CHAPTER 8

Cross-Cutting Resource Requirements and Environmental Impacts

SUMMARY

Throughout this report, unique objectives and constraints have been applied for forest management, agricultural-soils management, biomass with carbon removal and storage (BiCRS), and direct air capture with storage (DACS) to determine the potential magnitude and costs of large-scale CO_2 removal. Each strategy yields some environmental co-benefits, such as reduced wildfire risk, and places some new demands on constrained natural resources. This chapter discusses the potential timing for scale-up of each CO_2-removal strategy and the implications of large-scale carbon removal for three natural resources: land, water, and air. First, we established cross-cutting land-use constraints for BiCRS and DACS and set priorities to de-conflict land use between the technologies discussed in this report (**Figure 8-1**). We considered protected lands, developed land, and wetlands to be unavailable for development and placed buffers around critical infrastructure based on existing guidelines and regulations. We only considered DACS to be viable on lands that are directly above confirmed geologic-storage potential or that have access to CO_2 pipelines. Further, to prevent competition between grid decarbonization and on-site renewable energy for DACS, we set aside land needed for developing wind turbines and solar energy to enable a decarbonized grid. We mapped the impacts of these decisions sequentially. This approach allowed us to visualize how each constraint impacted total land availability and how the remaining fraction of the land considered viable for development was distributed between disadvantaged and non-disadvantaged communities. Finally, in this chapter we present de-conflicted scenarios for land use and land conversion to show how changes to the landscape may be distributed across each region.

Based on the de-conflicted scenarios for forest management, agricultural-soils management, BiCRS, and DACS, we charted the path to scaling up each of these strategies and discuss what factors may impact the timing. Based on the scale of carbon removal across each strategy, this chapter evaluates the freshwater requirements for DACS and BiCRS facilities and the geographic distribution of these water needs (**Figure 8-2**). We then mapped these water needs to hydrologic regions to determine the likelihood that large-scale CO_2 removal would exacerbate water stress in regions expected to experience water scarcity under future climate change. Last, we evaluated potential air-quality impacts associated with large-scale CO_2 removal. Wildfire-risk reduction as a result of forest-management practices, while difficult to tie to specific reductions in fine particulate matter concentrations in the atmosphere, is expected to yield substantial air quality co-benefits across large regions in the United States. Any increases in air-pollutant emissions resulting

CHAPTER SCOPE

In this chapter, we discuss the potential timing for scale-up of each CO_2-removal strategy and the implications of large-scale carbon removal for three natural resources: land, water, and air. Topics include:

- Timing deployment of CO_2-removal strategies
- Land suitability and land-use priorities for large-scale CO_2 removal
- Water demand for biomass with carbon removal and storage (BiCRS) and direct air capture with storage (DACS)
- Potential air quality co-benefits and emissions

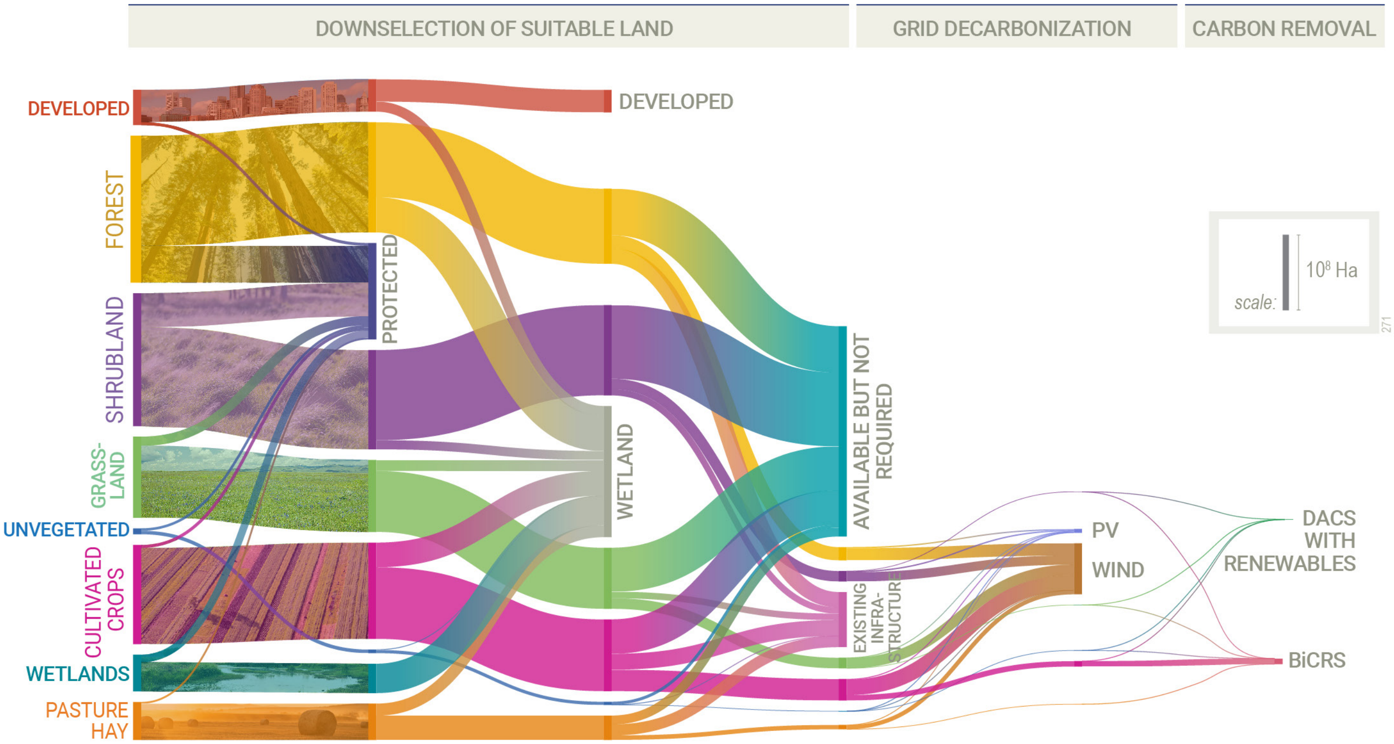

Figure 8-1. *Down-selection of land resources across the United States for large-scale carbon removal, accounting for grid decarbonization needs. The lefthand side summarizes all land cover types in the United States. We excluded wetlands, protected lands, developed land, forests, and land occupied by existing infrastructure from consideration. Major land requirements to reach at least 1 billion tonnes of CO_2 removal are shown on the far righthand side, including land for cultivation of carbon crops and land for adsorbent DACS co-located with renewable energy generation. Original land cover data is from the National Land Cover Database. For clarity, land originally classified as "herbaceous" is labeled here as grassland and land classified as "barren" is labeled unvegetated.*

from the carbon-removal technologies discussed in this report would likely be dependent on the use of solvent DACS, the choice of carbon-capture solvents in BiCRS facilities, and the portion of those solvents that are lost to thermal decomposition.

Key Findings

- CO_2 removal must not compete with or stand in the way of decarbonization efforts (e.g., increasing renewable energy supply and reducing fossil fuel demand). It is possible to allocate constrained resources, particularly land, such that sufficient resources remain available for decarbonization and food production, while also avoiding development in sensitive ecosystems and other protected lands.
- Based on the scenarios explored in this report, the land footprint of large-scale carbon removal will be driven by cultivation of carbon crops and, to a lesser extent, additional renewable energy to power DACS systems. In the zero-cropland-change scenario described in **Chapter 6 – BiCRS**, approximately 20 million hectares (ha) are needed for growing carbon crops, equating to roughly 0.9 billion tonnes of CO_2 removal per year. To achieve an additional 0.2 billion tonnes of CO_2 removal per year via adsorbent DACS paired with renewable energy, 0.8 million ha of land will be required for renewable power generation. The land footprint for additional solvent DACS using natural gas will be minimal. Two-thirds of the potential land area for DACS co-located with renewables is best suited for wind-based power generation, which only occupies 2% of its gross land area and can be located alongside agriculture or other land uses. One-third of the potential land for renewables with DACS is best suited for solar-photovoltaics-based energy generation. However, the total land area that is potentially suitable for DACS co-located with renewables and that also has on-site geologic storage is vast: 35 million ha across the United States. Only a small fraction of that land will be required.
- Each CO_2-removal approach differs in its timeline to implementation and in its durability of carbon storage. De-conflicting the four approaches and combining them allows us to evaluate their total carbon-removal potential and determine how quickly they can be scaled up. If all approaches were implemented together to achieve the lowest-cost path to 1 billion tonnes of CO_2 removal per year, the annual cost would be approximately $128 billion per year. Forest management and agricultural-soils man-

agement offer removal in the near-term, with the need for continued investment to maintain ecosystem CO_2 storage (“renting”). The build-out of BiCRS and DACS will be comparatively slower but has a larger overall potential by 2050 and greater durability of geologic CO_2 storage (“buying”).

- Water consumption per tonne of CO_2 removal is expected to be similar for BiCRS and adsorbent DACS, although DACS water-use varies depending on both the technology used and the temperature and humidity of the local climate. Building sufficient DACS and BiCRS capacity to enable total carbon removal of 1 billion tonnes of CO_2 per year would result in cumulative water consumption under 5 million m^3/day, most of which is required for cooling at BiCRS facilities. For perspective, this total is equivalent to approximately 1% of US water consumption for irrigation. A large fraction of adsorbent DACS potential exists in regions expected to experience water scarcity in 2050, whereas more than 70% of BiCRS-related water use is projected to occur in hydrologic regions that will experience water scarcity less than 1% of the time see **Figure 8-2**.
- Large-scale CO_2-removal efforts are likely to result in net improvements to air quality, particularly when accounting for wildfire-risk mitigation. Forest management will reduce wildfire-smoke emissions, which, in the United States, are responsible for up to 25% of total fine particulate matter concentrations in the air. Emissions can occur at solvent DACS and BiCRS facilities as a result of thermal decomposition of carbon-capture solvents, although the magnitude and composition of these emissions remain uncertain. Emissions of other combustion by-products at BiCRS facilities—such as nitrogen oxides (NO_x), sulfur oxides (SO_x), and fine particulate matter—will depend on which post-combustion flue gases are directed to carbon-capture systems and how effectively these systems can trap them.

Introduction

Large-scale CO_2 removal requires that multiple strategies be implemented strategically and often in tandem, ranging from soil management and forestry to construction of BiCRS and DACS facilities. Individual carbon-removal strategies discussed in this report may compete for resources, including land area, water, financing, and energy infrastructure. Further, implementation of these strategies would not occur in a vacuum; they would happen alongside broader decarbonization of the US economy. For example, wind and solar energy will need to be expanded to decarbonize the electrical grid. This means that we had to set aside substantial land area in our analysis to avoid double counting these resources for the possible construction of DACS co-located with renewable energy. In this chapter, we present the approaches employed in this report to (1) de-conflict forest-management, BiCRS, DACS, and soil-carbon strategies and (2) determine how rapidly each strategy can be scaled up across the United States. We also explore the potential pressures on, and competition for, natural resources that may result from large-scale carbon removal and the best practices for assessing individual technologies in the future.

Satisfying US energy and carbon-management needs will require expanding the land area used for decarbonization and carbon-removal practices. Some land-intensive applications can be co-located, such as agricultural production and wind energy, while others are mutually exclusive. For example, growing perennial carbon crops requires converting some cropland and grazing land, which can have far-reaching market and emissions implications [2]. While land requirements for carbon management are extensive compared to the comparatively modest land footprint of fossil-fuel extraction and conversion, many of those fossil-fuel

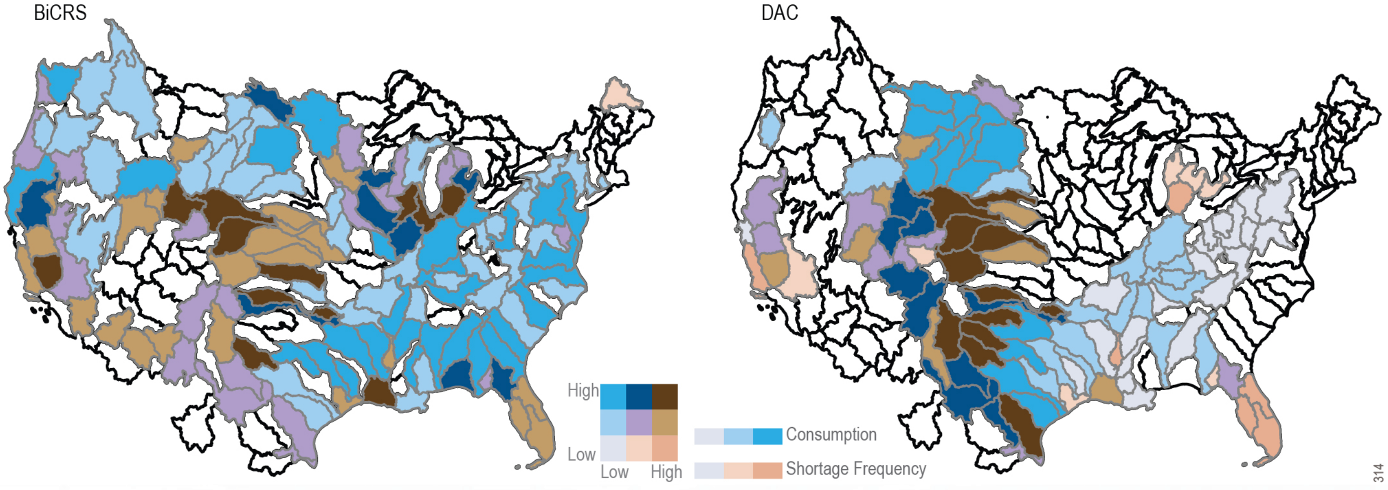

Figure 8-2. *Summary Map. Distribution of potential water use for BiCRS and DACS as compared to future water-scarcity risk mapped at the watershed level.*

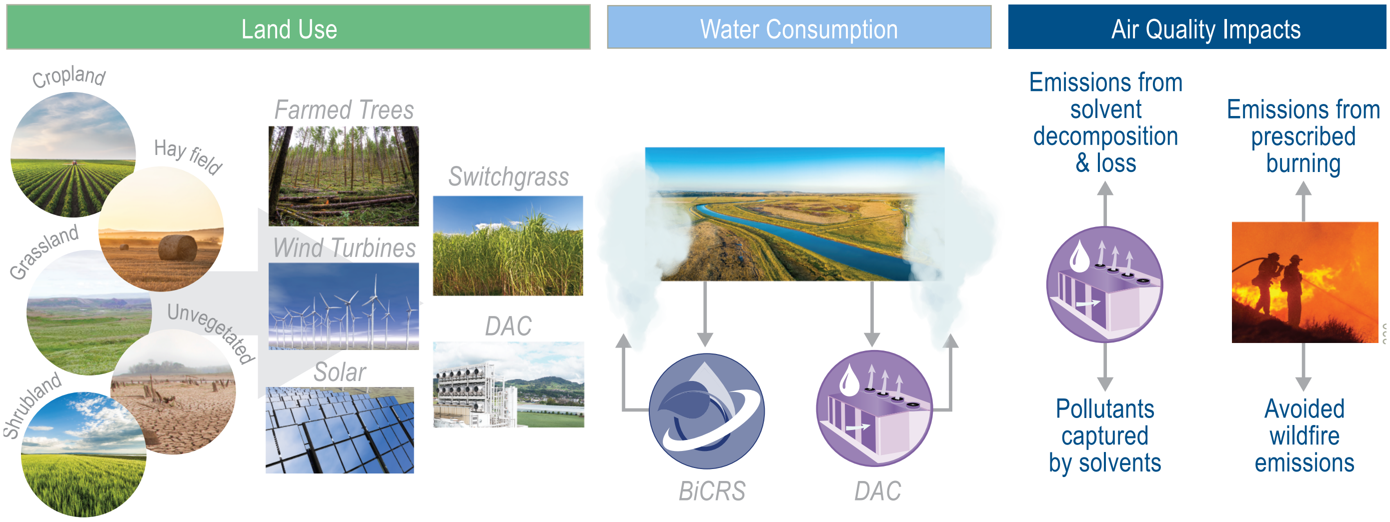

Figure 8-3. *Scope of Natural Resource Impact Assessment.*

activities result in lasting contamination that limits future development of that land for decades or longer and may result in substantial costs for remediation [3].

Below we discuss three major types of natural resource impacts from carbon-removal strategies. **Figure 8-3** summarizes the primary focus of our analysis.

Potential Impacts on Natural Resources

Land Cover

We consider two types of land use in this report. The first involves a change in management without changing the fundamental function or land-cover type. Cover cropping, perennial field borders, and the use of no-till farming, all discussed in **Chapter 3 – Soils**, constitute changes in land management. None of these strategies are expected to meaningfully impact agricultural output, aside from any effects on primary crop yields resulting from changes in soil texture and water-holding capacity. Changes in forest management also constitute a shift in land management and may result in visible changes to the landscape when forests are thinned, but the land-cover type itself and function as an ecosystem will not change. The second type of land use in this report requires a conversion from one cover type to another. In contrast with forest and agricultural land-management practices, BiCRS and DACS both require conversion of land; a small area is required for the physical facilities and supporting infrastructure, while a larger land area is required for cultivating biomass feedstocks and generating renewable energy.

The BiCRS strategies presented in this report rely, in part, on cultivating rainfed perennial carbon crops. Land conversion for DACS is driven by the need to co-locate facilities with additional renewable energy generation (wind or solar) that does not compete with resources needed for grid decarbonization, while also ensuring facilities have on-site access to geologic CO_2 storage. This chapter accounts for constraints on siting DACS and BiCRS facilities based on such factors such as local streamflow and the need to avoid building on ecologically sensitive or otherwise protected land. However, this chapter does not explicitly account for land area occupied by facilities themselves (BiCRS or DACS), nor does it include areas partially occupied by CO_2-injection wells, in part because of the uncertainty associated with these estimates and because the area they occupy will be small compared to the areas required for cropland and renewable-energy generation.

Freshwater

As is the case with land, the availability of adequate freshwater resources can impact facility siting decisions. Water resources can be impacted both in terms of their availability and quality. This chapter focuses on water availability because the carbon-removal strategies presented in this report are unlikely to have substantial negative impact on water quality (rather, some may offer water-quality co-benefits). Climate change is also likely to shift both the quantity and geospatial distribution of available freshwater resources by 2050 [4].

Consumptive freshwater use in the United States is dominated by irrigated agriculture, which used approximately 450 million m^3 of water per day in 2015; in contrast, thermoelectric power plants consumed only 11 million m^3 per day [5]. In this report, we only considered rainfed crops for soil-carbon management and BiCRS-feedstock production because relying on irrigation is likely to be both economically infeasible and problematic from a water-resource standpoint. We estimated biomass production accordingly. Therefore, we did not explicitly constrain agricultural production or changes in agricultural land-management based on ground or surface-water availability.

Similarly, changes in forest-management practices are unlikely to directly require appreciable quantities of water. However, changing land-management practices can impact evapotranspiration and thus the quantity of precipitation available for surface runoff or percolating into groundwater aquifers. Water lost through evapotranspiration is sometimes referred to as green-water use [6]; although worthy of further study, we did not include green water in the scope of this report. Instead, this chapter focuses on blue-water consumption, referring to water that is withdrawn from surface or groundwater sources and subsequently evaporated or otherwise removed from its original watershed (e.g., incorporated into a product).

BiCRS and DACS facilities are the two drivers of water consumption in this report. BiCRS facilities require varying quantities of process and cooling water, depending on the type of facility (e.g., bio-hydrogen, pyrolysis, fermentation), and are designed to recycle process water to the greatest extent possible. In this report, we explicitly constrained BiCRS-facility locations to areas deemed to have adequate streamflow. DACS facilities also require water, although the quantity consumed is highly variable depending on the local climate and choice of liquid solvent versus solid adsorbent. In this report, we did not constrain DACS facility locations based on local water availability; however, water availability may impact siting decisions in the future

Air Quality

Clean air, like clean water, is an important natural resource. The primary driver of air-pollution-related human-health damages is fine particles with a diameter less than 2.5 microns (PM2.5) [7, 8]. Air quality is often communicated publicly on the basis of PM2.5 concentrations (e.g., the commonly used air quality index (AQI) corresponds to the ambient PM2.5 concentration). Fine particles can be emitted directly to the atmosphere (referred to as primary PM2.5) from vehicle tailpipes, industrial or power-plant smokestacks, or natural sources, such as wildfires. Particles also form in the atmosphere because of chemical reactions, referred to as secondary PM2.5. Ammonia (NH_3), NO_x, SO_x, and volatile organic compounds (VOCs) all contribute to the formation of secondary PM2.5. Local meteorology and background pollutant concentrations dictate how a change in emissions will impact PM2.5 concentrations, while population density in the affected areas dictates the resulting total health damages that occur. This chapter assesses the likely drivers of air-quality impacts (positive or negative) for forest management, soils and agricultural management, BiCRS, and DACS.

Natural Resources-Impact Assessment

Land Use

All land-suitability analyses presented in this report used the 2019 National Land Cover Database (NLCD) [1], which categorizes each 30-meter x 30-meter pixel as one of 16 classes, including open water, perennial ice/snow, developed (split into 4 subclasses), barren (unvegetated), forest (3 subclasses), shrub/scrub, grassland/herbaceous, pasture/hay, cultivated crops, and wetlands (2 subclasses). **Figure 8-4** shows the land-cover classes along with areas that have confirmed accessible geologic CO_2 storage. We also supplemented the land-cover data with additional sources to identify various classes of protected lands (**Appendix 8**). In our analysis, we applied several overarching constraints on land use. Specifically, we excluded wetlands—including a 300-meter buffer area—and protected lands from development for any wind power, solar photovoltaics, BiCRS facilities, or DACS facilities, for the purposes of this report. We also excluded wetlands from cultivation of carbon crops, as discussed further in **Chapter 6 – BiCRS**.

Our exclusion of protected land and wetlands (including buffers around them) had the greatest impact on land in and around forests. This is because approximately one third of forestland in the United States is actually forested wetlands **(Box 8-1**). In total, approximately half of forestlands in the United States are either protected and/or designated as wetland **(Figure 8-5)**. Conservatively, we also excluded land that is already designated as developed from further development for DACS, BiCRS, and renewable energy. However, some co-location of renewables projects with

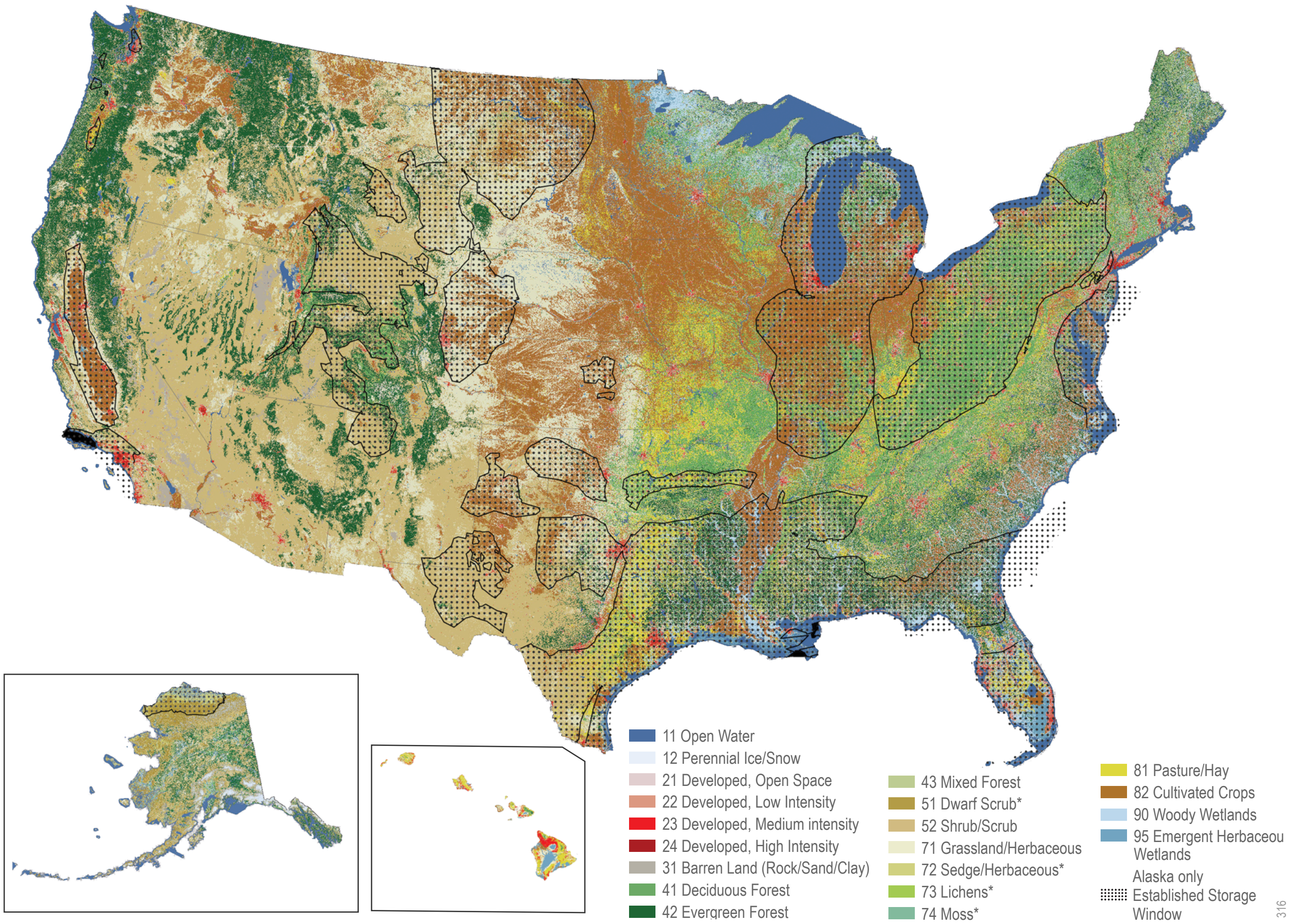

Figure 8-4. *Land-cover types across the United States (data from the National Land Cover Database (NLCD) [1]) and the geologic CO_2-storage window used in this report.*

BOX 8-1

Importance of Preserving Wetlands

Wetlands are ecologically important to preservation and many serve as important carbon sinks [10]. This report excludes wetlands from any possible future development using the National Land Cover Database classifications. This particularly impacts carbon removal potential in the Southeastern United States, where geologic CO_2 storage potential and high simulated carbon crop yields would otherwise make this a high-potential region for BiCRS. Recent evidence suggests that wetlands play an important role in decreasing the nitrogen loading from nitrate-affected watersheds and that targeted wetland restoration projects could decrease the export of excess nutrients to coastal waters [11]. Additionally, the United States Federal Government has worked to discourage draining wetlands for agricultural production. The "Swampbuster Program" in the 1985 Farm Bill made eligibility for certain United States Department of Agriculture (USDA) benefits contingent on compliance with provisions aimed at conserving wetlands; namely, farmers could be excluded from some USDA benefits if their land was found to be former wetland converted after 1985 [12]. There are four major types of wetlands in the United States: marshes, swamps, bogs, and fens. Forested swamps are common in the Southeastern United States, and include mangroves, cypress/tupelo swamps, bottomland, hardwoods, pocosins and Carolina bays, flatwoods, and mountain fens [13]. The carbon stored in the soils of wetlands can vary considerably; many coastal wetlands have comparatively low organic matter and high sand content whereas wetlands in the Midwestern United States have soils with higher organic matter and carbon contents [14]

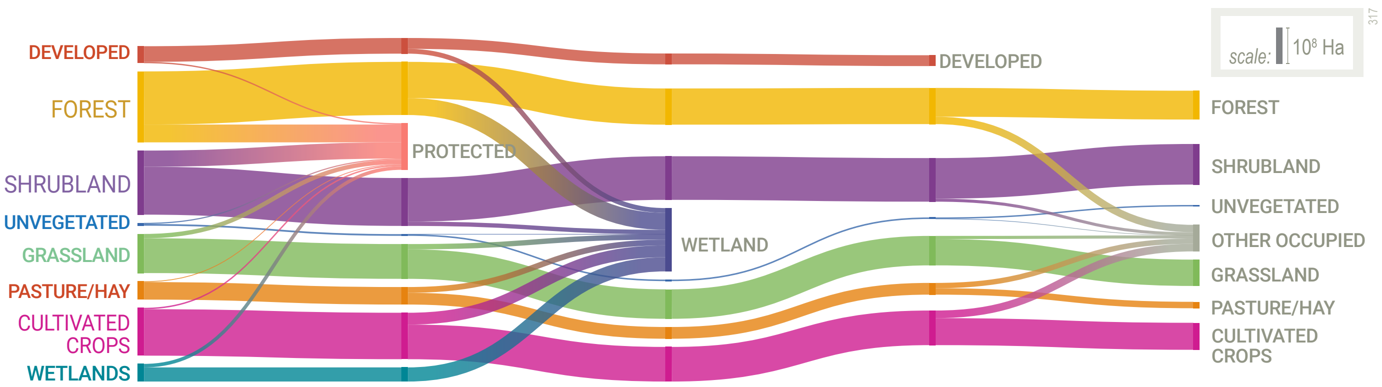

Figure 8-5. *Initial land-use constraints applied to renewable-energy development, DACS, and BiCRS for the contiguous United States*

developed land may be acceptable; wind turbines are built increasingly close to residences [9] and solar photovoltaic projects can be built near or on top of buildings and parking lots (although this can increase costs).

Land-Use Considerations for Siting Renewable Energy with DACS Facilities

The total potential for DACS, as well as its siting constraints, depend on its required energy source(s). Although **Chapter 7 – DACS** includes near-term potential for high-temperature solvent DACS using natural gas, in this chapter we focus on the long-term prospects of DACS integrated with renewable energy. Developing DACS co-located with wind energy is relatively flexible in terms of siting constraints. Specifically, any topographic slope less than 20% is suitable, and we required that individual sites have access to at least 500 ha of contiguous space for development. However, we did set aside all land required for developing renewable energy in pursuit of grid decarbonization and deemed this land unavailable for developing DACS co-located with renewables. Our decarbonized grid scenario is based on the outputs of the National Renewable Energy Laboratory's (NREL's) 100% Clean Electricity by 2035 report [15], as discussed in greater detail in **Chapter 7 – DACS** and **Appendix 8**. Based on NREL's grid decarbonization scenario results and our conservative buffer areas around those areas, half of all suitable cultivated land, half of suitable forested land, and more than a quarter of herbaceous (grass) lands are designated as prioritized for grid decarbonization (**Figure 8-6)**. These results underscore the importance of setting aside the resources necessary to achieve decarbonizaton as a prerequisite to building large-scale carbon removal. The extent to which wind development is allowed to occur on forested land, enabled by high hub heights and large rotor diameters, also has implications for the future of forest ecosystems and management. For example, the construction of access roads needed to reach turbines may have negative ecosystem impacts, but these roads could also provide the additional access required to collect and remove forest thinnings, thus providing an alternative to greater prescribed burning .

Figures 8-6 and **8-7** indicate the magnitude of potential land suitable for co-location of DACS with wind turbines and solar photovoltaics, respectively, across the United States. Both figures also indicate what fraction of this land is located in census tracts designated as disadvantaged, partially disadvantaged, and not disadvantaged communities in the Climate and Economic Justice Screening Tool [16]. Based on the classifications in the screening tool, approximately 30% of the US population resides in a census tract categorized as disadvantaged [16]. Additional wind-energy potential (to be co-located with DACS) is distributed roughly evenly between disadvantaged and non-disadvantaged communities on the basis of land area. New development of DACS co-located with renewable energy can bring substantial economic benefits but may also raise concerns that must be addressed about impacts on local residents. Monitoring noise impacts—particularly for wind turbines co-located with DACS facilities—will be important; numerous studies have examined wind turbine noise [17], although very little work has been done on the potential noise impacts of DACS facilities.

In contrast to wind energy, the development of solar photovoltaics is primarily limited by topographic slope, which is capped at 5%. Most of the remaining suitable land for co-locating solar photovoltaics and DACS is classified as shrubland and herbaceous (grass) land, and nearly two-thirds

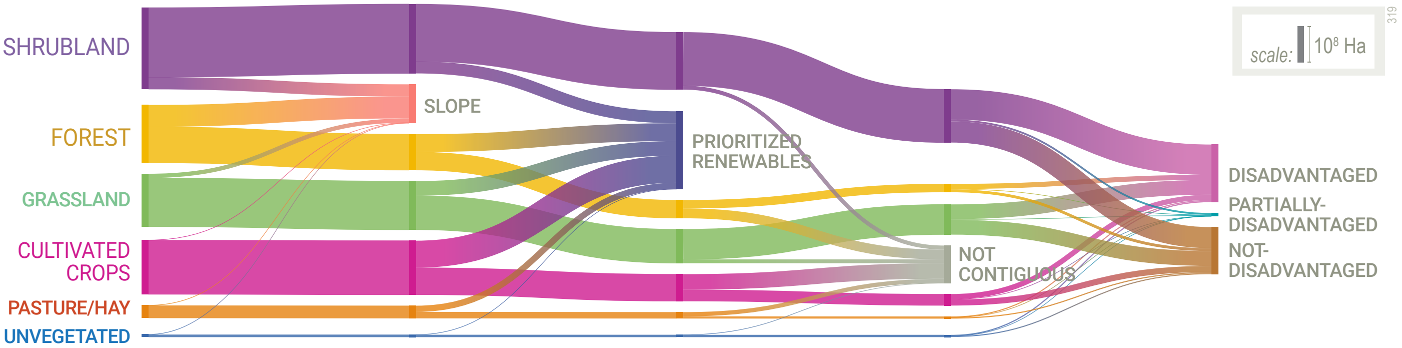

Figure 8-6. *The down-selection of land identified as suitable for wind energy to support DACS in the contiguous United States. Suitable land not required for grid decarbonization is categorized based on the area that falls in disadvantaged and non-disadvantaged communities according to data in the Climate and Economic Justice Screening Tool.*

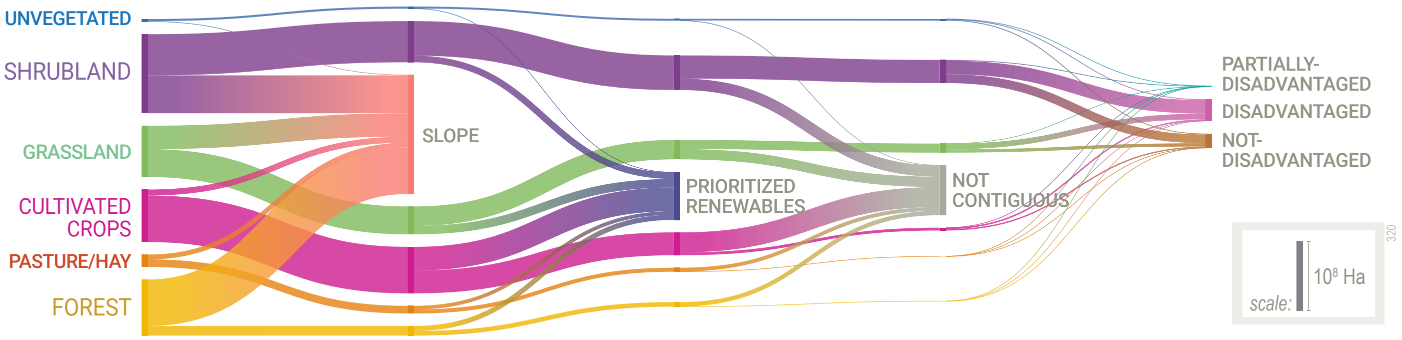

Figure 8-7. *The down-selection process to identify land suitable for solar-photovoltaic energy development to support DACS in the contiguous United States. Suitable land not set aside for grid decarbonization is categorized based on the area that falls in disadvantaged and non-disadvantaged communities according to data in the Climate and Economic Justice Screening Tool.*

of this land area is located in disadvantaged communities. In the cases of both solar photovoltaics and wind turbines co-located with DACS, a key consideration in siting—and for local communities weighing in on development decisions—will be how CO_2 is captured, stored, transported, and injected.

Land-Use Considerations for Siting DACS Near Geologic Storage or Pipeline

One of the most important factors in siting new DACS facilities is whether CO_2 can be injected directly into geologic storage or a pipeline for low-cost transportation to an injection site. This report constrains DACS development to sites with potential future CO_2 pipeline access (**Chapter 5 – Transportation**) or on-site geologic-storage access to avoid unnecessary CO_2 transportation costs. This strategy takes advantage of the relative flexibility that DACS offers compared to BiCRS, which must be located based on both biomass feedstock access and geologic CO_2 storage (or pipeline) access (**Chapters 5 – Transportation and 6 – BiCRS**). The land otherwise suitable for co-locating DACS with renewable energy is divided as follows regarding the availability of geologic storage or pipeline access:

- Approximately one third has no geologic storage or pipeline access (**Figure 8-8)**.
- Approximately one-third is located in areas deemed part of the "prospective storage window," which refers to areas that require more exploration but could offer geologic CO_2 storage at unknown costs (**Chapter 4 – Geologic Storage**).
- Less than one-third offers access to known geologic storage.

Note that, although Figure 8-8 shows both existing and proposed pipelines as offering minimal additional DACS potential, this topic is worthy of additional research. In particular, we only include trunk CO_2 pipelines in this study; the construction of gathering pipelines could substantially increase pipelines' impact on total DACS potential.

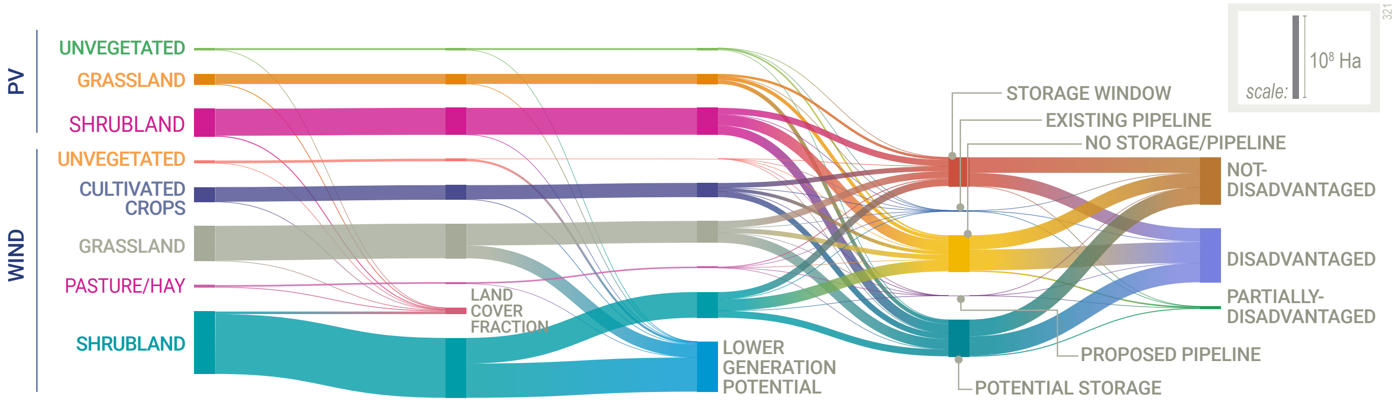

Figure 8-8. *Land suitable for co-located DACS and renewables based on proximity to geologic CO_2 storage and pipelines for the contiguous United States*

Land-Use Considerations for Growing BiCRS Feedstocks

While the land footprint of DACS is dominated by co-located renewable energy generation, the footprint of BiCRS is entirely dependent on what purpose-grown feedstocks are cultivated and where. Growing biomass crops on valuable agricultural land may result in higher yields and a lower overall land footprint, but the opportunity cost associated with displacing other agricultural production on highly productive cropland is greater relative to lower-productivity marginal lands. Conversely, growing carbon crops on marginal lands can, at least in part, mitigate the impacts on agricultural production and food prices (**Chapter 6 – BiCRS**). **Figure 8-9** shows the fraction of total land area on which switchgrass would be planted for both BiCRS scenarios. **Figure 8-10** shows the land area planted for each type of BiCRS feedstock crop by county in the maximum-economic-potential scenario. Switchgrass represents the largest contributor to the overall land footprint and, in this scenario, it is planted on both cultivated croplands and pasture/hay lands, with net soil-carbon benefits primarily accruing on converted croplands (**Chapter 3 – Soils**).

Because switchgrass makes up the majority of land use and dedicated biomass production for BiCRS, we analyzed its impact on county-level land use across two scenarios from **Chapter 6 – BiCRS:** the zero-cropland-change scenario (using a \$60/tonne CO_2 price) and the maximum-economic-potential scenario. The zero-cropland-change scenario is highly restrictive in the amount of cultivated cropland that can be converted, prioritizing abandoned and marginal cropland instead, whereas the maximum-economic-potential scenario does not explicitly constrain the conversion of currently cultivated land. Figure 8-9 shows the fraction of total land area on which switchgrass would be planted for both BiCRS scenarios. Despite lower productivity under rainfed conditions, both scenarios indicate that as much as one third or more

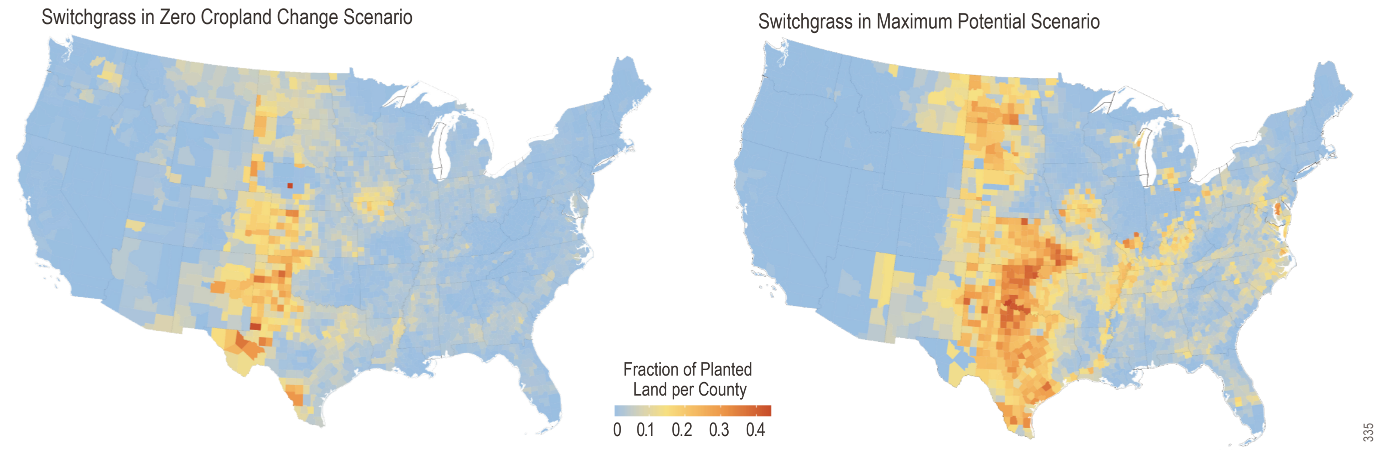

Figure 8-9. *Fraction of total land area by county planted with Switchgrass in two BiCRS scenarios. Hawai'i and Alaska not shown because there is no cultivation in those states.*

of land in counties across Texas, Oklahoma, Kansas, and the Dakotas may be economically viable for growing switchgrass. The implications of such a shift are worthy of further study, particularly in the context of climate change and intensification of livestock grazing.

Implications for Regional Land Cover

This chapter has so far covered the constraints placed on developing BiCRS, DACS, and renewable energy. However, the primary consideration centers on how US land use and land management will be transformed as we approach our goals for decarbonization and net carbon removal. To capture this issue, here we present land-cover changes for each of the 20 regions—defined for the purposes of this report—in the contiguous United States. We discuss the two remaining regions, Alaska and Hawai'i, separately. **Figure 8-11** shows these regions and the current total land area and land-cover types by region. **Chapter 10 – Regional Opportunities** provides more complete descriptions of individual regions.

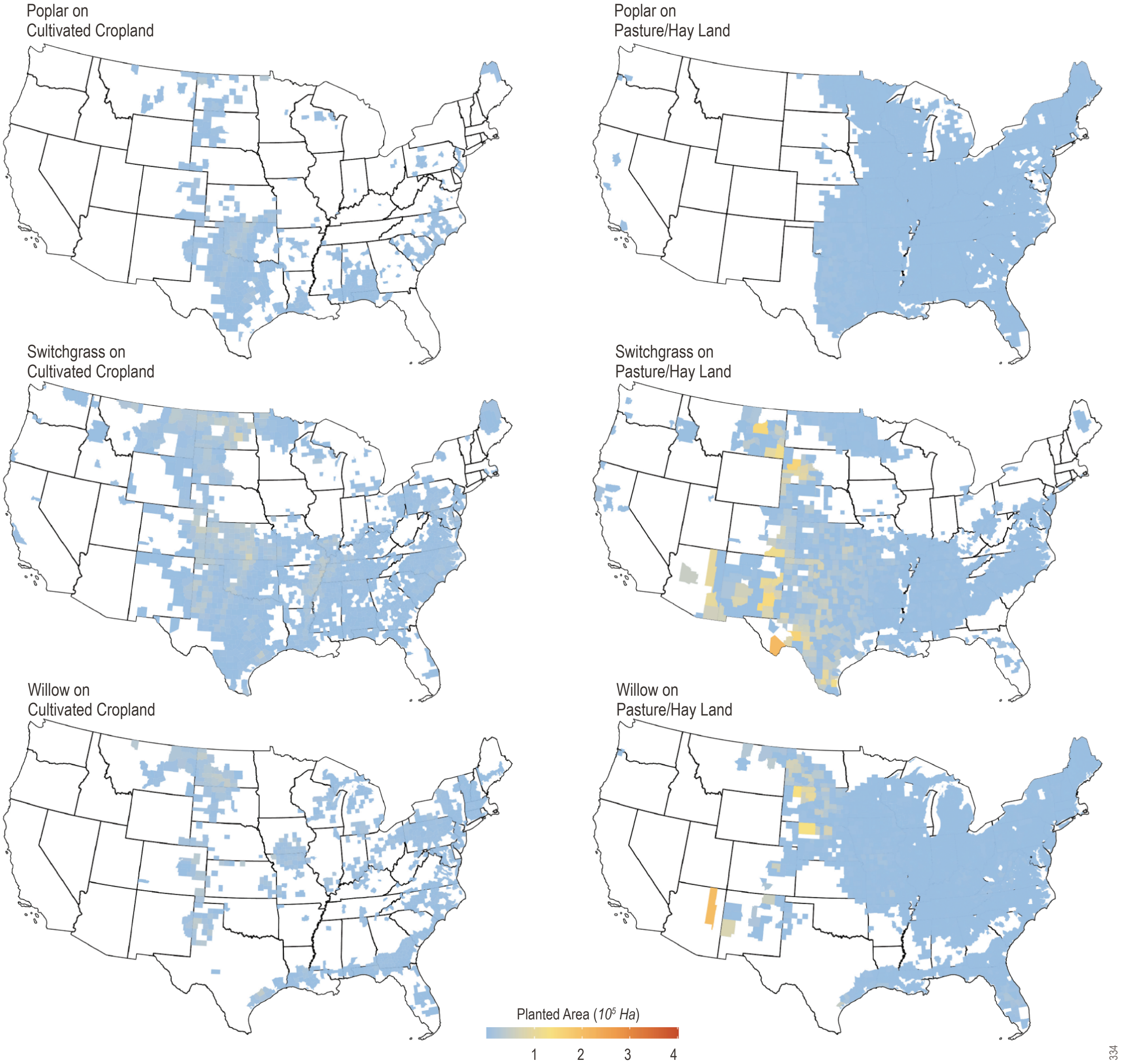

Figure 8-10. *Planted area by county for BiCRS feedstock crops in the Maximum Potential scenario. Hawai'i and Alaska not shown because there is no cultivation in those states.*

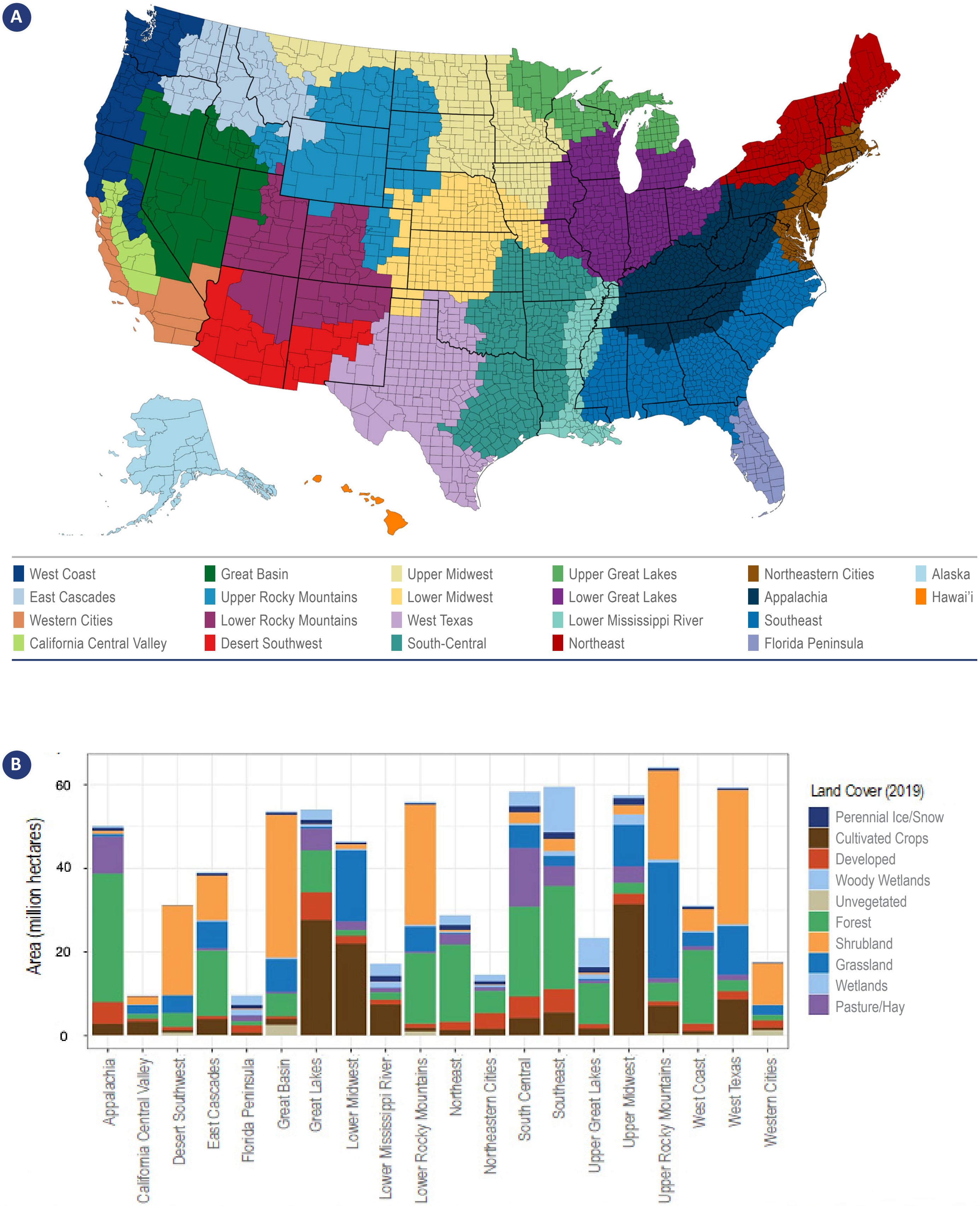

Figure 8-11. *Region map (A) and regional land cover by class (B)*

To understand how current land cover (Figure 8-11) might change in the future, we assembled data on forest-management strategies (**Chapter 2 – Forests**), land conversion to dedicated biomass crops (**Chapter 6 – BiCRS**), maximum potential land area for solid adsorbent DACS co-located with renewable energy (wind and solar) (**Chapter 7 – DACS**), and the land area required for grid decarbonization (NREL data [15]). **Figure 8-13** shows our findings, indicating how future land-cover in areas with high potential for carbon-removal strategies (discussed in this report) and grid decarbonization (based on the NREL's clean grid scenario) with an added buffer around those renewables compares with current land cover across the contiguous United States (Alaska and Hawai'i are discussed separately in **Box 8-2**.) Land for DACS co-located with renewable energy reflects all suitable land, only a small fraction of which is needed to contribute to an overall annual removal rate of 1 billion tonnes of CO_2.

Figure 8-13 conveys the fraction of lands that could visibly change, either through incorporation of wind turbines on cropland or through forest-thinning practices, if large-scale CO_2-removal strategies are implemented under the maximum-economic-potential BiCRS scenario. **Figure 8-14** shows fractions of land-cover change under the BiCRS zero-cropland-change scenario. We do not visualize the land that would be impacted by changes to agricultural practices, as those changes (e.g., shifting to no-till practices) will be less visibly transformative than those associated with changes in forest management.

Our scenarios suggest that the largest changes in land-management practices could occur across forests in the East Cascades, Lower Rocky Mountains, and West Coast regions. However, Figure 8-13 reflects the cumulative land managed over several decades. Each year, different portions of these forests would be undergoing active management, so the forested land area being actively managed in any given year would be a smaller fraction of that total. The fraction of land being actively managed in any given year would depend on the resources devoted to forest management and the resulting timeline for implementing widespread forest-thinning operations.

Changes in land cover as part of a large-scale CO_2-removal strategy are likely to be driven by renewable-energy generation. There is high potential for co-locating DACS and wind energy in California Central Valley, the Upper Rocky Mountains, and West Texas. Co-located solar photovoltaics and DACS have high potential mostly in the Upper Rocky Mountains and West Texas. The largest impacts of land-use

BOX 8-2

Resources in Hawai'i and Alaska

So far, the results presented only include the contiguous United States. Hawai'i and Alaska are both treated as separate, distinct regions and are subject to their own unique opportunities and constraints. Because Hawai'i does not offer proven geologic CO_2 storage opportunities (this report does not incorporate basalt storage), no BiCRS or DACS facilities would be located there in the scenarios produced for this report. Alaska, however, does offer some DACS potential because of the geologic storage capacity on the North Slope, where wind turbines and DACS facilities can be co-located. As shown in Figure 8-12, much of the land area in Alaska is protected, and substantial portions of the remaining land are unavailable for developing renewable energy.

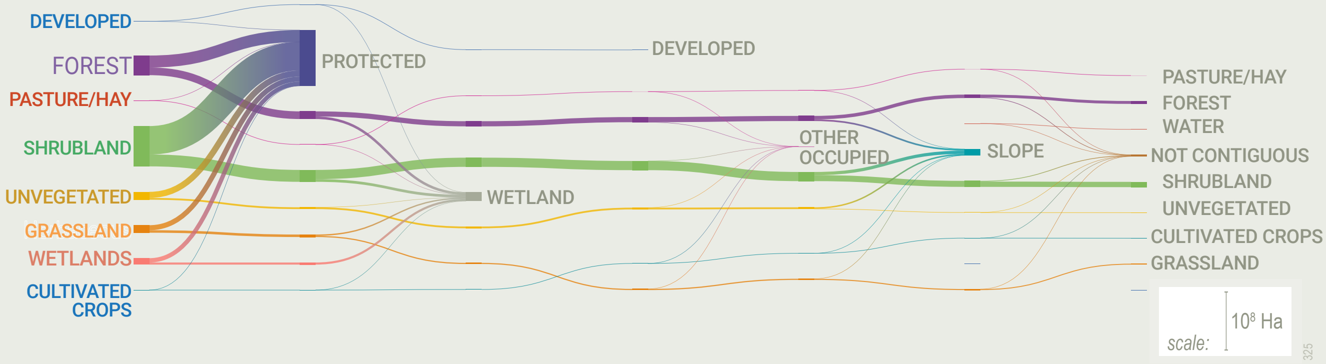

__Figure 8-12.__ The down-selection process for land suitability for DACS facilities and co-located renewable energy in Alaska. Most land is protected and is thus considered unavailable for development for the purposes of this report. The lefthand side reflects land cover types and the righthand side reflects land that could be available for development of DACS and renewables

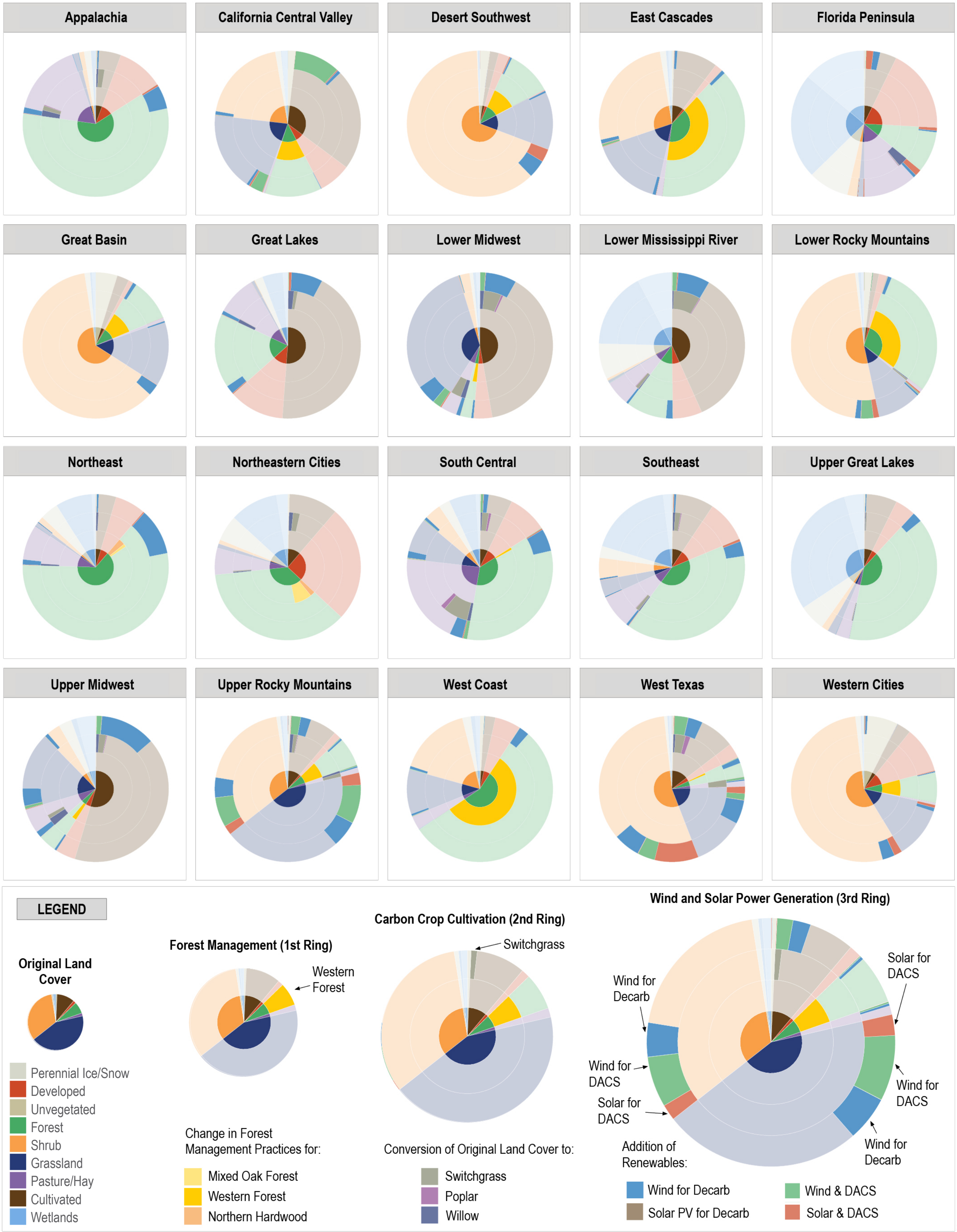

Figure 8-13. *De-Conflicted Regional Changes in Land Use and Management for Carbon Removal and Grid Decarbonization Using the BiCRS Maximum Potential Scenario. Renewables for DACS reflects the total maximum potential of 8.5 billion tonnes CO_2 removal annually. Opaque sections indicate a land use change. Semi-transparent sections indicate land use remains unchanged. Developed land and wetlands are excluded from crop production or utility scale renewables.*

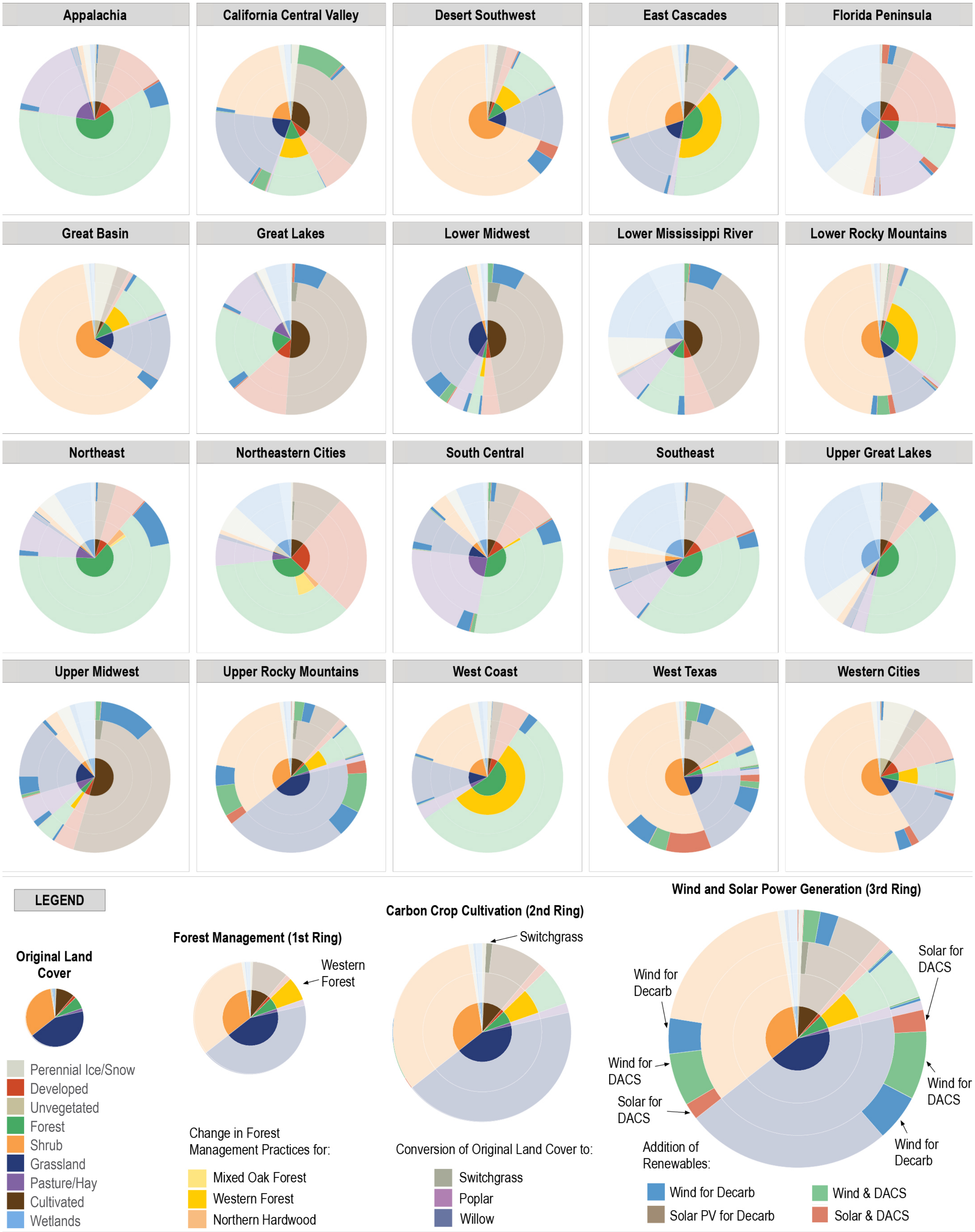

Figure 8-14. *De-Conflicted Regional Changes in Land Use and Management for Carbon Removal and Grid Decarbonization Using the BiCRS Zero Cropland Change Scenario. Renewables for DACS reflects the total maximum potential of 8.5 billion tonnes CO_2 removal annually. Opaque sections indicate a land use change. Semi-transparent sections indicate land use remains unchanged.*

change as a fraction of total land cover occur in West Texas, where as much as 15% of total land area is suitable for co-locating DACS and renewable energy; the Upper Rocky Mountains region also has substantial potential. However, only around 2% of all suitable land across the United States is needed to reach a national total of 200 million tonnes of CO_2 captured annually with solid sorbent DACS, so the actual fraction of land developed in these regions is likely to be much smaller than the maximum potential. Note that DACS co-located with renewable-energy development is consolidated in specific regions due to the constraint that these facilities have to be located with on-site access to geologic CO_2 storage or pipeline. In contrast, renewable-energy generation for decarbonizing the grid is not subject to this constraint and would be spread across a larger number of regions. For example, much more of the wind energy required for grid decarbonization is expected to be built in regions without confirmed geologic storage access , including the agricultural regions in the Midwest where wind turbines can be built on cultivated cropland.

The total suitable land for dedicated cultivation of carbon crops is smaller than the total suitable land for DACS co-located with renewable energy. However, because BiCRS remains the lower-cost option relative to DACS, a larger fraction of the total BiCRS potential may be built to reach an overall annual removal rate of 1 billion tonnes of CO_2 in 2050, resulting in a larger land footprint for carbon crops. Switchgrass, which serves as a useful proxy for perennial grasses, is the most commonly selected carbon crop. It can be grown primarily on pasture/hay land in the South-Central region and on cropland in the Lower Midwest. These results reflect the maximum-economic-potential scenario outlined in **Chapter 6**, which does not constrain the types of land brought into production and, rather, simulates farmers' economic decisions using selling prices for biomass feedstocks.

Timeline for Deploying CO_2 Removal

The four approaches to CO_2 removal presented in this report have different timelines to implementation and different storage durabilities. These timelines are explicitly modeled for these approaches to calculate the annual rate of CO_2 removal and the cumulative CO_2 removed as a function of time (**Figure 8-15**).

For forest management and soil-carbon-based approaches, treatments and practices can begin immediately, resulting in large rates of CO_2 removal in the near-term. These approaches can have multiple co-benefits for productivity, biodiversity, water conservation, environmental quality,

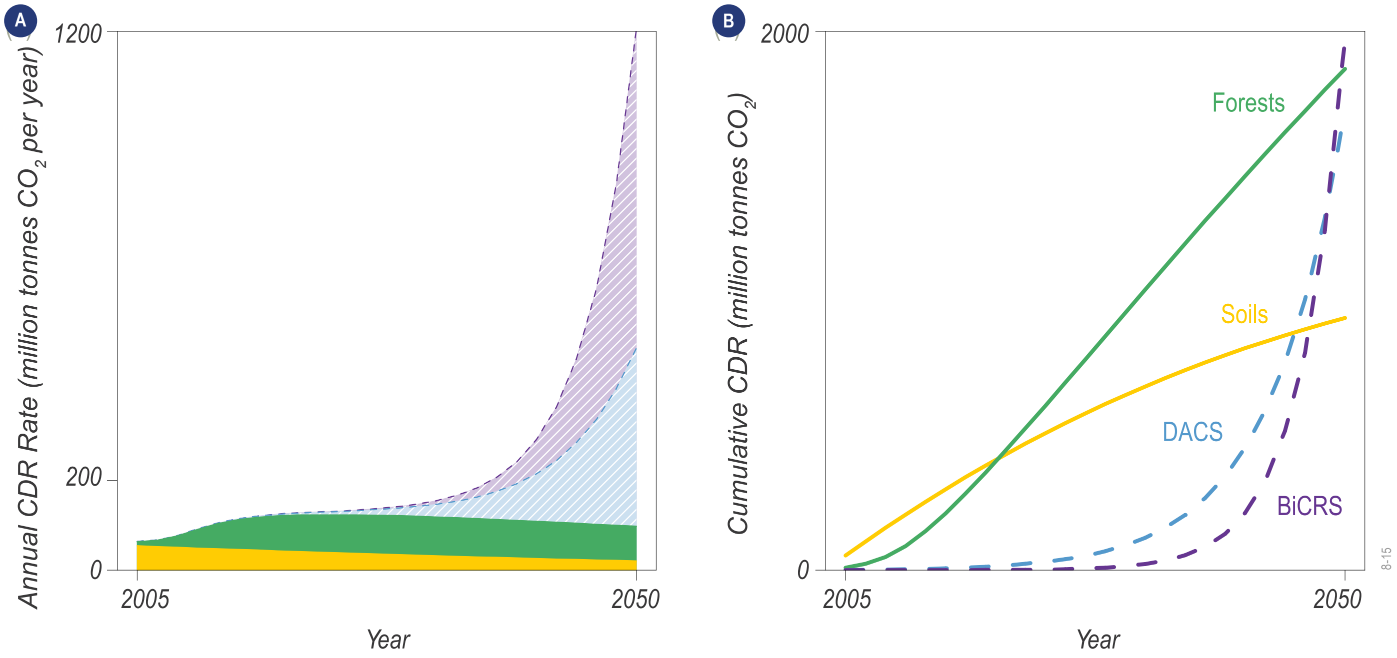

Figure 8-15. *(a) Projected annual CO_2-removal rate between 2025 and 2050 for CO_2-removal pathways considered in this report. Shaded areas show the relative amount of cumulative CO_2 removed, whereas vertical height indicates the relative annual rates of CO_2-removal in a given year. (b) Cumulative CO_2 removed from 2025 to 2050 based on the rates depicted in subpanel (a). Cumulative amounts for reforestation and soil are drawn from Chapters 2 – Forests and 3 – Soils. Hashed areas and dashed lines indicate that we did not rigorously model BiCRS and DACS rates of deployment and that the qualitative shape should be taken as notional. Rates for BiCRS and DACS assume exponential growth to reach the rates shown in Figure 8-16 as of 2050, with DACS starting at a higher baseline (541,000 tonnes deployed in 2025) than BiCRS (10,000 tonnes deployed in 2025) (Chapters 6 – BiCRS and 7 – DACS), but with BiCRS reaching a larger deployed value in 2050.*

and resilience to climate change. Critically, they may be rapidly deployed, and do not require energy resources that would otherwise go toward decarbonizing the rest of the US economy. CO_2 stored in soils and forests is also vulnerable to reversal via management disruption, wildfire, or other disturbances, requiring continued investment to maintain stored CO_2 over time, much like "renting" storage. Soils-based approaches start with the highest annual CO_2 removal rate; this rate slowly decreases with time as soil organic carbon (SOC) stocks increase and cropland ecosystems equilibrate to the practice. The trajectory for forest-based approaches depends on the type of forest management. Planting new trees can immediately increase the carbon sequestration capacity of an area as those new forests grow. Forest management that involves tree removal—which for some forests is necessary for creating healthier, more disturbance-resilient forests—will cause initial decline in forest-carbon stocks that will then recover as the forest regrows. Forest stands with younger trees remove CO_2 from the atmosphere at relatively higher rates than ecologically similar forest stands with older trees; however, older forests store more total carbon than younger forests.

CO_2 removal via BiCRS and DACS is coupled with geologic storage, which is a highly durable, long-term storage reservoir and is the most secure final storage location for CO_2. This highly durable geologic CO_2 storage can be considered effective after a single investment, essentially "buying" CO_2 storage. BiCRS and DACS are expected to grow more slowly than forest management and soil-based storage due to the need for permitting geologic storage and securing large capital investments. Here, we modeled deployed BiCRS and DACS capacity with an exponential growth curve, with BiCRS reaching approximately 700 million tonnes per year and DACS reaching 400 million tonnes per year in 2050. We note that this exponential growth model is notional and the actual shape of the curve will depend on societal, market, and other factors that we do not explicitly consider in this report. The growth model we selected has a large impact on the cumulative CO_2 removed by DACS and BiCRS and represents a somewhat conservative outlook, with relatively little CO_2 removal by these approaches through much of the 2020s and 2030s, and 90% of the facilities being constructed in the 2040s. Other models with more rapid growth in the near-term would result in larger cumulative quantities of CO_2 removed.

We constructed a representative overall supply curve for CO_2-removal pathways in 2050; **Figure 8-16** indicates the annual quantity of CO_2 removed and the average cost for each pathway, in order of lowest to highest cost. These results suggest that, to achieve a rate of CO_2 removal on the horizontal axis, society would have to bear an annual cost equal to the area of the bars to the left of that cost. For example, if all pathways were implemented to achieve the 1 billion tonnes shown in the figure, the annual cost would be approximately $128 billion per year. It is possible that we will need more or less CO_2 removal to meet net-zero goals; the total cost to society would decrease or increase accordingly. The combination of contrasting costs and durabilities of ecosystem CO_2 storage with technologies supporting geologic CO_2 storage suggests that continued investment or "renting" of ecosystem CO_2 storage in the near term is key to getting quickly to 2050 climate targets, and that "buying" highly durable geologic storage will be the end-goal for a long-term and continuous climate-change-mitigation strategy.

Water Demand and Constraints

Particularly in the context of climate change, carbon removal must not place undue pressures on local water resources. If engineered solutions, including DACS and BiCRS, must scale up rapidly, establishing best practices for responsible facility siting in light of local resource availability will be critical. Broader decarbonization of the economy is likely to alleviate some burdens on water resources as fossil-fuel-fired power plants that require cooling water are decommissioned. However, as noted in the introduction, irrigation is by far the largest contributor to total water consumption in the United States and any changes in precipitation and diets could increase or decrease irrigation needs. This report models all carbon crops based on an assumption that they must be exclusively rainfed, so cultivation of switchgrass and other feedstocks should not directly impact irrigation-water demand. Thus, we focus on the water impacts of BiCRS and DACS facilities, both of which consume water for thermal management and, in the case of biomass-to-hydrogen routes, as a source of hydrogen in the water-gas shift reaction.

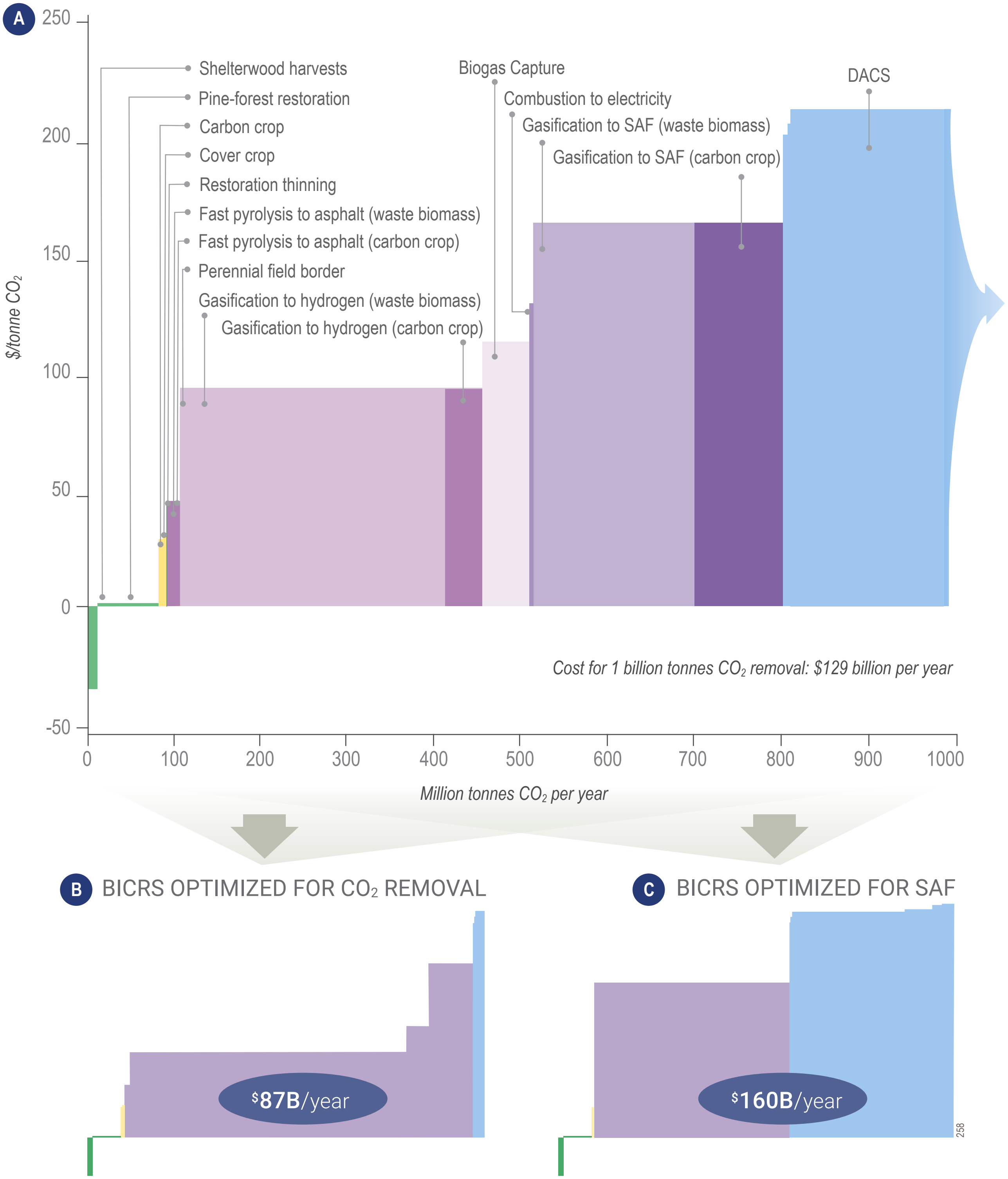

Figure 8-16. *Representative 2050 supply curve for US carbon removal at a rate of 1 billion tonnes per year, calculated from a high-resolution, county-level analysis. Amounts are constrained by resource availability, land use, and energy supply and ordered by estimated cost. Waste and crop biomass could be used for many important national priorities—here, a subset of the national biomass supply is allocated to produce sustainable aviation fuel (SAF) (17 billion gallons per year), and the remainder is modeled to minimize carbon-removal cost. The potential DACS capacity is larger than is shown here, with a technical potential >14 billion tonnes of CO$_2$ per year at less than $250/tonne. All costs include capital, operation, transportation, and all life-cycle costs and carbon impacts*

BiCRS Facilities

All BiCRS scenarios in this report are subject to streamflow constraints. Suitable sites as defined in the Biocarbon Infrastructure, Logistics, and Transportation (BILT) model (**Chapter 6 – BiCRS**) must be within 32 km of a water source with streamflow exceeding 473 m^3/min. This constraint is relatively conservative, and the input data likely exclude sites for not having a large river even though they may have access to several smaller or unconventional water sources whose combined flow exceeds the minimum threshold. **Figure 8-18** shows areas that are excluded from development of BiCRS facilities and how these areas align with confirmed geologic storage, existing and potential future CO_2 pipelines, and potential BiCRS facilities modeled in **Chapter 6 – BiCRS** (maximum-economic-potential scenario).

Although the streamflow constraints shown in Figure 8-18 are based only on historical streamflow data, they align well with the projected frequency of water scarcity. Specifically, Brown et al. [4] estimated the fraction of time that each US hydrologic subregion (also known as four-digit hydrologic units) is expected to spend in a state of water scarcity based on 14 different climate scenarios (**Appendix 8)**. Note that, in the results shown in the appendix, “mining” groundwater from aquifers is not considered a viable source of water if they are not recharged at the same rate as water is drawn from them.

As illustrated in **Figure 8-17**, the streamflow constraints excluded a substantial portion of otherwise suitable land from BiCRS-facility development. Topographic slope, which we limit to less than 12%, is another important constraint, excluding more than half of otherwise suitable forested land. Based on the BiCRS facility locations shown in Figure 8-18, we were able to assign water-consumption factors and estimate the fraction of water use that would occur in each hydrologic subregion (**Appendix 8**). For example, we estimated biomass gasification for hydrogen production to consume 0.023 m^3 of water per kg of H_2 produced, which aligns well with previously published values for water use in biomass gasification facilities [18] and, incidentally, is on the same order of magnitude as many water-use estimates for centralized electrolysis [19]. In general, the BiCRS technologies that emerged as the most cost-effective options per unit of CO_2 removed leveraged thermochemical routes, including gasification and pyrolysis, which tend to be less water-intensive than processes that rely on fermentation.

The resulting total water consumption for all BiCRS facilities is 3.2–4.2 million m^3 per day, corresponding to around 0.71–0.88 billion tonnes of net CO_2 removal per year, using the zero-cropland-change scenario for feedstock availability and the two BiCRS supply curves produced in **Chapter 6 – BiCRS**. This range makes up less than 1% of the total US irrigation needs in 2015 (450 million m^3 per day) and less than half of the total water consumption for thermoelectric power generation in that year (11 million m^3 per day). Unlike irrigation demand, which geographically correlates with low-precipitation regions, most BiCRS water demand would occur in regions that are not projected to experience frequent water stress. Specifically, 91% of BiCRS water demand would occur in regions projected to experience water scarcity <20% of the time, 85% is in regions with <10% water scarcity, 77% falls in regions that spend <5% in water scarcity, and 71% occurs in regions that experience water scarcity <1% of the time (**Figure 8-19**). As shown in Figure 8-19, the areas of greatest concern are the California Central Valley and parts of the midwestern US that are currently reliant on groundwater, particularly Nebraska. The predicted water-shortage frequencies we use do not account for any unsustainable use of groundwater resources, which impacts the agricultural regions that are currently reliant on the Ogallala Aquifer.

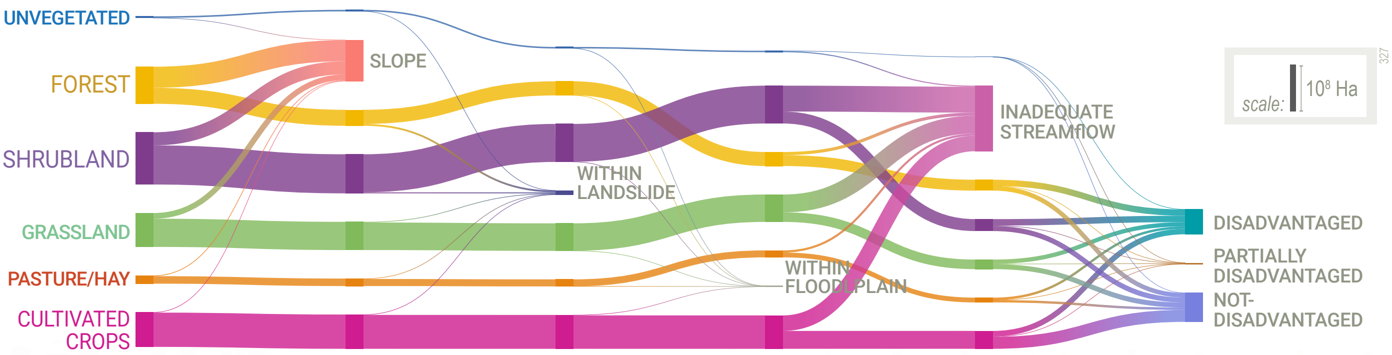

Figure 8-17. *Suitability of Land for BiCRS Facility Siting and the Impact of Local Water Availability.*

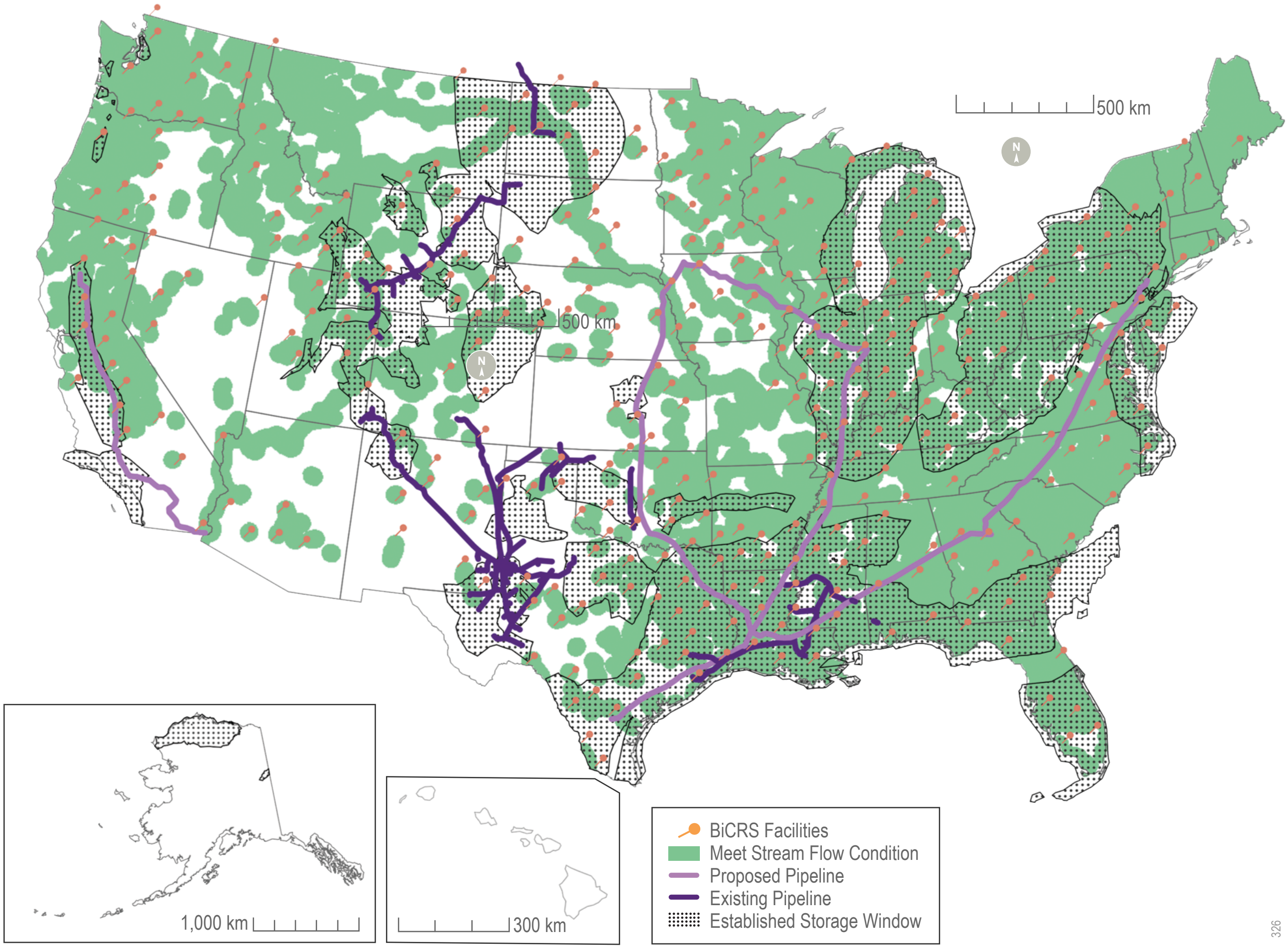

Figure 8-18. *BiCRS Facilities in the Zero Cropland Change Scenario, Geologic Storage, and Pipeline Locations Compared with Streamflow Siting Constraints for BiCRS Facilities*

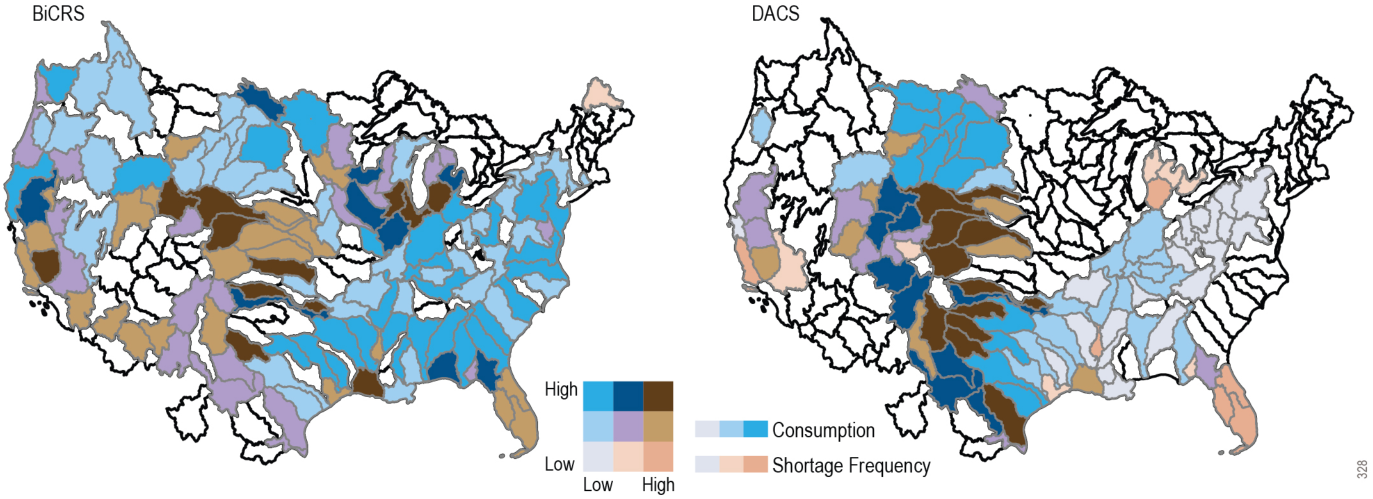

Figure 8-19. *Projected water-shortage frequency by hydrologic basin assuming (1) only consumption of renewable water resources (for the years 2046–2070) from Brown et al. [4]. This shortage frequency is mapped alongside the potential water-use distribution for BiCRS and DACS based on the 2050 maximum-economic-potential BiCRS and the total potential for solid-adsorbent DACS (which includes a vast area of land exceeding what is needed for 1 billion tonnes of* CO_2 *removal).*

DACS Facilities

The amount of water consumed at DACS facilities is highly dependent on the specific DACS technology deployed. A commonly cited figure is that DACS can consume anywhere between 1 and 7 tonnes of water per tonne of CO_2 captured [20]. The actual value depends on the local climate and whether the facility uses a liquid solvent or a solid adsorbent. Cool and wet climates can result in DACS facilities consuming very little water or even being net producers of water (in the form of atmospheric water vapor condensed to liquid water), whereas hot and dry climates are more likely to cause DACS facilities to be net water consumers. For the purposes of this chapter, we assumed that most DACS facilities constructed by 2050 and beyond would use a solid-adsorbent system (**Chapter 7 – DACS**), which can require less water than liquid-solvent systems. This information, combined with an understanding of where most of the capacity will be installed, provided a basis on which we could estimate a range of total evaporative losses associated with large-scale DACS deployment.

Using an estimate of 1.6 tonnes of water evaporated per tonne of CO_2 removed in an adsorbent system with steam regeneration and operating in a relatively dry environment [21], we estimated that building DACS facilities that remove 200 million tonnes of CO_2 annually would consume 0.8 million m^3 of water per day, corresponding to around 8% of current water use for all thermoelectric power generation. If DACS water consumption is on the high end of the estimated range (7 tonnes of water per tonne of CO_2 captured), total water consumption would total 3.5 million m^3 of water per day, corresponding to <1% of total irrigation-water demand or approximately one third of power-plant cooling-water demand. The DACS maximum potential (totaling around 8.5 billion tonnes of CO_2 removal annually) would consume considerably more water (37 million m^3 of water per day if using the 1.6 tonnes of water per tonne of CO_2-removal rate), corresponding to approximately three times the water required for all US thermoelectric power generation. However, installing the maximum DACS potential is not an approach recommended in this report; indeed, the entirety of US net annual greenhouse gas (GHG) emissions are estimated to be 5.6 billion tonnes of CO_2 equivalents (CO_2e) as of 2021 [22], so installing 8.5 billion tonnes of annual CO_2 removal via DACS would exceed current emissions by a wide margin.

Although the total magnitude of DACS water consumption is likely to be very small relative to agricultural water needs and power generation, the geospatial distribution of water demand is an equally important factor for consideration, as water stress is highly variable across the United States. If DACS facilities are prioritized on sites with on-site access to geologic CO_2 storage and in wind or solar-rich regions, this raises the question of whether DACS potential is concentrated in regions that are more likely to experience water scarcity. To understand the regional distribution of DACS potential and its alignment with water resources, we used the total suitable land for solid-adsorbent DACS (corresponding to 8.5 billion tonnes of CO_2 removal per year) to map the distribution of potential water consumption in different hydrologic regions (see Figure 8-19). We mapped water demand against projected future water scarcity from Brown et al. [4]. Because the total national potential for DACS is enormous, these results should not raise alarm; rather, the results are intended to highlight regions that warrant additional consideration when installing large-scale DACS to ensure that water resources are being responsibly managed. Montana, North Dakota, South Dakota, and Wyoming are all highlighted in Figure 8-19 as having strong DACS potential and relatively infrequent future water scarcity under climate change. In contrast, Colorado and West Texas both have strong DACS potential while also being subject to comparatively high future water-scarcity risk. Based on the geospatial distribution of total DACS potential in 2050, 84% of DACS potential (and corresponding water use) is located in hydrologic subregions projected to experience water scarcity <20% of the time, while 26% of DACS potential is located in regions with less than a 1% frequency of water scarcity. Thus, there is ample DACS potential in regions that are not projected to experience frequent water stress. However, in regions where water resources are limited, carefully tracking and minimizing water use for DACS or finding new sustainable non-traditional water sources will be important. Although this report does not explicitly constrain DACS development based on local water resource availability, future work is needed to understand minimum streamflow requirements to support DACS facilities, including a range of technologies, such as liquid solvent and solid adsorbent.

Infrastructure Requirements and Constraints

Chapter 5 – Transportation discusses CO_2 pipelines in detail, which could enable development of DACS and BiCRS facilities in regions that are otherwise economically infeasible because prospective sites lack access to confirmed geologic CO_2 storage. However, several other infrastructure systems will also play an important role in enabling large-scale CO_2

removal. Both DACS and BiCRS facilities will likely require a grid interconnection. Many of the BiCRS facility designs analyzed in **Chapter 6 – BiCRS** generate electricity on-site and some may generate more power than they require to operate, allowing for some net export to the grid. DACS facilities, while co-located with renewable energy in our 2050 scenario (see **Chapter 7 – DACS**), will likely require the ability to both import and export electricity from the grid because we have not incorporated on-site energy storage. This is because we expect DACS facilities to run continuously to avoid operational challenges and prohibitively high costs. This assumption is in contrast to NREL's 100% Clean Electricity by 2035 report [16], which treats DACS as a dispatchable resource, capable of shutting down or reducing operations during hours when intermittent renewable-energy sources are less available and electricity prices are elevated. However, both the NREL report and this report do rely on the assumption that DACS facilities are connected to the grid. **Figure 8-20** shows how access to high-capacity lines will vary across the United States based on current transmission lines and NREL's "All Options" scenario for 2050. Both DACS (**Chapter 7**) and BiCRS (**Chapter 6**) have high potential in areas extending from West Texas and New Mexico, through Colorado, Kansas, Nebraska, Wyoming, Montana, and the Dakotas. Many of these states are part of the Western Interconnect (a large electrical grid region) and have higher-than average distances to high-capacity lines, even after accounting for potential future infrastructure investments. Thus, expansion of DACS and BiCRS facilities may need to be strategically sited to ensure adequate access to transmission infrastructure.

Air Quality Impacts

This report assumes that the United States will pursue electricity grid decarbonization and transportation electrification to the greatest extent possible through 2050 and beyond. As previously noted, all scenarios in this report reflect our guiding principle that resources should go toward decarbonization first and that carbon removal should be scaled up only to compensate for past emissions and on-going emissions that are prohibitively expensive or impractical to mitigate. Broader decarbonization of the US economy would ultimately reduce or eliminate many of the primary emissions sources that contribute to life-cycle air-pollutant emissions inventories. However, some equipment may still be impractical to electrify. For example, equipment required

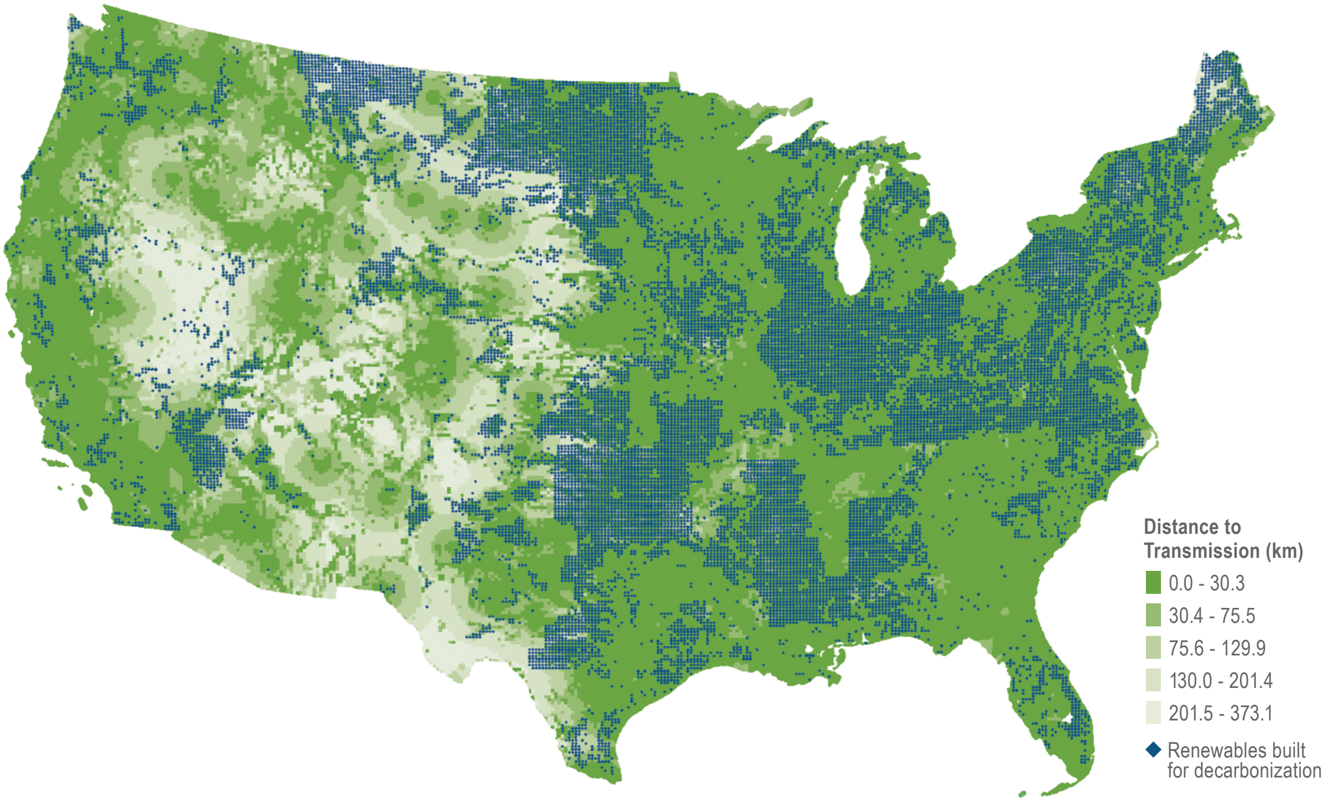

Figure 8-20. *Distances From Nearest Electric Transmission Lines (Existing and Simulated for 2050 in National Renewable Energy Laboratory's Clean Grid "All Options" 2050 Standard Scenario). Blue points indicate locations where land has been prioritized for potential renewable energy generation to decarbonize the grid.*

to conduct forest-management activities in remote areas may rely on combusting liquid or gaseous fuels. The same may be true for some farming equipment. This chapter does not include a full inventory of all potential emissions sources associated with large-scale carbon removal. Instead, this section enumerates the most likely emissions sources and avoidance opportunities.

As noted in the introduction to this chapter, fine particulate matter (PM2.5) is the primary driver of air-pollution-related human health impacts. Thus, this section will focus on primary PM2.5 emissions and other air pollutants that contribute to the formation of secondary PM2.5 (fine particles formed via chemical reactions in the atmosphere), which include NO_x (the sum of NO and NO_2, reported as the mass of NO_2-equivalent), SO_x (reported as mass of SO_2), VOCs, and NH_3. **Table 8-1** lists likely emissions sources and mechanisms for avoidance or capture that correspond to each of the carbon-removal strategies explored in this report. Most of these pollutants are emitted as combustion byproducts and, while economy-wide emissions are likely to decrease dramatically as a result of decarbonization, this report does include some sources of emissions.

PM2.5, carbon monoxide (CO), and some VOCs are products of incomplete combustion, so emissions will be elevated when perfect fuel-air mixing cannot be achieved and/or when higher-moisture fuels are combusted. VOCs are also emitted naturally by plants, and these emissions are involved in a variety of ecological functions [23]. SO_x emissions are driven by fuel composition; fuels with higher sulfur content will result in greater SO_x emissions. NO_x emissions are the result of both fuel composition and flame temperature; nitrogen present in the fuel can oxidize and hotter combustion can also oxidize N_2 present in air. CO is also routinely regulated and, for this reason, it is included in Table 8.1. CO plays a role in the formation of tropospheric ozone (O_3), and it can pose asphyxiation risks if emitted in enclosed spaces, but it does not contribute directly to the formation of secondary PM2.5.

Ammonia Emissions

NH_3 emissions in the United States primarily occur as a result of volatilization from nitrogen-based fertilizer application, so changes in fertilizer application (positive or negative) will impact NH_3 emissions. Biomass burning is another major source of air pollution; low-temperature, smoldering fires most likely to occur during wildfires or agricultural residue burning emit NH_3 [24]. However, NH_3, other amine, and VOC emissions are an emerging area of study for carbon-capture systems. These emissions can occur when solvents undergo thermal decomposition, and volatile fractions are emitted along with non-CO_2 gases. It is worth noting that there are strong economic incentives to avoid excessive solvent losses

Table 8-1. *Air Pollutant Emissions Sources and Avoidance/Capture Mechanisms Relevant to Large-Scale Carbon Removal.*

Strategy	Emissions Source	Emissions Avoidance or Capture
Forest Management	— Forest management equipment (PM2.5, NO_x, CO, VOCs) — Prescribed burning (PM2.5, NO_x, SO_x, CO, VOCs, NH_3) — Non-electrified truck transport (PM2.5, NO_x, VOCs, NH_3)	— Wildfires (PM2.5, NO_x, SO_x, CO, VOCs, NH_3)
Soil and Agricultural Management	— Farm equipment (PM2.5, NO_x, VOCs, NH_3) — Nitrogen fertilizer application to previously fallow lands (NH_3)	— On-farm residue burning (PM2.5, NO_x, SO_x, CO, VOCs, NH_3) — Reduced nitrogen fertilizer application to former corn lands (NH_3)
BiCRS	— Char, lignin, and gaseous fuel combustion (PM2.5, NO_x, VOCs, NH_3) — Amine solvent loss from carbon capture system (NH_3, other amines, VOCs) — Non-electrified truck transport (PM2.5, NO_x, VOCs, NH_3) — Non-electrified rail transport (PM2.5, NO_x, VOCs, NH_3)	— Landfill gas releases/flaring (PM2.5, NO_x, SO_x, VOCs, NH_3) — Organic waste composting (CO, VOCs, NO_x, NH_3) — Manure management (CO, VOCs, NH_3) — Capture of ambient pollutants in inlet air during carbon capture and sequestration (highly uncertain)
DAC	— Solvent loss (NH_3, other amines, VOCs)	— Potential reduction in ambient pollutant concentration in air processed in DAC system (highly uncertain)

and newer solvents are designed with this in mind. However, most existing literature focuses on the well-known solvent, monoethanolamine (MEA). Heo et al. [25] estimated that the use of an MEA solvent to capture CO_2 from a coal or natural-gas plant could emit between 16 and 240 g of NH_3 per tonne of CO_2 captured (corresponding to an MEA solvent loss of 0.1 to 1.5 kg MEA per tonne of CO_2).

DACS

Because we expect that future expansion of DACS will largely rely on solid-adsorbent technologies and advanced solvents for which thermal decomposition and loss is minimized, the long-term impacts of DACS on air quality (positive or negative) are expected to be comparatively small and are essentially unknown. For this reason, we have not included air quality impacts from DACS in our assessment, although this is an area worthy of further study.

Forest and Soil/Agriculture Management

Both forest management and soil and agricultural management can have more substantial impacts on air quality. Reducing the frequency and severity of wildfires will yield critical co-benefits unrelated to carbon removal, of which air quality is just one. PM2.5, NO_x, SO_x, VOCs, CO, and NH_3 are all emitted in large quantities during wildfires. Burke et al. [26] estimated that wildfires contributed up to 25% of all PM2.5 across the United States in recent years, resulting in net increases in PM2.5 concentrations between 1 and 4 $\mu g/m^3$ across much of the West and Upper Midwest regions in the last 2 decades. Forest management will result in the removal of some woody biomass for use in BiCRS facilities. Other material will be impractical to haul out and may be managed through prescribed burning as part of a broader forest-management strategy, which does emit air pollutants. The quantity and nature of air pollutants emitted from prescribed burning as compared to uncontrolled wildfires is an area of ongoing study. However, prior literature has so far indicated that prescribed burning is less harmful from an air-quality standpoint for several reasons: (1) prescribed burning is usually implemented when meteorological conditions are favorable to limit human exposure and (2) the smoke composition, quantity of emissions, and duration of exposure associated with wildfires appears to increase the human-health damages compared to prescribed burns [27].

BiCRS

Although it is difficult to quantify the impact that improved forest management could have on net emissions in the future, it is possible, if not probable, that the net air-quality benefits associated with wildfire-risk reduction could far outweigh any other factors listed in Table 8-1. To better understand whether this assumption may be valid, we considered what is likely to be the largest source of new air-pollutant emissions within the CO_2-removal approaches presented in this report: BiCRS facilities. BiCRS facilities are likely to require management of a variety of gaseous, liquid, and solid residues and in many cases the fate of these materials is unknown. Some material, such as biochar or biosolids, may be suitable for inclusion in compost, while some waste gases may need to be flared. The BiCRS facility configurations considered in **Chapter 6 – BiCRS** do incorporate on-site combustion of fuels for process heat and electricity. Even in the case of bio-hydrogen production, some syngas is routed to combustion for the purposes of heat and power generation. The resulting flue gases are routed to solvent-based carbon-capture systems and costs are estimated based on MEA as the solvent, although future facilities are likely to use more advanced solvents with lower thermal-decomposition rates. Thus, BiCRS facilities may produce air pollutants from two sources: (1) the pollutants produced during combustion of solid, liquid, or gaseous fuels, a large portion of which may be captured before or during solvent-based carbon capture and (2) air pollutants produced and emitted as a result of thermal decomposition of the carbon-capture solvent itself. All of these pollutants can be estimated and entered into an integrated assessment model to quantify their impact on local PM2.5 concentrations. However, currently available integrated-assessment models are all based on historical background pollutant concentrations and meteorology. These models do not incorporate the possibility of widespread decarbonization and the resulting reductions in economy-wide air-pollution emissions. Nevertheless, we estimated air-pollutant emissions from potential BiCRS facilities and used the Intervention Model for Air Pollution (InMAP) to estimate their resulting impact on PM2.5 concentrations and human health (given current population densities) if these emissions were to occur under current atmospheric conditions (**Appendix 8**).

Our air quality analysis indicated that, in a worst-case scenario, any increases on local PM2.5 concentrations resulting from carbon-capture systems in BiCRS facilities would likely be an order of magnitude smaller than the reduction in PM2.5 concentrations due to wildfire smoke discussed previously. We found that, because most economically favorable BiCRS facilities produce concentrated CO_2 streams through the production of hydrogen, the magnitude of emissions from post-combustion flue gases is small. Furthermore, each BiCRS facility routes post-combustion flue gases to carbon capture and sequestration. Assuming 90% of all pollutants present in the flue gases are either treated prior to entering the carbon-capture system or are captured in the solvent itself, the primary source of air pollutants is likely to be any thermal decomposition of the solvent. Calculated impacts are driven by NH_3 emissions from the thermal decomposition of carbon capture, and these impacts are likely overestimated by InMAP due to known issues with predicting NH_3 impacts on particulate matter formation, particularly in agricultural regions where the local atmosphere is not likely to be NH_3-limited.

Geographic Distribution of Air Quality Impacts

From an environmental justice standpoint, one consideration is the geographic distribution of the air-pollution emissions and avoidance. The main co-benefit offered by large-scale CO_2 removal, namely reductions in wildfire smoke, may occur in regions that do not align with the regions where most new BiCRS-related emissions and health impacts will occur. As shown in **Appendix 8**, any additional air pollution burdens, however minimal, may be concentrated in the Lower Midwest and Southeast regions. Wildfire smoke impacts are less predictable and vary from decade-to-decade, but historical impacts have been mostly in the West and Upper Midwest regions, as illustrated by Burke et al. [26]. Tracking and minimizing air-pollutant emissions, particularly from any untreated flue gases (e.g., from flares) and from carbon-capture systems, will be key to ensuring that large-scale CO_2 removal offers net air-quality benefits in all regions of the United States.

Additional Resource Constraints and Environmental Impacts

This report focuses on just a small subset of the constraints and impacts that are relevant for large-scale CO_2 removal. Life-cycle environmental impact assessments commonly include a wider set of metrics, including human-toxicity impacts (extending beyond fine particulate matter), freshwater eutrophication, freshwater ecotoxicity, terrestrial acidification, terrestrial ecotoxicity, and depletion of constrained resources, including critical minerals [28]. The magnitude of many of these impacts will depend on how key infrastructure is produced, including solar photovoltaic panels, wind turbines, and the metals required for renewables and other equipment/infrastructure. These impacts extend far beyond US borders and are worthy of future study. Ensuring sustainable, reliable, and resilient supply chains for the infrastructure needed to support both decarbonization and large-scale CO_2 removal requires international cooperation. Freshwater eutrophication impacts will most likely be driven by the implementation of agricultural-soil management and cultivation of carbon crops. Cultivation of switchgrass is predicted to yield numerous ecosystem services, including reductions in nutrient and sediment runoff into local water bodies [29]. However, any change in agricultural land management will have some market effects, even carbon-crop cultivation centers on marginal/abandoned croplands or grazing lands. Intensification of livestock grazing and changes in supply of animal feed (e.g., from co-products of corn-ethanol production) are just two examples that could have secondary effects on emissions to air and water. Further work is needed to combine the best-available agroecosystems modeling and measurements with economic models for the purpose of better understanding how to manage the transition to large-scale BiCRS and agricultural soil management.

Conclusions

Large-scale carbon removal has implications for land cover, freshwater resources, and air quality. However, if carbon removal is employed as a strategy to offset only the emissions from difficult-to-decarbonize sectors rather than compensating for the continued widespread use of fossil fuels, the magnitude of these natural-resource implications is modest and manageable.

Reaching 1 billion tonnes of CO_2 removal per year will require around 2% of land area in the United States, most of which is required to grow carbon crops used in BiCRS facilities. However, we demonstrated in this chapter that it is possible to place meaningful guardrails on land use and prioritize constrained resources for decarbonization before allocating additional land for carbon removal. DACS has enormous potential across the United States, even if developments are constrained to regions with access to confirmed geologic storage. We will need only a small fraction of this total potential, provided cheaper CO_2-removal strategies are employed first before DACS. Our analysis suggests that forest and agricultural soil management can provide near-term carbon storage at modest (and sometimes negative) costs, while constructing BiCRS and DACS facilities along with the necessary supporting infrastructure is subject to a longer timeline. Particularly for adsorbent DACS facilities that rely on renewable electricity, transmission infrastructure investments will play a key role in economically viable operation and minimizing energy-storage requirements.

Selecting regions for developing BiCRS and DACS requires careful consideration of ecosystem and water-resource impacts. For DACS co-located with renewable-energy production, water constraints will be an important consideration, as some of the highest-potential regions are also expected to experience increasing water scarcity due to climate change. However, the magnitude of water required for DACS remains highly uncertain and is technology dependent. Particularly in hot dry regions, DACS water use should be monitored and publicly reported as new facilities are built.

Like water use, the air quality implications for large-scale CO_2 removal are uncertain but are likely to result in substantial net benefits. Improved forest management can decrease the risk of uncontrolled wildfires and reduce the associated harmful smoke emissions. If DACS facilities rely primarily on solid adsorbents in the future, any emissions from such facilities will likely be minimal. Thus, BiCRS facilities that combust solid, liquid, or gaseous residues on-site and utilize liquid solvents for carbon capture are likely to be the primary source of new emissions. However, such emissions may be one or more orders of magnitude smaller than the net benefits from reduced wildfires.

Our understanding of land, water, and air quality impacts of large-scale CO_2 removal remain uncertain but the results in this chapter are encouraging and suggest that these factors will not be primary constraints for the industry if carefully managed. Building a solid foundation of best practices for siting new facilities, building trust with local communities, and carefully considering local resource constraints and ecosystems will be key to realizing the full potential of large-scale CO_2 removal.

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