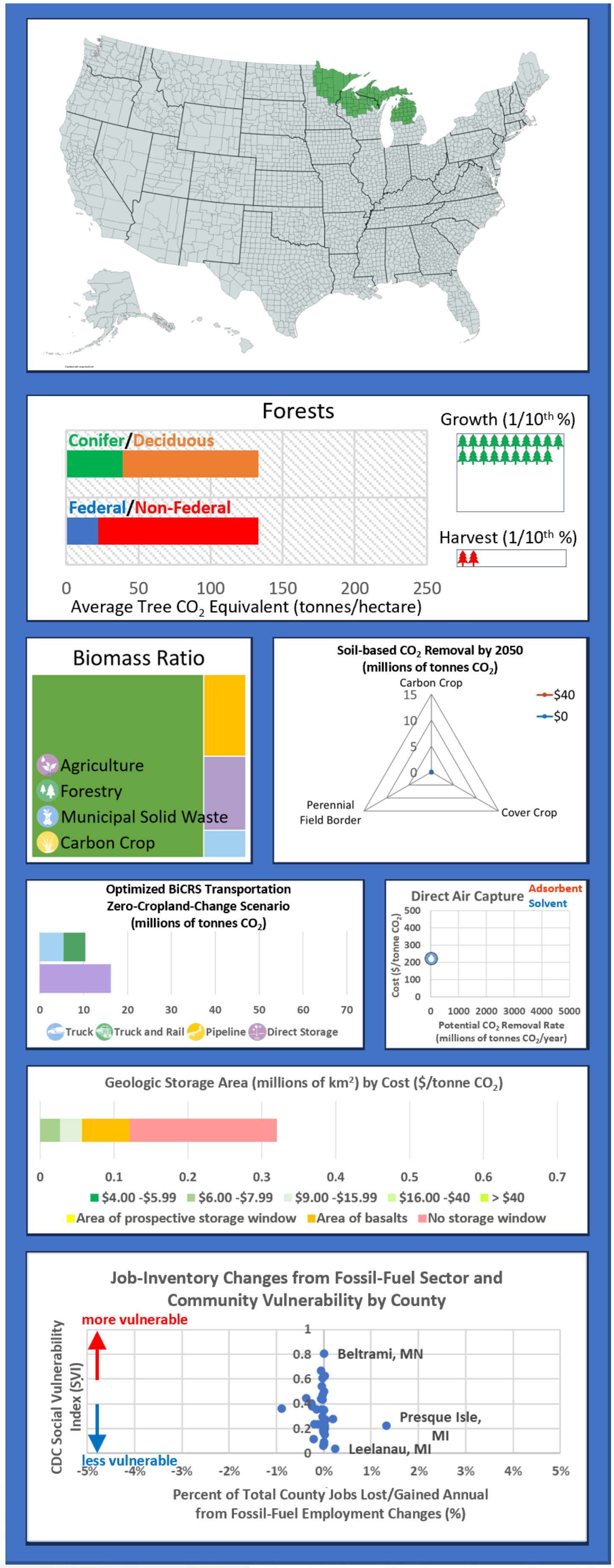
Geologic Storage and Transportation

This region has favorable geologic CO_2 storage capacity in the sedimentary rocks that extend throughout the Michigan Basin. The same basaltic rocks found in the Upper Midwest continue into the Upper Great Lakes region; these rocks have not been assessed for storage but, because of considerable age, are likely to have lost the permeability needed to assist mineral trapping.

This region does not have CO_2 pipelines today, but lower Michigan benefits from a dense rail network and proposed pipelines connecting with the Lower Great Lakes region. The rest of the region is connected to the Upper Midwest via rail, but no pipelines are proposed there. This region also benefits from many waterways and port infrastructure, enabling CO_2 transport by barges.

Cross-Cutting Factors

The Upper Great Lakes region is heavily forested, making it unsuitable for large-scale production of renewable solar and wind energy. Additionally, little is known about the geologic-storage quality in this region. These factors limit the amount of DACS of that can be performed here. Additionally, because it is sparsely populated, much of this region contains similar infrastructure constraints as the East Cascades region.



Energy Equity and Environmental Justice (EEEJ)

Despite the low population density, this region has had an outsized loss of forestry and logging jobs, which could be reinvigorated with broader forest-management practices. These forests were heavily harvested in the late 19th century to open space for agriculture and provide lumber for the expanding US population and economy. The second-growth forests of this region are now middle-aged forests and are economically important for wood production. Most of the forests are under non-corporate ownership, with corporate ownership common only in the Upper Peninsula of Michigan. In addition to these family owners, incorporating the insights and perspectives of the many tribal nations throughout this region to find synergies between tribal practices and resource management may improve outcomes.

Constraints

The maple and red pine forest biomass contained in this region is quite similar to the biomass of the Northeast region, due in part to a similar latitude and the connectivity through Canada north of the Lower Great Lakes. However, we defined this area as a separate region due to geographic distance and the discontinuity across the contiguous United States. The boundaries follow largely along the extents of the state and national forests north of Minneapolis, Minnesota; Green Bay, Wisconsin; and Grand Rapids, Michigan.

Lower Great Lakes

Delineation, Forests, and Cropland Soils

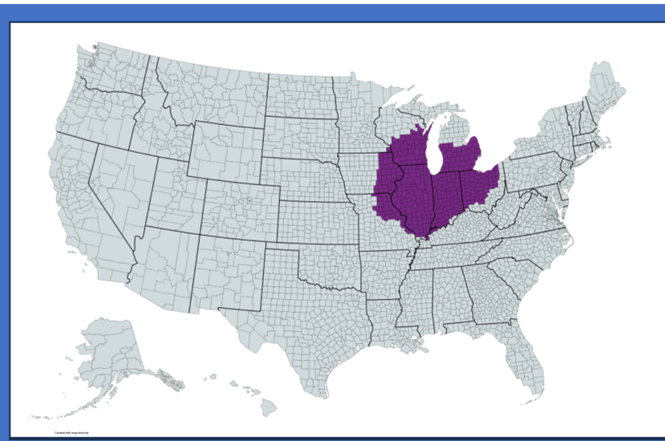
The Lower Great Lakes region encompasses the rich farming areas from eastern Iowa and Missouri through the majority of Illinois, Indiana, and Ohio, as well as the southern halves of Wisconsin and Michigan. Oak-hickory forests used to cover much of this region but have largely been cleared for agriculture and are a small part of the present-day landscape; large proportions of the regional biodiversity can be found in scattered forest habitats. Next to the Upper and Lower Midwest regions, this region contains some of the most abundant agricultural feedstocks in the country and is located above rock with notable geologic CO_2-storage capacity. The Lower Great Lakes region, which is dense with commodity-grain-crop agriculture, has a high potential for soil-based CO_2 removal with cover cropping, perennial field borders, and conversion of annual bioenergy crops to perennial carbon crops due in part to the relatively large amount of cropland amenable to these practices and the productive climate and soil characteristics of the region.

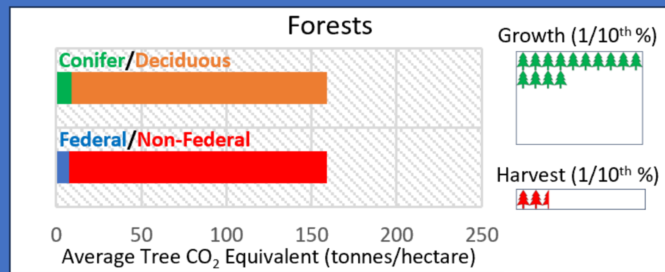
Geologic Storage and Biomass Carbon Removal and Storage (BiCRS)

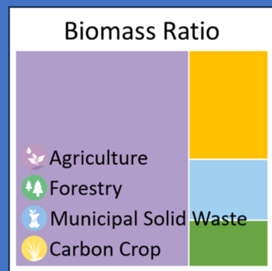
The Lower Great Lakes region can potentially provide among the highest CO_2-removal capacity in the United States according to the models for biorefinery-siting optimization. This capacity is due to favorable co-location of high biomass density, biorefinery-siting locations available within the siting criteria, and the proximate geologic storage. The predominant BiCRS feedstock in this region is corn stover. There is also extensive modeled carbon-crop potential from abandoned and marginal lands, land that may become available from lower corn demand, and conservation reserve program (CRP) lands.

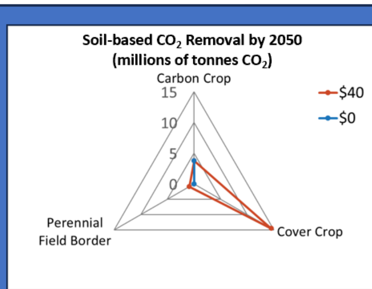
Cross-Cutting Factors, Transportation, and Geologic Storage

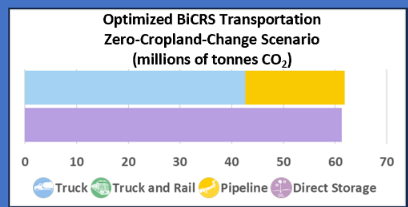
The region is split between two watersheds, which feed the Lower Great Lakes to the north and the Mississippi River to the south, but its centralized location has made it a historic hub for transportation, including pipelines south to the Gulf Coast and east to the Atlantic Seaboard. Many proposals for future CO_2 pipelines aim to connect this region and the South-Central region to intersect the agricultural resources with seafaring transportation infrastructure.

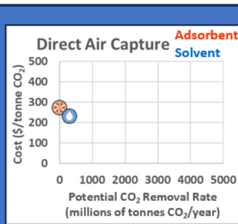


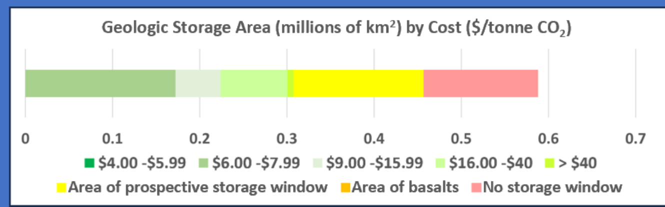


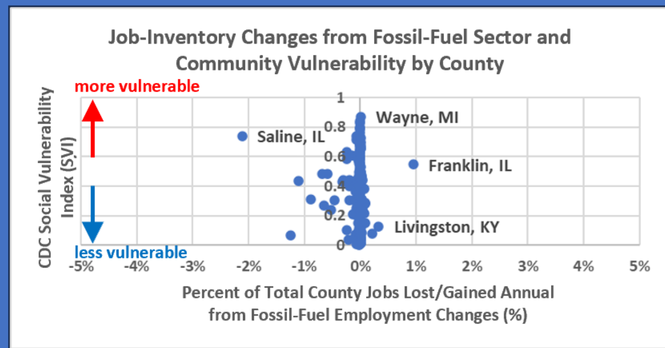












The Lower Great Lakes region also has multiple existing rail, trucking, and barge transportation options and dense transportation networks. Due to the presence of CO_2-storage capacity in a large part of this region, local CO_2 might not have to be transported far, and the extensive transportation network would also make it a good destination for incoming CO_2. Geologically, this region is centered on the Paleozoic-age sedimentary-rock-filled Illinois and Michigan Basins. The most regionally favorable and tested storage formation is basal sandstones of the Mount Simon Formation; limits on the general favorability of this unit include induced seismic risk because of proximity to stiff and stressed Precambrian-age rocks and local thinning and permeability reduction. Shallower carbonates, sandstones, and reef deposits are semi-regional storage resources that have been tested and used for storage.

Direct Air Capture with Storage (DACS)

The Lower Great Lakes region has large amounts of cultivated cropland that could in principle support large amounts of co-located renewable wind-energy production. However, this wind energy is largely already accounted for in decarbonizing the electrical grid due to proximity to major city centers, making it unavailable for DACS. This region also contains a good local geologic storage option in the Illinois basin.

Energy Equity and Environmental Justice (EEEJ)

Despite its rich agricultural conditions, the Lower Great Lakes region is prone to high soil erodibility, particularly within the southern Mississippi and Ohio River Basins. This is an important consideration for any future land-use changes and may benefit from land-management practices that improve soil stability and decrease water- and wind-borne erosion. Additionally, this region contains a high density of abandoned oil wells, particularly in southern Illinois and throughout Ohio; plans for remediating or repurposing these abandoned wells for geologic CO_2 sequestration can benefit from evaluating the environmental risks to both people and ecosystems proximate to and potentially impacted by industrial activity in this area.

Constraints

While the boundaries of the Lower Great Lakes region to the north, east, and south are fairly well defined by the handoff from agricultural biomass to forest biomass, the intersection with the Upper and Lower Midwest regions to the west are less clearly defined, bridged generally by the corn belt. The rough differentiation between the regions is the soil types in east and west Iowa, but other considerations could easily justify shifting the boundary.

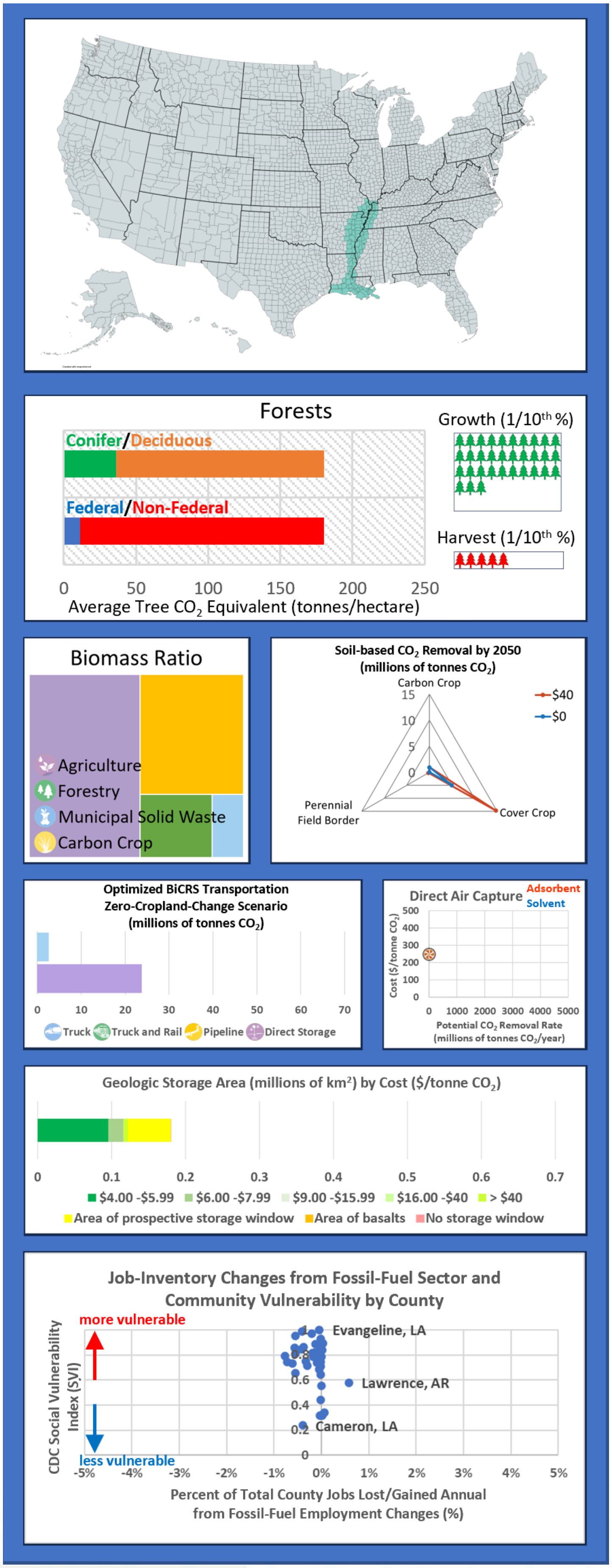
Lower Mississippi River

Delineation, Forests, Biomass Carbon Removal and Storage (BiCRS), and Cropland Soils

The Lower Mississippi River region contains the Mississippi River Floodplain from the southern tip of Illinois to the Louisiana coast. This unique region is almost completely surrounded by forests but is notable for its large secondary-waste capacity as a carbon feedstock. The historic forests have been largely converted to highly productive agricultural lands with the remaining areas comprising bottomland hardwoods, including oak-gum cypress swamps and elm-ash-cottonwood riparian forests. The Lower Mississippi River region has large areas of cultivated cropland and some wetlands, particularly near the Gulf Coast, and has the highest potential in the country for economically viable cover cropping for soil-based CO_2 removal. This region also has moderately high potential for soil-based CO_2 removal through conversion of annual crops to perennial carbon crops. There is a large opportunity for BiCRS in this region, particularly from agricultural residues that are suitable for thermochemical conversion approaches: rice straw, suitable primarily for combustion, and sugarcane bagasse, which can be processed with combustion, fermentation, pyrolysis, or gasification. Further, this region has very high BiCRS potential through carbon crops grown on marginal and abandoned lands. The Lower Mississippi River region also has well-characterized, low-cost geologic storage and proximity to chemical-processing facilities that might provide a market for biomass-derived products.

Geologic Storage, Transportation, and Direct Air Capture with Storage (DACS)

The southern portion of the Lower Mississippi River region contains substantial geologic CO_2-storage capacity and already has a dense network of carbon-transportation infrastructure, particularly on the seaward edges of Louisiana. The Lower Mississippi River geology contains the same favorable Mesozoic- and Tertiary-age storage formation as the South-Central region and has many announced storage projects in development in its southern part. In the northern part of the region, the rocks in the storage window are less well known but are prospective storage locations. The rocks of the Illinois Basin at the north end of the region can accept injected CO_2, but the potential interactions



with the New Madrid and associated faults would have to be assessed to reduce seismic risks. While geologic storage near the Gulf Coast is good, the amount of DACS deployable here is limited due to unsuitable land types.

This region shows multiple existing and proposed transport options and dense transport networks. Due to the presence of CO_2-storage capacity, local CO_2 might not have to be transported far, and the extensive transport network would also make this region a good destination for incoming or transiting CO_2. The Mississippi River could also be used to transport CO_2 on barges.

Cross-Cutting Factors and Energy Equity and Environmental Justice (EEEJ)

The agricultural floodplain of the Mississippi River is prone to high levels of soil erosion and recently has experienced outsized crop-production job losses. The major agricultural activity within the expansive watershed makes this portion of the river prone to eutrophication. Furthermore, while this region is critical to existing and future carbon infrastructure, it is infamously known for high levels of chemical pollutants in the air, water, and soils. This pollution issue is punctuated by the large number of abandoned oil wells in Louisiana and along the coast. Any land-use changes or expanded infrastructure projects may consider weighing the further impact on local populations and ecosystems and may benefit from including potentially impacted people as key decision makers.

Constraints

The Lower Mississippi River region is very geographically defined and distinct from its neighboring regions. However, the subsurface geologic CO_2-storage capacity is contiguous along the Gulf Coast from the southern tip of Texas to Georgia. Therefore, while surface secondary-waste resources are considerably differentiated from the forest biomass resources in the surrounding area, a comprehensive plan developed throughout the southeastern United States on how to best use the shared geologic storage capacity may benefit long-term carbon-management activities.

Northeast

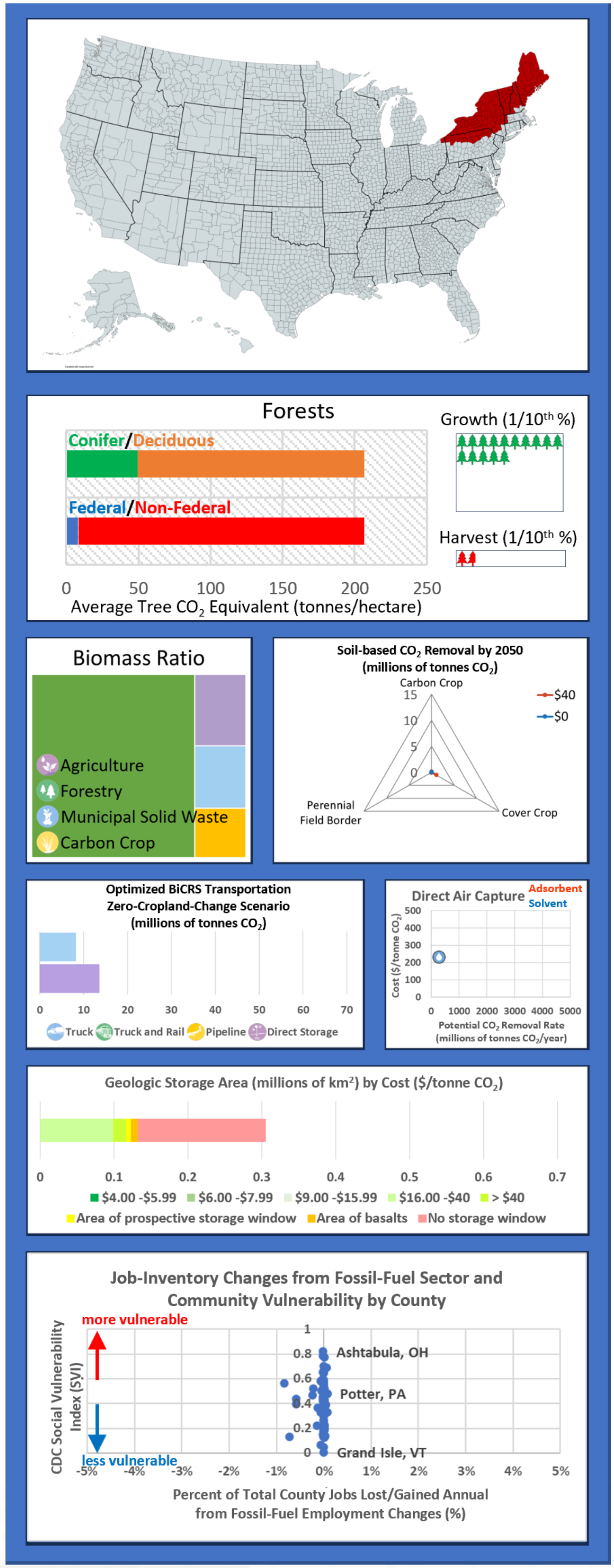
Delineation, Forests, and Cropland Soils

The Northeast region spans from the northern extent of Maine through the rural, forested regions of New England into the northern edge of Pennsylvania. This region is characterized by dense stands of hardwood—maple-beech-birch—at lower latitudes and white, red, and jack pine plus Douglas fir in the far north. Even with a moderate carbon density, these forests are integral to protecting the water supplies for the major urban areas of the adjacent Northeastern Cities region. Increasing drought, wind or ice storm frequency, pests, and pathogens are raising tree mortality and lowering forest health in the Northeast region. Except for counties in New York state where perennial carbon crops and perennial field borders would be viable with a $40/tonne incentive, the Northeast region has moderately low potential for cropland soil-based CO_2 removal.

Geologic Storage, Transportation, and Cross-Cutting Factors

This region contains moderate and moderately well-known geologic CO_2-storage capacity in the Paleozoic-age sedimentary rocks of western New York and Pennsylvania, which is known for its natural-gas resources stored in shale. Otherwise, most of the Northeast lacks conventional storage resources. Some unassessed old basalts located in this region are not likely to have preserved sufficient permeability to support mineral trapping at large scales.

Mostly only short-distance transport could be needed in the southwestern part of the region because of the presence of storage. No pipelines are currently built; however, proposed pipeline networks would connect the northeast of the region to the Northeastern Cities. The rail network is relatively dense and well connected to surrounding regions, including Canada, and is mostly owned by Class II and III carriers. Whereas much of the northern parts of the Northeast region are geographically isolated, the presence of the Erie Canal across Upstate New York provides substantial water and transportation resources to connect carbon resources along the Atlantic Coast with storage resources in the Great Lakes region.



Renewably powered DACS potential in the Northeast region is limited due to the lack of local geologic storage and the highly forested areas that are unsuitable for large solar or wind installations.

Energy Equity and Environmental Justice (EEEJ)

Though logged widely in the 19th century to clear land for agriculture and pastures, the naturally regenerating second-growth forests are largely family-forest owned (non-commercial private ownership), and expansion of forest-management practices presents new employment opportunities and supports natural ecosystems and biodiversity. Timber harvesting is already a billion-dollar industry in northern Maine, but the Northeast region has experienced an outsized loss of forestry and logging jobs that impacts many smaller counties. This situation is exacerbated by the economic challenges that come from increasing tax pressure, rising land values, and lack of professional management, leading to sales of forestland for development, which also contributes to a loss of forest carbon. Additionally in this region, there are high densities of abandoned oil and gas wells, particularly in Pennsylvania and western New York, which have corresponding fossil-fuel job losses; management of these areas may benefit from accounting for local economies and ecosystems.

Constraints

The border between the Northeast and the Appalachia regions is broadly defined by the transition from maple to oak forests, which contain inherent overlaps in biomass. The boundary with the Northeastern Cities region defines a rough delineation between urban and rural counties while allowing the regions to be contiguous. Several counties in western Massachusetts may reasonably be considered in the Northeast region and are likely able to participate in the carbon resources for both regions.

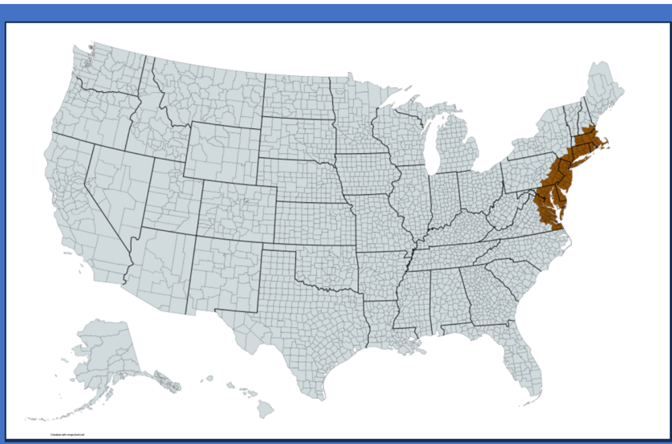
Northeastern Cities

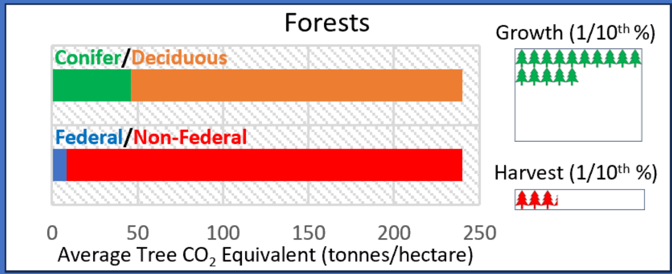
Delineation, Forests, and Cropland Soils

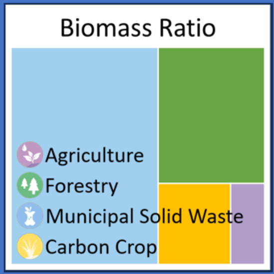
The Northeastern Cities region encompasses the major urban areas along the north Atlantic seaboard, including Portsmouth, New Hampshire and Boston, Massachusetts to the north and Norfolk, Virginia in the south. Containing densely populated cities, this region produces a large amount of municipal solid waste (MSW)—chiefly paper and paperboard and construction and demolition waste—that could be diverted from landfills. The second most abundant feedstock in this region is the harvest of hardwoods from commercial forestry operations, outside of current use. The northeastern urban megalopolis corridor has caused high fragmentation of the largely mixed-oak and pine forests in that area, impacting biodiversity and biomass resiliency. Most of these forests are family-forest owned (non-commercial private ownership). However, land values and property taxes are high, leading to high conversion to developments. Aspects of the financial incentives for promoting forest management, specifically regenerative-focused tree cultivation in the northeastern United States, are explored in Chapter 2 – Forests. Northeastern Cities have relatively little cropland and therefore low potential for cropland soil-based CO_2 removal.

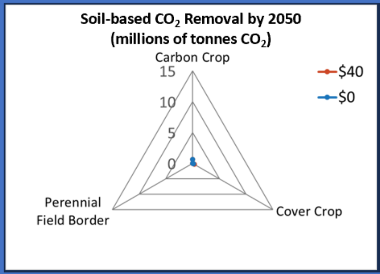
Geologic Storage and Biomass Carbon Removal and Storage (BiCRS)

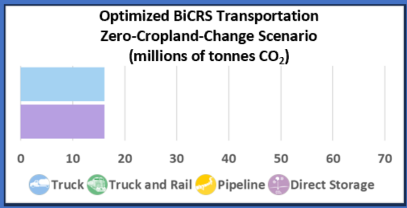
This region has some geologic CO_2-storage capacity in the Mesozoic-age rock along the Atlantic seaboard from southern New Jersey to North Carolina, especially near the coast and increasing in capacity offshore [12]. Deep, circulating freshwater resources may limit usable CO_2-storage volumes onshore. The northern part of the region lacks storage potential except for local areas of basalts, which early tests have suggested may lack sufficient permeability to allow effective mineral trapping. Due to the low-priced feedstock and availability of geologic storage (if sites can be found outside of population centers), our BiCRS optimization modeling shows that the Northeastern Cities region could have among the lowest feedstock and transportation costs.

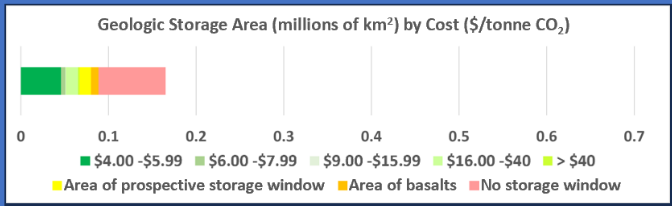


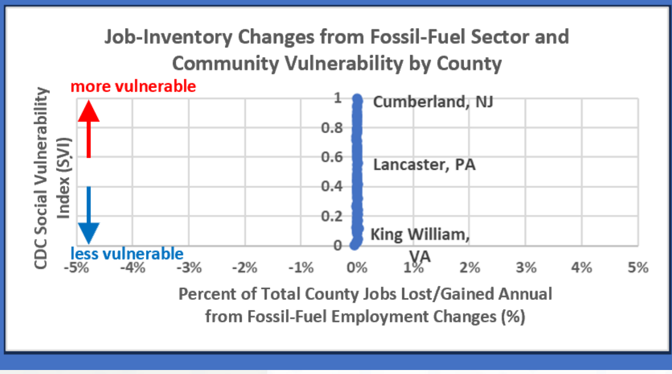












Transportation and Cross-Cutting Factors

This region benefits from a dense rail network—dominated by Class II and III carriers—and access to ports and is well connected to the Northeast, Appalachia, and Southeast regions. No pipelines are currently operational, but there are proposed pipeline networks that would run through the region or connect it with the Appalachia region. Even with technically suitable storage, CO_2 from this region might have to be moved for storage away from densely populated areas. Due to the extensive port infrastructure, barges could also be used to transport CO_2 to more appropriate storage locations.

Renewably powered DACS potential in the Northeastern Cities region is limited due to the lack of local geologic storage and the highly forested and urban developed areas that are unsuitable for large solar or wind installations. Additionally, while there are substantial wind resources off the coast, thoughtful considerations of urban and maritime needs are important factors when selecting viable locations for large infrastructure projects.

Energy Equity and Environmental Justice (EEEJ)

Because much of the land in the Northeastern Cities region is densely urban or suburban, waste-management practices, including collection, transportation, processing, and disposal of MSW and sewage, may be important due to their acute and chronic impacts on the health of local populations and surrounding ecosystems, particularly Atlantic Ocean wildlife. Robust waste-management plans could enable the separation of carbon resources and a decrease in harmful- or toxic-material exposures. Terrestrially, mixed-oak forests in large urban areas provide a multitude of services for city populations, including reducing urban temperatures, flooding, and air pollution and providing biodiverse habitats while storing carbon. High deer density and browsing pressure in suburban and urban areas are halting forest regeneration and reducing plant diversity, stunting recovery after disturbances, such as drought, wind or ice storms, pests, and pathogens.

Constraints

The Northeastern Cities region is intended to contain a contiguous set of large cities, which notably omits the major urban centers of Upstate New York, across Pennsylvania, and decorated throughout the portion of Virginia west of Richmond. There are of course large urban centers throughout the southeast United States, but the low geographic density, discontinuity from the Northeast, and high surrounding biomass resources provide a rationale for distinguishing between the two. Taking resources and infrastructure—particularly the availability of natural or anthropogenic carbon sources—into consideration county by county may improve outcomes when determining local action in the Northeastern Cities region.

Appalachia

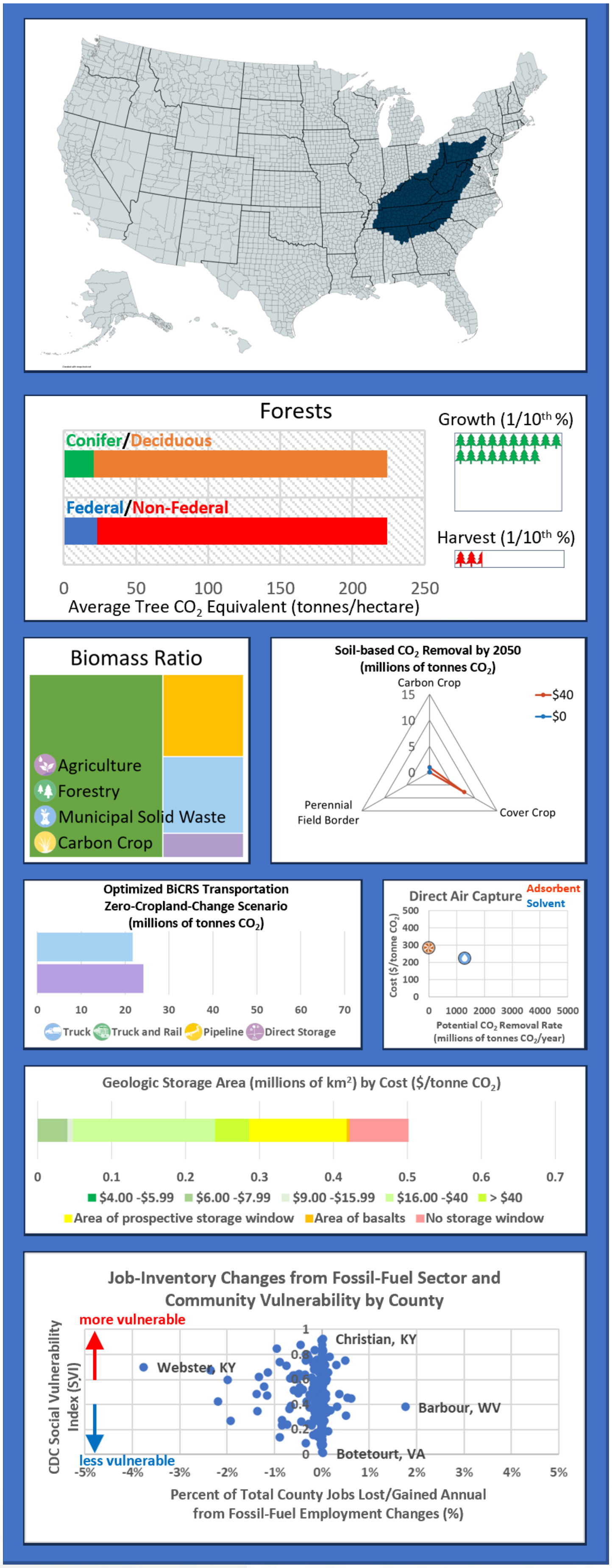
Delineation, Forests, and Cropland Soils

The Appalachia region spans from central Pennsylvania southwest along the Appalachian Mountain Range and into the northern portions of Alabama and Georgia. The region is characterized by dense oak-hickory forests and is bordered by the loblolly pine forests of the Atlantic Coast to the south and the agriculture of the Great Lakes region to the northwest. The hardwood from commercial forestry operations is the largest source of biomass in this region; the fluctuating elevation gradients, warm weather, and high precipitation promote some of the most tree-diverse and carbon-rich forests in the United States. Forest ownership is predominantly family-forest (non-commercial private ownership) with major national parks and forests, including Shenandoah, Great Smoky Mountain, and Blue Ridge, along the highest elevations. Cropland in Appalachia is well-suited for soil-based CO_2-removal practices, with moderately high technical and economic potential for planting perennial carbon crops and cover cropping in the annual cropland in the region.

Geologic Storage, Transportation, and Direct Air Capture with Storage (DACS)

With notable geologic CO_2-storage capacity in Pennsylvania, West Virginia, and Kentucky, the Appalachia region has many similar characteristics to the neighboring Northeast and Southeast regions, with the exception of the forest species type, which are important factors when considering the carbon capture and storage potentials of these connected regions. The northwest area of folded Paleozoic-age rocks in the Valley and Ridge Province of the Appalachian Mountains has some moderate and locally moderately well-known CO_2 injectivity, but regional studies underway may be important for determining how widespread suitable permeable formations are for storage. The southeast Blue Ridge area in the Appalachia region has no conventional storage in metamorphic and granitic rocks of the area. There are local areas of metamorphosed basalts in the Appalachia region that still require injectivity assessments.

Given the presence of storage basins, the Appalachia region does not necessarily need to transport CO_2 out of the region. Transport networks are constrained by the topography of the Appalachian Mountains. Proposed



pipeline networks are bordering the region, with more extensive networks running smaller lines inward. Still, a dense rail network dominated by the Norfolk Southern Railway and CSX Transportation has been developed by the now declining coal industry, and it could be progressively repurposed for the growing carbon-management industry with the goal of retaining jobs in the region.

Renewably powered DACS potential in the Appalachia region is limited due to the high topography of the region and the highly forested areas that are unsuitable for large solar or wind installations.

Cross-Cutting Factors and Energy Equity and Environmental Justice (EEEJ)

The mountainous Appalachia region is susceptible to high soil erodibility in the Ohio River Basin despite its high forest density. It has high densities of abandoned oil and gas wells, particularly in Kentucky, West Virginia, and Pennsylvania and a correspondingly high number of lost jobs in these same areas. The region's forests have been heavily disturbed over the past century owing to mineral and coal extraction, timber harvesting, and development. Nearly all are secondary-growth forests recovering from widespread clearcutting and logging in the late 19th century. The collapse of the forest industry in the 1920s caused extreme economic hardship to the communities in the region and ignited interest in conservation and developing forest-management practices. Additionally, a rise in pests and pathogens are increasing tree mortality, reducing forest regeneration, and changing forest composition. Expansion of forest- and carbon-management practices in these areas could provide both employment and land-conservation opportunities to support ecological and economic flourishing.

Constraints

The Appalachia region has blurred boundaries along all borders due to oak forests being its primary defining characteristic. Oak forests extend north up through Massachusetts, overlapping with the Northeast region, and into Indiana, intersecting with the Great Lakes region. Even though these trees extend deep into the South-Central region to the west, for regional continuity, the Appalachia region stops at the intersection with the Mississippi River floodplain. Because much of this region is mountainous, particular care with respect to transportation infrastructure, specifically for woody biomass, may improve outcomes.

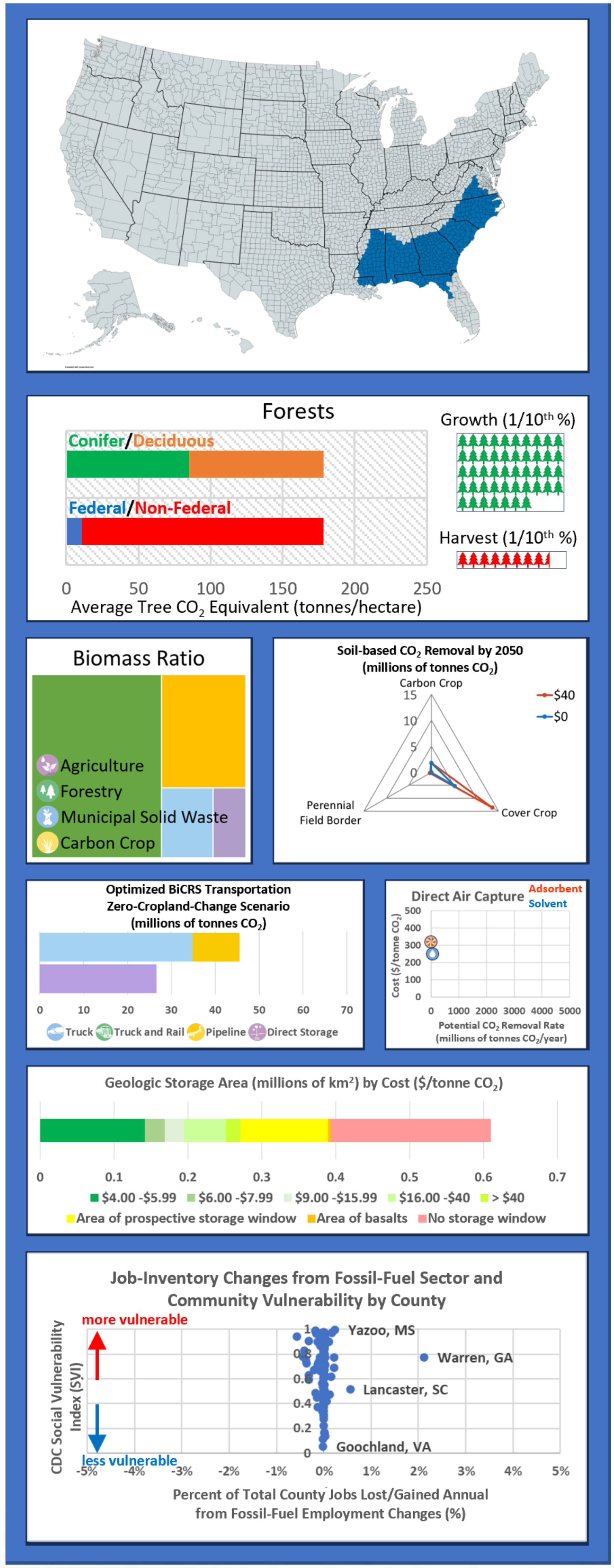
Southeast

Delineation, Forests, and Cropland Soils

The Southeast region follows the Atlantic seaboard from central Virginia south to the Florida panhandle and west along the Gulf Coast to the Mississippi River floodplain. The region is characterized by dense forests, largely loblolly-shortleaf in the Piedmont pine but also including longleaf-slash pine and cypress along the southern coastal extents. These forests meet over half of the US wood-production needs given the decline in timber harvesting in other regions of the country. The warm, temperate climate of this region allows fast growth of native pine trees, and an active wood-based economy makes this region a key area for promoting harvesting practices that can sustain wood and fiber needs and keep forestlands from conversion under development pressure. Chapter 2 – Forests explores this in its thorough case study on planting loblolly pine trees, expanding carbon storage in woody biomass, and advancing novel wood markets and economies. The Southeast region also has high potential for cropland soil-based CO_2 removal, particularly along the Atlantic Coast. The east coast of this region has great potential for soil-based CO_2 removal through adoption of cover cropping and a shift from annual crops to perennial carbon crops. This region also has potential to benefit the greatest percentage of black land managers through CO_2-removal incentives compared to other regions.

Biomass Carbon Removal and Storage (BiCRS)

The Southeast is a tremendously important BiCRS region due both to availability of biomass from forestry and to marginal and abandoned land area that could be used for production of perennial carbon crops. Population centers in the Southeast could also provide municipal solid waste (MSW) to blend with the forestry biomass, which could help mitigate feedstock variability from pure MSW streams. Additionally, the Southeast region has ample geologic storage along its southern half. These large geologic CO_2 storage formations that extend along the Gulf Coast are contained in the southern portions of the Southeast region.



Geologic Storage, Transportation, and Direct Air Capture with Storage (DACS)

The area spanning south Georgia, north Florida, Alabama, and Mississippi contains Mesozoic-age rock with good permeability that is moderately well known, and multiple site characterization and testing programs have been conducted [13]. Moderate storage potential is found in Paleozoic-age rocks of the Black Warrior Basin. The Piedmont area has no conventional storage in metamorphic and granitic rocks, which crop out or are found at shallow depths. Local areas of basalts and associated redbed sediments, which would require assessment for injectivity, occur in Triassic-age grabens in this region, but early tests show limited potential for storage [14].

This region shows multiple existing (rail, trucking, barges, and pipelines) and proposed (pipelines) transport options and a dense rail network with most of the Class I rail carriers present in the region. Due to the presence of CO_2 storage in the southern part of this region, local CO_2 might not always have to be transported far. Proposed pipelines border the Appalachia region or connect to it to the Southeast, potentially expanding the rates of CO_2 transport. Further, the extensive transport network of the Southeast region would make it a good destination for incoming CO_2.

Renewably powered DACS potential in the Southeast region is limited due to the highly forested, developed, and wetland areas that are unsuitable for large solar or wind installations. There is good geologic storage in parts of this region along the Gulf Coast, but these tend to be protected wetlands areas.

Energy Equity and Environmental Justice (EEEJ)

With an interspersed network of forests and agricultural activity, the Southeast region is susceptible to high rates of soil erosion. The coastal area of North Carolina has a high density of livestock operations, which provides an opportunity for manure-carbon management, but also presents potential challenges to the health of local people and ecosystems. This situation is exacerbated by high PM2.5 from local fires, particularly crop- and rangeland burning. The Southeast region is also a patchwork of counties adjacent to one another, many with either substantial gains or losses in forestry employment, driven in part by the amalgam of commercial and privately owned and managed pinelands alongside substantial private, non-corporate ownership. Future plans for land and resource management may benefit from pursuing equitable distribution of job opportunities and other benefits among all counties. Further, accounting for tree mortality exacerbated by increasing weather events (e.g., hurricanes, tornadoes and windstorms), pest outbreaks (e.g., the southern pine beetle), and development activity may improve forest management in particular.

Constraints

The densely forested Southeast region is also heavily decorated with a wide variety of agricultural products, and consideration to land allocation for future carbon-management practices may benefit from a wholistic, localized assessment of land use. Additionally, the boundary with the Florida Peninsula region to the south is blurred by the overlap of pine forests and urban zones, specifically around Gainesville and Jacksonville, Florida. Further, the boundary between loblolly pine and oak stands in the Appalachia regions is indistinct; county-level considerations on how to participate in future carbon-management practices may improve aggregate outcomes.

Florida Peninsula

Delineation, Forests, and Cropland Soils

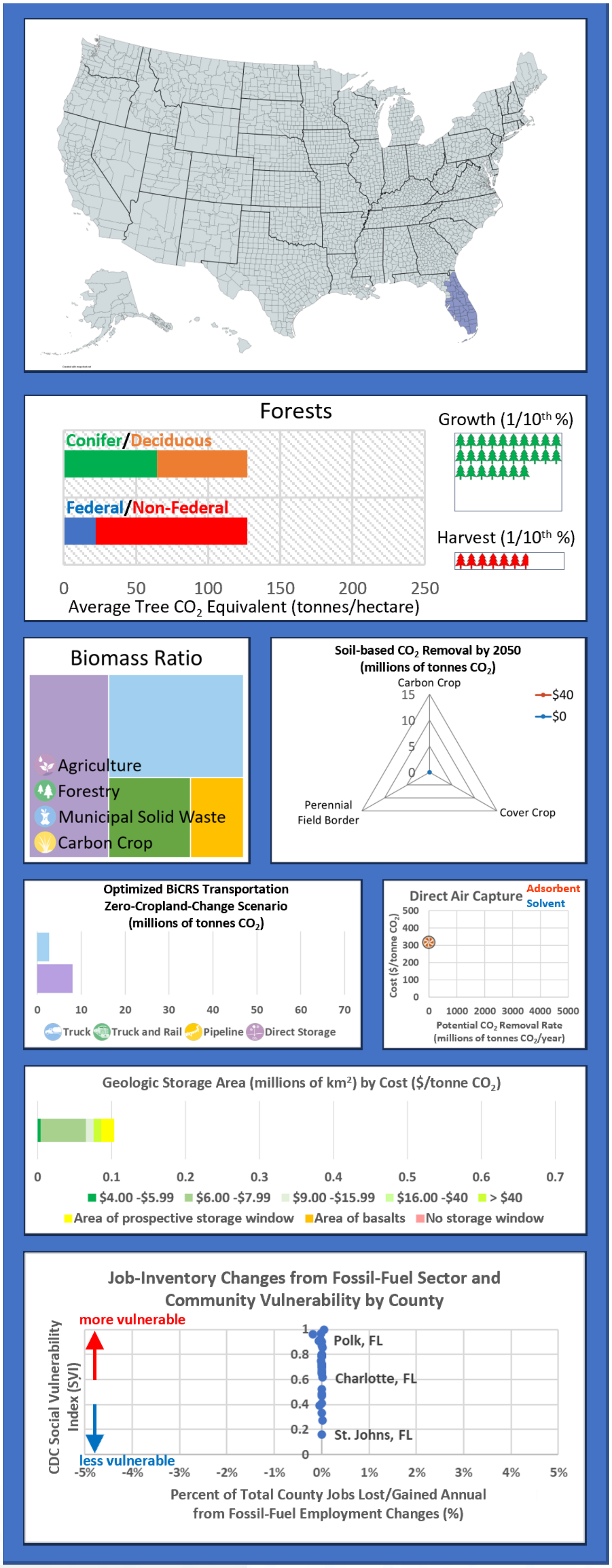
The Florida Peninsula region extends from Jacksonville, Florida in the north to the Everglades in the south, excluding the Florida Panhandle which is contained in the neighboring Southeast region. The Florida Peninsula region is characterized by low-lying wetland with agricultural trimmings from citrus farming and contains several major urban areas with municipal solid waste (MSW). In this heavily developed region, the remaining forests are predominantly wet oak-gum-cypress swamps, many of which are found in federally owned and managed sites, such as Everglades National Park and the Big Cypress National Preserve. Cropland on the Florida Peninsula grows mainly perennial specialty crops, including citrus, sugar cane, or vegetables. The soil-based CO_2-removal practices analyzed in this report are more conducive to rotating grain or legume crops. Thus, while these practices would likely benefit soil-conservation in the Florida Peninsula, this region has relatively little potential for cropland CO_2 removal through these practices.

Biomass Carbon Removal and Storage (BiCRS)

Biomass in the Florida Peninsula suitable for carbon removal and storage is of the most diverse in the United States, with large fractions from agriculture, MSW, carbon crops, and, to a lesser extent, forestry. The agricultural biomass is predominantly from citrus residues (the high moisture of citrus residues makes them more suitable for fermentation than the thermochemical approaches) and sugarcane bagasse, and the state also has land area that could support carbon crops without impacting current cropland.

Geologic Storage and Transportation

Geologic CO_2-storage potential in south Florida occurs in Mesozoic-age carbonate rocks. Work is needed to extrapolate the extent of permeable formation from sparse data in hydrocarbon-producing trends [15]. Further, unassessed but prospective sedimentary rocks cover the northern part of the region. However, failing to demonstrate protection of the overlying but deep Floridan aquifer would be a risk to storage development.



Nevertheless, if suitable storage were identified, CO_2 could be stored onsite in most of the region, using CO_2 transport for only short distances. Alternatively, the rail network—including the Class I carriers CSXT and the Norfolk Southern Railway—and extensive proposed pipeline networks could provide various routes connecting to the Southeast region. Alternatively, barges could be used to connect the Florida Peninsula region to other coastal regions. Of note, renewably powered DACS potential in the Florida Peninsula region is limited due to the large wetland areas that are unsuitable for large solar or wind installations.

Energy Equity and Environmental Justice (EEEJ)

The Florida Peninsula region has had an outsized loss of crop-production jobs, predominantly in the center of the state. Furthermore, large amounts of crop burning leads to high PM2.5 exposure in the state. Also, given the region's low elevation, future sea-level rising presents a unique challenge for infrastructure development projects.

Constraints

The Florida Peninsula region has a blurred border with the Southeast region in the intermixing between urban and forested counties, particularly around Jacksonville, Florida. The region is prone to heavy rain and hurricanes, which may hinder large infrastructure projects for carbon capture and storage. Particular consideration to the present and future climate in this region, including rising ocean levels, may benefit long-term planning activities.

Alaska

Delineation, Forests, Cropland Soils, and Biomass Carbon Removal and Storage (BiCRS)

The Alaska region contains the entire state and is characterized by permafrost tundra and dense but largely inaccessible boreal forests, which account for 90% of the 130 million acres of forestland. The remaining 10%, located in the coastal temperate rainforests, is dominated by Sitka spruce and western hemlock; the majority of the forest industry is located in this part of the region's forestland. Because of high biomass transportation costs, two-thirds of the wood products remain in the region. The Alaska region contains very little common-commodity cropland and therefore has little potential for cropland CO_2 removal from the practices analyzed in this report. BiCRS in Alaska highlights forest thinning for wildfire risk reduction in the Kenai Peninsula Borough area. This biomass sits on top of a prospective geologic storage window.

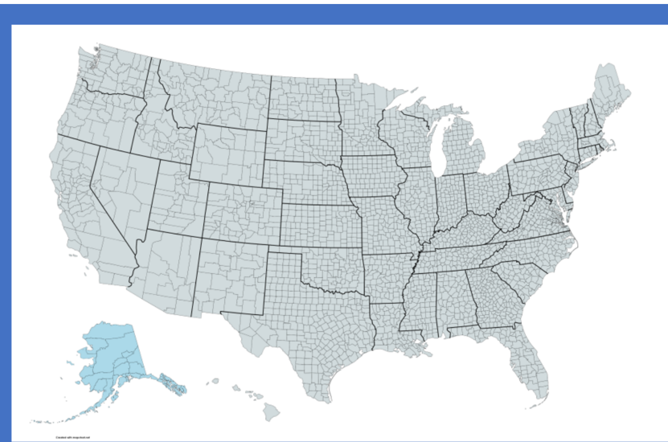
Geologic Storage and Transportation

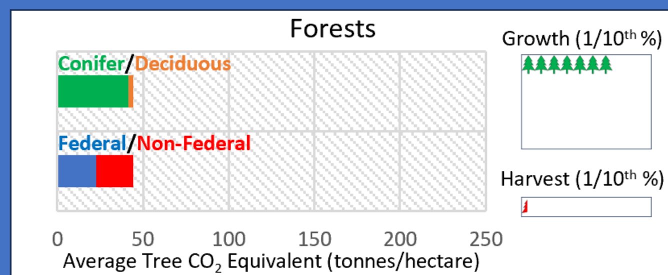
The region's best documented geologic CO_2-storage potential is beneath the late Paleozoic- and Mesozoic-age hydrocarbon-producing areas of the North Slope [16], which are portions of the state currently being used or proposed for oil exploration and extraction. Smaller intermontane sedimentary basins that have not been assessed for storage potential sit between mountain and basement areas that have no storage potential. A number of basaltic rocks are present but have not been assessed.

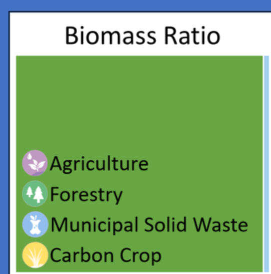
With no existing or proposed CO_2 pipelines and very few rail lines that lack connections to the North Slope Basin, carrying CO_2 through Alaska could be a major challenge and would have to be done by truck.

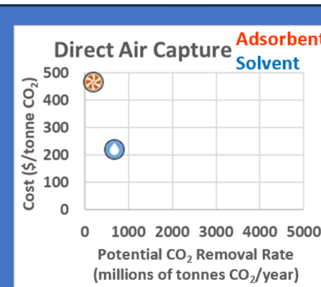
Direct Air Capture with Storage (DACS) and Cross-Cutting Factors

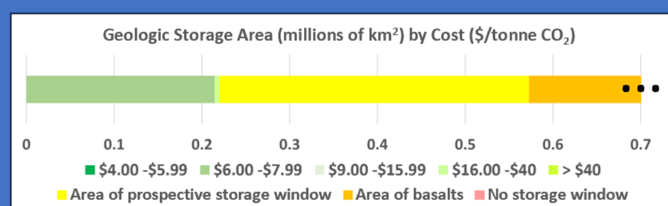
Alaska has some good options for DACS, with abundant geologic storage and potential for wind energy generation, particularly on the North Slope. Additionally, locating natural-gas-powered, high-temperature solvent DAC—as well as and capturing the emissions from

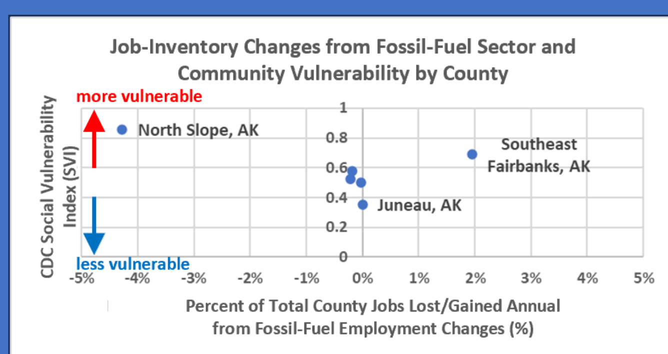












natural-gas use—in this area may be an important near-term strategy; it would allow rapid deployment of facilities while not conflicting with decarbonizing the electrical grid. In particular, stranded natural-gas resources in the North Slope may provide a particularly unique opportunity for harnessing an otherwise unused resource for CO_2 management and removal.

Energy Equity and Environmental Justice (EEEJ)

There is high wildfire risk in central Alaska, an issue exacerbated by climate change, which is projected to increase the PM2.5 exposure for Alaskans in central and eastern Alaska, including Fairbanks. Forests are habitats for diverse wildlife species and are vital to the protection of the riverine habitats that are home to Alaska's five salmon species; forest wildlife and fish are economically and culturally vital to Alaskan communities. The area also has a high existing energy burden, requiring firm power in the winter when solar electricity is not an option. Rural communities that heat and power homes and buildings with diesel fuel could benefit from switching to cheaper and renewable wood products as substitutes. Remote locations and small tribal nations make energy security a top priority. Both southern Alaska and the North Slope have recently experienced fossil-fuel job losses that have had outsized impacts on their counties. This region has 228 federally recognized Native Alaskan tribes, who are represented by 12 different Alaska Native regional corporations. While two-thirds of forests are owned and managed by federal agencies, about 10% are held by these corporations. Future infrastructure projects may garner helpful insights from these groups.

Constraints

The similar forest type and general proximity to that of the West Coast region may be reason to combine the Alaska region with the continental United States, but for geographic continuity, it has been given its own distinct zone.

Hawai'i

Delineation and Biomass Carbon Removal and Storage (BiCRS)

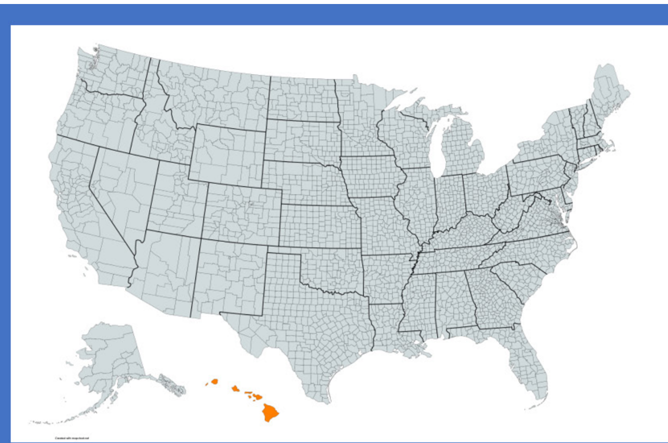
The Hawai'i region consists of all the associated islands in the Pacific Ocean. This region is characterized by its tropical climate, mountainous geography, and biomass diversity. Because of its small size, lack of dense urban areas, and minimal agriculture, the region is very heterogeneous in its biomass availability. The major opportunities for BiCRS in Hawai'i are through thermochemical conversion of municipal solid waste (MSW) and capturing CO_2 from landfill gas to produce carbon-negative biomethane. Hawai'i is very land-limited, and landfills are reaching capacity. BiCRS in Hawai'i would serve to divert biogenic waste from landfills, capture CO_2, and provide other fuel or bioproduct needs for the islands.

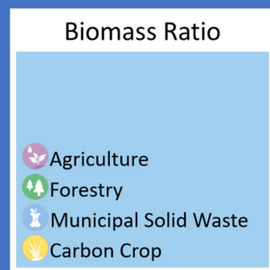
Forests and Cropland Soils

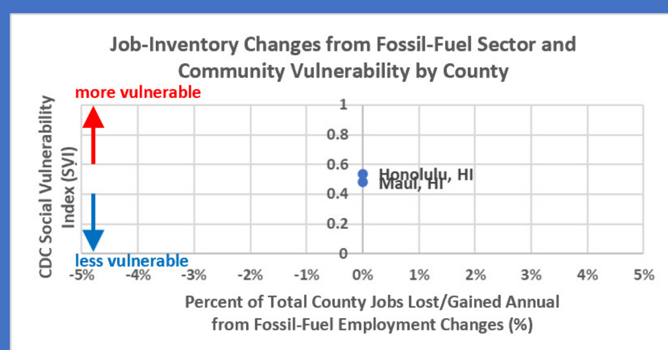
The tropical forests in Hawai'i are biodiverse and include dry forests found on the leeward side of the islands and wet forests on the windward side. Cropland in Hawai'i is cultivated mainly for specialty crops. The unique climate and soil-properties in Hawai'i relative to the continental United States require a specialized biogeochemical-model calibration, which was outside of the scope of this report. It is likely that climate- and soil-chemistry-modified versions of the practices analyzed in this report could have soil-based CO_2-removal potential in Hawaiian croplands.

Geologic Storage, Transportation, and Direct Air Capture with Storage (DACS)

The subsurface of Hawai'i is all young volcanic basaltic rocks that have the potential for preserving permeability and allowing mineral trapping [17]. These options are now under study in the state. Beyond geologic storage, the options for biomass-derived carbon are in producing long-lived bioproducts, such as biochar or bioasphalt. Due to the remoteness of Hawai'i, the CO_2 would have to be stored in basalts on the islands. With no CO_2 pipelines and very limited rail lines, carrying







CO_2 in Hawai'i would be limited to trucking or barges once the port infrastructure is built. Hawai'i does not have a lot of land usable for large-scale DACS installations due to the topography, protected lands, and competing land use with population centers. When more is understood about the potential and cost for CO_2 storage in basalts, Hawai'i may be able to support some small amounts of DACS.

Cross-Cutting Factors and Energy Equity and Environmental Justice (EEEJ)

Due to its geographic isolation, the Hawai'i region is largely powered by diesel power plants, though expansion of solar photovoltaics and battery storage are increasingly common. The islands have waste-management challenges due to limited land availability or suitability for landfills. Native Hawaiian peoples do not have reservation lands, and there are disparities with historic land tenures, which makes it imperative to have early public engagement and public-perception assessments before proposing any carbon-management projects. Additionally, this region contains high biodiversity, which is increasingly at risk due to infrastructure encroachment and climate change, contributing to more forest disturbances, such as wildfires on the arid sides of the islands. Dominant trees are the ōhi'a lehua and the koa that have immense ecological and cultural value on the islands; major threats to the forests are invasive species, including pests, pathogens, plants, pigs, and ungulates that reduce forest tree-seedling regeneration and health.

Constraints

While the isolation of the Hawai'i region limits its participation in carbon-management practices, this same isolation provides an ideal testing platform for microgrids and distributed technologies, which may become pivotally important when developing solutions to be used across the continental United States and around the world.

Conclusions

Each of the 22 geographic regions in the United States contain unique geographies, ecologies, populations, infrastructure, and carbon resources that present both opportunities and challenges for CO_2 removal. While some regions have an outsized opportunity to participate along the road to carbon removal, each region has an important role to play. Identifying the synergies among carbon-removal strategies and job creation, resource conservation, and wildlife enrichment will be critical both on a local level and at the country scale. Co-benefits, such as air-quality improvements from wildfire prevention and eutrophication reduction from perennial cover crops, are important considerations. Tradeoffs, such as allocated land use and the risks of unintended or unanticipated consequences, also need to be identified. Furthermore, collaborations between regions are imperative, not only to leverage division of labor and resources, but also to distribute the burden of work and opportunity across the nation. While the multifaceted considerations for land use, dollars spent, jobs created, and resources managed are admittedly complex, the contents of this regional analysis chapter provide a consolidated sketch of high-level considerations that can be discussed and explored by decision makers. Inhabitants of each county within each region may find aspects of their local environment that are underrepresented in this regional analysis chapter and should be encouraged to contribute their insights in broader conversations about how the country collectively can pursue net zero by or before 2050. Only with concerted effort at all scales throughout the country can we unite our regional capacities on the road to CO_2 removal.

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