draft report

INITIAL CONSIDERATIONS FOR LARGE-SCALE CARBON REMOVAL IN THE UNITED STATES

Description of methods, feedstocks and constraints

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INITIAL CONSIDERATIONS FOR LARGE-SCALE CARBON REMOVAL IN THE UNITED STATES: *DESCRIPTION OF METHODS, FEEDSTOCKS, AND CONSTRAINTS*

SUMMARY: The Biden Administration has established a goal of removing 1 Gt carbon dioxide equivalents per year (CO_{2e}/yr) from the atmosphere and of achieving net zero greenhouse gas emissions (GHG) by 2050.[1] Our team of leading academic and DOE national laboratory experts is conducting the first economy-wide technical evaluation of the options for achieving this carbon dioxide removal (CDR) goal. The net zero goal includes targets of 100% clean electricity by 2035 with 40% GHG emissions reductions by 2030, which helps set primary scenario boundaries for our analysis of the CDR supply curve. Our analysis will evaluate feasibility, performance, and costs on a county level for the entire USA (including AK and HI where possible), considering all removal methods that are currently well-enough developed for us to estimate the likely costs in 2050. We anticipate that more than 1 Gt CO_{2e} of removal will be available to the Nation. We will identify how much of each CO_2 removal approach is available in specific regions of the Nation and provide cumulative costs and volumes (a supply curve) by region for 2050. We expect to complete this detailed analysis by late 2023.

In this preliminary discussion, we consider the most important items that need to be resolved in this effort, and whether we will have the data necessary to complete the task. We are primarily concerned with five major questions:

1. Is it reasonable to expect that we can remove enough CO_2 from the air to meet the US atmospheric carbon removal goal using technologies that will be scalable in time to meet the targets?
2. What is the likely contribution of the component technologies and the amount of removal they can each supply? What is needed to quantify the contributions of each?
   a. Forest Sequestration
   b. Soil Sequestration
   } ***ecological solutions***
   c. Direct Air Capture (DAC) and Storage
   d. Biomass Carbon Removal and Storage (BiCRS)
   } ***engineered solutions***
3. Where can we reliably and permanently store CO_2 removed by engineered solutions (DAC and BiCRS) to ensure it does not return to the air?
4. Can we perform these tasks while improving the lives and prosperity of Americans, especially in communities with environmental justice concerns?
5. Will we have the data and knowledge necessary to calculate the cost of these removals?

EARLY INSIGHTS

It appears feasible to remove one gigaton of CO_{2e} per year within the United States through a combination of ecological and engineered solutions. Both can likely exceed a ~500 million metric ton target in our current analysis for the United States.

Ecological solutions:

To sequester carbon in our Nation's forests and soils, the major challenge is durability. Costs are likely to be low on an annual basis but may become significant over long periods of time. Can management

incentives maintain practices to keep carbon out of the atmosphere for the next century? Ultimately, durable ecological carbon storage is a function of both social factors that determine land-management decisions, as well as future climate effects, and hence requires a sustained commitment to ecosystem stewardship. Investments in measurement and verification will be critical, along with systems-level assessments of additionality. Solutions will need to be managed on a 'portfolio' basis, with explicit discounting of benefits for some expected number of project failures or changes.

The US has vast amounts of forested lands with high potential for increased carbon sequestration rates in forest tree growth and long-lived wood products. **Improved forest management practices like reducing stocking densities in high fire risk areas, lengthening rotations, and routing of timber to long-lived forest products have the potential to increase forest carbon stocks and decrease forest carbon emissions by promoting tree growth while still supplying critical wood products for market.**[2] Our ability to accurately quantify the potential of forest carbon sequestration will hinge on developing multi-scale sampling and analytical designs that can merge high- and low- resolution empirical data to build confidence in regional estimates of management effects on negative forest emissions.

On croplands and managed agricultural landscapes, **soil carbon storage can be increased most effectively with management strategies that increase the amount of year-round plant cover and root inputs on the landscape**. These strategies either integrate with existing annual crops (e.g., cover cropping and conservation buffers) or replace annual crops with perennial crops (e.g., land set-asides or perennial bioenergy crops). However, new research is urgently needed. All efforts to increase soil carbon storage can benefit from investment in cost-effective monitoring technology to quantify soil carbon and emissions of greenhouse gases from soil, particularly nitrous oxide. In addition, more distributed, well-replicated field trials are essential for establishing emerging soil-based carbon removal approaches and to fully explore established practices that target grazing lands (**Table 1**).

Engineered solutions

For technological CDR approaches—including Direct Air Capture (DAC) followed by subsurface geologic storage and Biomass Carbon Removal and Storage (BiCRS)—the availability of large quantities of CDR capacity is more assured than for ecological solutions, but the associated costs are likely higher and need to be established with confidence.

DAC is the most straight-forward yet expensive of the CDR approaches, requiring land, a source of low-carbon energy, and a place to permanently store the collected CO_2. **Several US regions with outstanding geologic storage are potential regions of opportunity for renewably powered DAC.** These facilities are likely to be cited in the southern and western United States to access geologic storage and zero-GHG emission power. Even with low renewable energy costs, DAC is likely to be the most expensive of the CDR pathways.

The Biomass Carbon Removal and Storage BiCRS pathway can provide significant and durable carbon removal while providing sustainable (aviation) fuels for decarbonization. Biomass CDR will likely represent the largest volume component of future US CO_2 removals. We project capacity from US biomass can provide at least 500 million metric tons of removals without affecting the ability of the US to use biomass to provide all of its sustainable aviation fuel requirements. The challenge with BiCRS is not capacity but implementation. BiCRS requires the engagement of multiple stakeholders who must produce, collect, and transport biomass, construct and operate of biomass conversion facilities, and transport CO_2 for geologic storage. While several biomass conversion technologies for BiCRS are mature, most have yet to be implemented at scale. For these reasons, we will focus on identifying lowest cost regional BiCRS solutions (including profit from generation of needed sustainable fuels) and co-benefits to communities to propel

the "leap" over this implementation gap. Using waste biomass (agricultural, forest, trash and food waste) is vital to achieving this goal.

Suitable geologic storage is available in many parts of the country where BiCRS and DAC methods can be used for CDR, and storage capacity is much greater than the 500 million metric tons/year goal, or any potential demand. Establishing the existence or lack thereof of viable storage in parts of the country with sparse data will require additional characterization efforts. However, the highly prospective areas are already relatively well studied and understood and represent more than adequate storage. For the areas of the country where viable storage is not available locally, CO_2 transportation to viable areas is generally possible.

Environmental justice is a major constraint on CDR—a large-scale endeavor that will touch so much of our land, population, and economy. At this point it is too early to say what changes and limitations must be placed on CDR approaches in order to improve the lives of all Americans, but it is clear that with the large number of CDR options available to the US, it will be possible to find solutions that provide environmental and socioeconomic co-benefits to the communities of our Nation.

While ecological and engineered CDR approaches can likely meet the Nation's carbon removal needs; we have identified a set of key research investments that will be critical to reducing costs, increasing confidence, and increasing the total amount of CDR, even after reaching the 2050 net-zero goal (**Table 1**).

Table 1. Topics where investment is urgently needed and would immediately benefit the accuracy of CDR supply curves

CDR Pathway	Research Investment Needs		
Forest Carbon Sequestration	Merged high-quality, fine-grained data with the singular- scale, coarser "out-of-the-box" data products for aboveground forest carbon	Perform multi-scale sampling and analytical designs for merging high- and low-resolution empirical data–to build confidence in regional estimates of management effects	Cost-effective monitoring and verification infrastructure; high-integrity protocols
Soil Carbon Sequestration	Establish cost-effective monitoring and verification infrastructure and high-integrity protocols	Development of inexpensive and scalable technology for measuring nitrous oxide emissions from soil	Expanded nationwide network of standardized agricultural test sites
Direct Air Capture (DAC)	Effects of ambient temperature and humidity on CO_2 throughput and material lifetime; bench-scale estimates of regeneration processes, methods for integrating regeneration with low-carbon energy and reducing energy intensity	More rigorous process modeling and analysis with unit operation mass and energy flows for all types of DAC processes, particularly moisture swing and calcium-looping methods	Assessments of regional ecological impact of large-scale DAC deployment
Biomass Carbon Capture and Storage (BiCRS)	Adapt thermochemical processes (e.g., gasification) to variable biomass feedstocks; understanding scaleup and deployment bottlenecks; performing scaling and process integration of BiCRS CO_2 capture	Gather empirical land-use decision data to maximize ecosystem services and carbon benefit (standing carbon stocks, soil carbon, biochar application) in BiCRS-relevant bioenergy crops	Collect data to address BiCRS feedstock cost uncertainties, including costs incurred during collection, storage, and degradation
Geologic Storage	Detailed information to select and permit secure sites in advantageous locations.	Improved strategies for containment assurance and risk avoidance, including management of well penetrations, induced seismicity, and long-term assurance	Basin wide cohesive management strategies to maximize effective use of available storage space

FOREST SEQUESTRATION

The US Forest Service estimates approximately 310 million hectares (~34%) of the US is forested[3] (**Figure 1**). From 2005-2016, net forest C sequestration equaled ~788 million tons CO_2/yr, but losses to forest fires (147 million tons CO_2/yr) and tree cutting (652 million tons CO_2/yr) represented major emission pathways.[3] Urban forested natural areas can also store large amounts of carbon[4] and improved management can lead to improved human health.[5] The wide array of management intervention options and fates of forest products suggest high potential to dramatically increase the CDR rates and reduce the atmospheric carbon emission rates associated with existing forest lands. Such practices—including lengthening harvest rotations, improving tree-stocking densities, planting more resilient forest tree species, and using novel wood product markets—could, conservatively, increase net removal by an additional 0.1 Gt C/yr for operations on existing forest lands while still supplying critical wood products for market.[2]

Early Insights

US Forests have large potential to store and sequester carbon in forest biomass, forest soils, and long-lived wood products.[6-10] Improved forest management practices have significant CDR potential. But specific forest management practices must be applied on a regional or sub-regional basis to match local ecological forest conditions (forest composition, age structure, and climate) and socioeconomic conditions (land ownership, land-development pressures, current wood markets). Importantly, improved management practices may also increase forest resiliency against future forest wildfire losses, pests and pathogens, and changing climate (drought, windstorms, increasing temperature) and thus may lead to co-benefits and avoided emissions from the forest sector. These avoided emissions are consequential—in the absence of interventions that extend the permanence of forest carbon, much more of the carbon in our nation's forests will end up in the atmosphere. This consequence makes these interventions akin to interventions that reduce national fossil fuel emissions.

Using USFS Forest Regions, we have outlined major regional drivers of forest-stock changes and have qualitatively assessed where opportunities for improved management practices are located (**Figure 2**). For our ongoing analysis, we will estimate the impacts of these forest management practices using quantitative and statistical models to produce regional estimates of forest CO_2 sequestration under shifting practices. At the regional level, we will combine estimates with economic models of wood-product markets to estimate costs of practices.

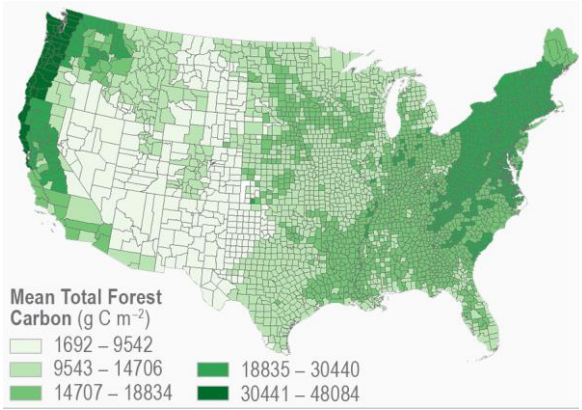

Figure 1: *Estimated 2010 standing forest carbon stocks (living vegetation, coarse woody debris, soils) and fluxes (new ecosystem productivity) for the conterminous United States derived from the National Forest Carbon Monitoring System (NFCMS). To create this map, we averaged the estimated total forest carbon (g C m^{-2}) for each county from 30-m-resolution grid cells provided in the NFCMS data. Improved forest-management practices like altering stocking densities, lengthening rotations, and promoting uneven-aged stands have the potential to increase forest carbon stocks and decrease forest carbon emissions by promoting tree growth while still supplying critical wood products for market.*

Methodology

To assess the potential for CDR in forests and forest wood products, we are assessing regional forestry management practices that have potential to increase forest tree growth, forest resilience to whole forest loss (fire, pests and pathogens, wind), and wood production that will lead to carbon storage in long-lived wood products or substitutable energy sources. We will synthesize existing estimates of standing carbon stocks and projected carbon fluxes[11] (**Figure 1**)

and combine these estimates with regional prescribed management and harvest scenarios to project future tree growth and wood-product potential by region. We will combine these scenarios with wood-product market models to estimate total CDR in forest growth and durable wood products at the national scale.

Analysis Boundaries

We will not conduct socioeconomic feasibility assessments of developing and implementing policies, regulations, or incentives that can drive changes in forest management, products, and product fates. However, we note that singular policy decisions can strongly drive changes in US forestry practice (e.g., when the EU made a policy decision to co-burn wood pellets). In our full analysis, we will note the importance of such drivers, to highlight vulnerabilities and opportunities that such external drivers present in relation to carbon sequestration rates.

Research and Development Needs

- Accurate quantification of CDR through improved management of US Forest lands through synthesis of "sentinel" case studies to refine avoided- and negative-emission estimates by **merging high-quality, fine-grained forest carbon data with singular scale, coarse "out-of-the-box" data products**
- Development of **multi-scale sampling and analytical designs that merge high- and low-resolution empirical data collection** to build confidence in regional estimates of management effects on avoided and negative emissions on forest lands
- Scenario development of **wood lifetime from tree to final fate** using life-cycle assessments (LCAs) to estimate reduced emissions comprehensively by quantifying "on-and-off" land carbon fates

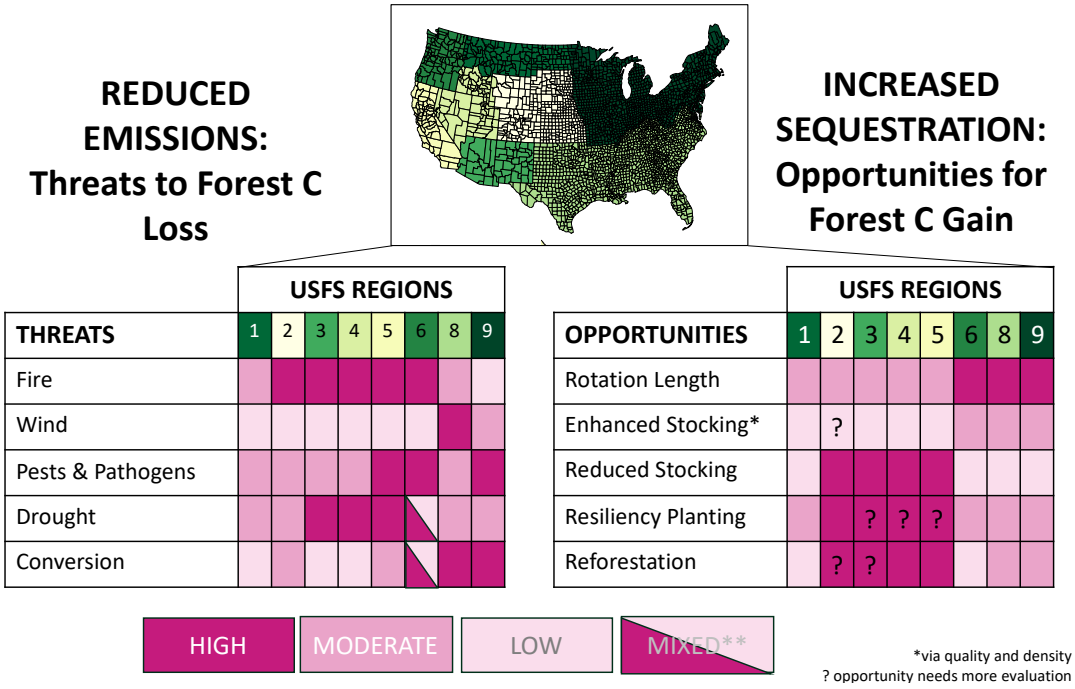

Figure 2: *Qualitative assessment of regional threats that could lead to increased forest CO_2 emissions and opportunities for management to increase forest sequestration. Consideration of both threats and opportunities for forest carbon stocks is imperative for building confidence in the durability of forest carbon stores. Additionally, many opportunities for improved management can reduce the impact of future forest carbon loss, thus increasing total carbon (C) stored on the land. Regions in this figure represent the 8 US Forest Service Regions in the conterminous United States. Future analyses may further subdivide regions to better match ecological and socioeconomic conditions and will include Alaskan forests.*

SOIL CARBON SEQUESTRATION

Early insights

US agricultural soils have lost a significant fraction of their natural stores of organic carbon since the onset of cultivation.[12] Optimizing agriculture to restore some of this organic carbon can remove CO_2 from the atmosphere. If improved agricultural management practices were applied to a significant fraction (10%) of US croplands, soils could potentially sequester 10s of millions of tons of CO_2 over a 10-20-year period.[13-20] In addition to sequestering carbon, improved crop and livestock management can reduce emissions of fossil CO_2 and the greenhouse gases N_2O and CH_4. These emissions reductions are a permanent climate benefit that may be comparable to gains from sequestering new carbon in soil. Consequently, soil carbon sequestration must complement broader efforts to reduce emissions from the agricultural sector, which currently accounts for 10% of US emissions.[21]

We have identified several land-management practices with the potential to increase soil carbon storage:

1. **Cover cropping.** In most annual croplands, planting cover crops has a moderate to high potential for increasing soil carbon storage relative to conventional management.[13, 15, 22] Cover crops can be integrated into existing crop rotations and have considerable room for increased adoption in US croplands (**Figure 3**). In addition to cover cropping in annual croplands, we will evaluate effects of replacing bare soil with cover crops in orchards.
2. **Conservation buffers**. We will also consider practices that establish perennial plant cover within conventional annual croplands. This family of practices includes windbreaks, shelter belts, and riparian buffer zones.[17] While these practices apply to a small fraction of agricultural land area, they may be cumulatively significant.
3. **Land set-aside.** Conversion of cropland to perennial cover (e.g., restoration of prairie or wetlands) can yield increases in soil carbon. Land set-asides are supported under the US Department of Agriculture (USDA) Conservation Reserve Program (CRP). We will consider cost tradeoffs between bioenergy production and CRP (see BiCRS section), identify economically marginal croplands that are allocated to CRP versus bioenergy, and calculate associated soil-carbon costs and benefits.
4. **Perennial bioenergy**. Conversion of annual cropland to perennial bioenergy crop production can sequester carbon in soil while supplying bioenergy feedstocks.[14, 19, 23] We will evaluate the amount of soil carbon that might be stored or lost if bioenergy crops are planted in CRP lands or in actively managed cropland currently used to

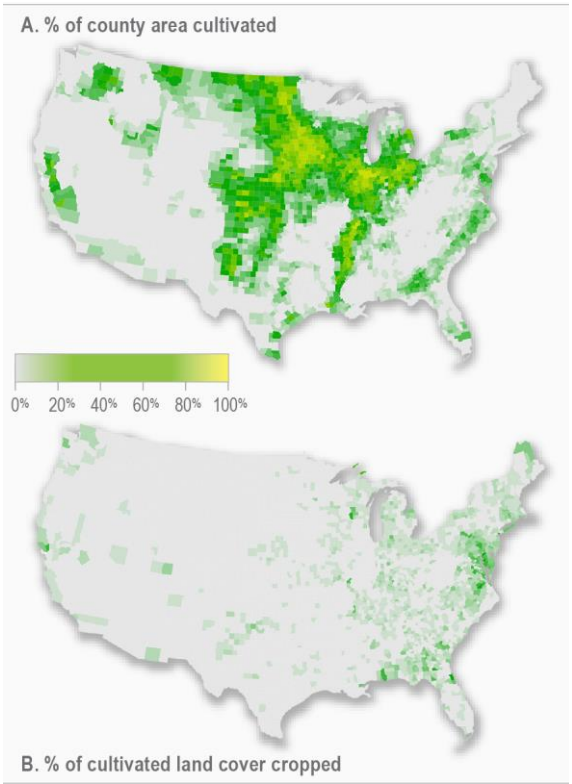

Figure 3. *Current land under cultivation (A) defines the target region for cover cropping, conservation buffers, land set-aside, and bioenergy cropping. Current adoption of cover cropping (B) is low relative to available land area, indicating high additionality and a large potential for expansion.*

produce bioethanol. This analysis will extend the four scenarios defined in our analysis of BiCRS-based carbon removal to consider soil-carbon impacts.

Methodology

In our ongoing analysis, we will use biogeochemical models based on future climate projections to estimate the effects of these management practices on soil carbon storage and emissions of greenhouse gases. We will combine these results with an economic model to simulate land-use decisions and their effects on soil carbon storage at the national scale. Our analysis will account for the costs of maintaining sequestered carbon at the national scale until 2050 and will include an extended evaluation of the persistence of this carbon and risks of carbon loss at a 100-year timeframe.

Analysis Boundaries

Several emerging agricultural technologies could potentially make contributions to carbon removal at a national scale but have not yet been widely tested or are difficult to verify using current measurement technologies (e.g., enhanced mineral weathering, novel deeply rooted crop cultivars). As well, some established land-management approaches may achieve carbon removal (e.g., adaptive grazing management), but field studies of these practices have not been conducted in a wide enough range of environments, or information about their baseline management practices is scarce. We have identified these technologies and practices as targets for increased research and development investment (see below) but will not consider them in our national-scale analysis.

Research and Development Needs

Cost-effective monitoring and verification infrastructure and high-integrity protocols for valuing soil carbon will ensure that carbon removal from soil management is robust. One specific priority is developing inexpensive and scalable technology for measuring nitrous oxide emissions from soil. Nitrous oxide is a potent greenhouse gas that is a byproduct of fertilizer use in agriculture, and it can determine whether management is a net harm or benefit to the climate. In addition, ground-based soil carbon measurements could be improved by sampling strategies informed by satellite and areal imagery. Broadly, all soil-based climate mitigation strategies could benefit from an expanded nationwide network of standardized agricultural test sites, where agronomic practices can be compared side-by side in large-scale experiments.

Specific emerging agricultural technologies that could benefit from increased research investment include development of genetically engineered deeply rooted cultivars,[24] compost application to grazing lands,[25] amendments of biochar from BiCRS residual,[18] and enhanced mineral weathering.[26] All these approaches could benefit from more extensive field trials to quantify their effects on crop and rangeland yields. In addition, compost, biochar, and mineral weathering involve transporting biomass or other amendments, so they require rigorous methodologies to quantify emissions associated with production and transport, alternative fates, and possible environmental and public health effects.

Data-deficient established management approaches are centered on grazing lands. Rangeland seeding with legumes[16, 27] and regenerative grazing practices[28] show promise, but national-scale data on baseline grazing practices do not yet exist and would be necessary for expanding and crediting these approaches. US grazing lands extend over a wide range of climates where management will have different effects, which means that more regional field trials are essential for improving management in this space.

DIRECT AIR CAPTURE (DAC)

Direct Air Capture (DAC) removes CO_2 from ambient atmospheric air, so it theoretically can be built anywhere. This flexibility means that DAC facilities can be sited as close as possible to suitable geologic sequestration sites or other end uses of CO_2. However, DAC is energy-intensive and energy availability is an important consideration for deployment. Buildout of new low-carbon energy will be prioritized for electrical grid decarbonization to meet the Biden administration's goal of 100% clean electricity by 2035, requiring that energy for DAC developments be provided by additional dedicated renewable energy facilities, and may have higher costs. Our analysis will identify locations around the Nation that are likely to be best for deploying DAC, quantify the feasible amounts and costs, and describe the infrastructure needs that will accompany such deployment.

Early Insights

To maximize the net carbon removed by an electrified DAC process, a clean source of electricity must be used. Use of electricity for DAC must not compete with other uses, such as decarbonizing the electrical grid. Therefore, regions with high potential for renewable electricity generation may offer an opportunity for supplying power to both the electrical grid and DAC processes.

Our initial investigation examined the intersection of (1) regions of geologic storage with high injectivity and (2) regions that currently produce large quantities of renewable electricity from solar and wind resources (**Figure 4**). This map shows several regions of high renewable electricity generation that are adjacent to or overlap regions with high injectivity, suggesting these may be potential regions of opportunity for co-deployment of DAC and additional renewable energy sources. These regions include parts of California, Texas, the northern Great Plains, and the Midwest.

In future work, we will draw upon existing analyses examining the distribution of untapped solar and wind generation capacity within the geologic storage regions of opportunity to gain a better understanding of the potential for DAC deployment in these regions. Ongoing analysis will also refine the cost models used for electrically driven DAC processes, incorporating the expected cost of additional renewable electricity deployment when considering regions for deploying DAC. We will combine this analysis with an assessment of the land available for deployment to generate a region-based supply curve for DAC.

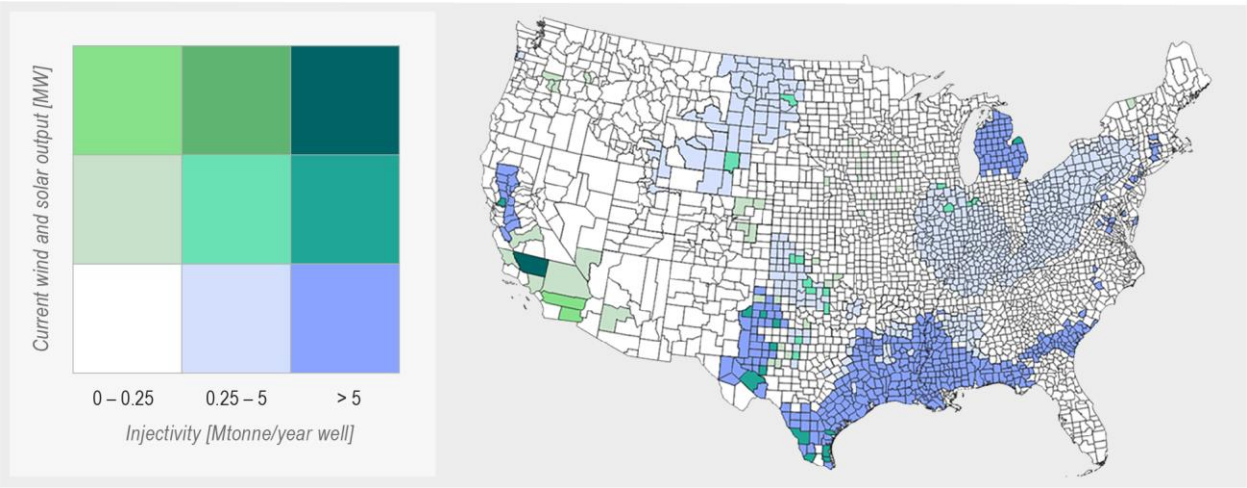

Figure 4. *Overlay of US geologic storage regions and currently deployed solar and wind electricity capacity, suggesting potential regions of opportunity for future deployment of renewably powered Direct Air Capture (DAC). Dark green counties indicate regions where both injectivity and current renewable electricity generation are high. We will evaluate the potential for renewable electricity generation in the blue counties as regions of opportunity.*

Methodology

To develop a supply curve for DAC deployment in the US, we are assessing the cost of deployment of DAC, the land available for that deployment, and the energy that will be used to power DAC. We will focus on currently available DAC technologies, nominally liquid solvent and solid sorbent approaches, and will evaluate the cost, energy use, and land area requirements of these processes. We will consider complete electrification of these processes for comparison with their fossil-driven counterparts. Due to the prioritization of clean electricity for decarbonization, we anticipate that any electricity used for DAC will be purpose-built and additional to renewable electricity needed to power the grid. These additional renewable electricity resources may come with a higher cost; we will draw upon existing analyses to understand these costs. We will integrate these cost results with the amount of available land near suitable sequestration to generate a supply curve for DAC.

Analysis Boundaries

We will not evaluate the tradeoffs between prioritizing renewable electricity for decarbonization and using the same renewable electricity for powering DAC; we will take the Biden administration's goals of 100% clean electricity by 2035 as a baseline. Therefore, any electricity used for DAC will need to be in addition to the electricity needed to power the grid. Currently we do not plan to deeply evaluate DAC processes based on using moisture swing, electro-swing, pH swing, or calcium-looping methods, due to a lack of published data about the economics and durability of complete processes using these methods. However, as new data are made publicly available, we may consider including one or more of these approaches in future analysis, as there are potential regional benefits for using some of these DAC types. Exclusion of particular DAC technologies from this analysis does not necessarily indicate they do not have promise but rather that publicly available data are lacking, making a rigorous analysis impossible.

Research and Development Needs

Several areas urgently need investment in DAC technology-development across the technology readiness level (TRL) scale:

- Lower TRL: Studies that examine the effect of ambient temperature and humidity on CO_2 throughput and material lifetime for all types of DAC processes
- Lower TRL: Bench-scale estimates of regeneration processes (kinetics and energy requirement) and methods of integrating regeneration with low-carbon energy; methods of reducing energy intensity of DAC regeneration
- Higher TRL: More rigorous published process-modeling and analysis of unit operation mass and energy flows[29] for all types of DAC processes and particularly for moisture swing and calcium-looping methods
- Land use impacts; regional environmental and socioeconomic impacts including Environmental Justice

BIOMASS CARBON REMOVAL AND STORAGE (BICRS)

BiCRS is a broad class of carbon removal pathways where biomass is processed so that its carbon, which originated from CO_2 in the air, can be sequestered, either geologically or through production of durable carbon products. BiCRS pathways can be tailored to produce electricity or liquid, gaseous, and hydrogen fuels and can therefore contribute to decarbonization (fossil fuel emission reductions) and CO_2 removal goals. In this report, we aim to provide an assessment of the scale, cost, regional considerations, and opportunities for BiCRS in the United States (in the context of other CDR pathways) to reach a 0.5 Gt CO_2/yr removal capacity by 2050. Because both BiCRS (as a method of CDR) and production of sustainable biofuels rely on the same biomass, concern arises that the two uses of biomass are mutually exclusive and at odds. Our preliminary analysis suggests that *BiCRS (using US biomass) can provide significant carbon removal toward the 0.5 Gt CO_2/yr goal* while *providing the needed sustainable fuels for decarbonization.*

Methodology

Our BiCRS carbon assessment is divided into two scenarios of biomass availability/potential and availability of emerging technologies and supporting infrastructure. We classify the two scenarios as "**current**" (based upon a 2025-time horizon), and "**mature**" (i.e., potential removal opportunities available through 2050). This distinction provides a useful context for understanding current opportunities and future potential, in terms of biomass availability, technology development, and the impacts of supporting infrastructure. We consider the potential availability of energy crops, such as perennial grasses, in our "mature/2050" biomass assessment. We will consider four bioenergy supply scenarios designed to protect current land/biomass carbon stocks and avoid leakage, while evaluating impacts of CRP and other land availability on bioenergy supply and cost. We have developed US BiCRS regions based on predominant feedstocks and will develop regional CO_2 supply curves to identify unique regional opportunities for BiCRS carbon-removal impact and co-benefits.

Early Insights

Our preliminary analysis suggests BiCRS has the capacity to fulfill the goal of 0.5 Gt CO_2/yr removal using multiple different conversion technologies for various bioproducts and carbon sequestration pathways. We considered bioproducts such as aviation fuel, hydrogen (H_2), methane (CH_4), gasoline, and diesel. We compared five different pathways, including two aviation-fuel production pathways: (1) fermentation to jet fuel (alcohol-to-jet) with carbon capture and storage (CCS), (2) gasification to Fischer-Tropsch (FT) fuel with CCS, (3) gasification to H_2 with CCS, (4) gasification to CH_4 with CCS, and (5) pyrolysis to gasoline/diesel fuel with biochar sequestration and CCS.

In **Table 2**, we provide an example portfolio of BiCRS technologies and products to achieve the 0.5 Gt CO_2/yr removal goal. In this example, we prioritize meeting 100% of the demand of the aviation fuel market with sustainable aviation fuel produced from cellulosic biomass fermentation (alcohol to jet) and gasification. We then fill the carbon-removal gap after sustainable aviation-fuel production with an arbitrary mix of three additional bioproduct production pathways. **Table 2** shows this combination of pathways to meet the 0.5 Gt CO_2/yr removal goal requires a total of 0.8 billion tons biomass, with a market saturation ratio ranging from 0.03-1.

This preliminary analysis demonstrates a brief example with limitations that we will address in future analysis: (1) we will consider how market demand will change with time—for example, current US domestic H_2 demand is reported as ~10 million t/yr but has been projected to be 2-4 times the current demand in 2050[30]; (2) we will include additional technologies and product pathways with consideration of the biomass suitability to different technologies; (3) we will use a model (BILT) to optimize biomass usage, CO_2 removal

potential, market saturation, and costs and to provide the optimal regional solution portfolios; and (4) we will provide an in-depth analysis of biomass availability/cost for different bioproduct pathways.

Table 2. *Our preliminary findings suggest BiCRS can provide 100% of current US sustainable aviation fuel supply while also contributing significantly to the 0.5 Gt CO_2/yr removal target for engineered solutions. In the example below, aviation fuel is produced through fermentation and gasification conversion pathways with carbon capture and storage (CCS). The remaining 0.5 Gt CO_2/yr of removal is achieved through an arbitrary mix of BiCRS technology pathways, including gasification and pyrolysis; this set of BiCRS pathways would require approximately 0.8 billion metric tons of biomass suitable for these pathways. The current market saturation column shows the ratio of product produced using the BiCRS pathway compared with the current market. GGE is an abbreviation for gasoline gallon equivalent.*

	CO_2 Removal Potential (Gt CO_2/yr)	Biomass Consumption (billion dry metric tons/yr)	Bioproduct Production	Current Market Demand	Product Unit	Current Market Saturation
PRIORITIZE AVIATION FUEL PRODUCTION						
Fermentation (alcohol) to jet fuel with CCS	0.05	0.23	12.6	25.2[2]	billion GGE/yr	0.5
Gasification to Fischer-Tropsch (FT; jet) fuel with CCS	0.1	0.18	12.6			0.5
Subtotal	*0.1*	*0.4*	*25.2*			*1.0*
FULFILL THE REMAINING CARBON REMOVAL GAP WITH MULTIPLE PATHWAYS						
Gasification to H_2 with CCS	0.2	0.11	0.01	0.01[1]	billion t/yr	1.0
Gasification to CH_4 with CCS	0.1	0.09	28.2	864.0[3]	billion m^3/yr	0.03
Pyrolysis to liquid fuel with char sequestration and CCS	0.1	0.19	16.2	175.3[4,5]	billion GGE/yr	0.1
Total	0.5	0.8				

2025 Spatial Distribution of Biomass/Point Sources and Biogenic Carbon Supply

For our 2025 scenario, we have identified locations of biogenic industrial emissions and overlayed them on the spatial distribution of BiCRS-relevant biomass density (from forestry, agricultural, and biogenic wastes) drawn from the Billion Ton Report[30] (**Figure 5A**). This map reveals significant BiCRS resources over a vast fraction of the 48 contiguous US states, with clustering of biogenic emissions according to regional population density and agriculture.

To estimate the maximum potential of the primary BiCRS carbon sources for our 2025 scenario (excluding purpose grown biomass for energy), we converted the carbon in the preliminary biomass feedstock supply to CO_2 equivalents (**Figure 5B**). We find that current fermentation, pulp and paper, and biogas emissions (which we term biogenic industrial emissions) are a major source of carbon that can be captured for negative emissions. We note that these biogenic industrial emissions represent an upper bound on CO_2 removal and do not represent a full LCA; therefore, *net* negative emissions will lower. We find that the total maximum "current" resource—CO_2 equivalents from all biomass and from current biogenic industrial emissions—totals more than 0.5 Gt, strongly indicating that the current US waste-biomass supply has the potential for significant impact on the 0.5 Gt CO_2/yr engineered carbon removal goal. We emphasize that

this is a maximum potential, and a sizable fraction of carbon in some biomass sources (e.g., manure) and via some conversion pathways (e.g., to produce liquid fuels) will not be recovered.

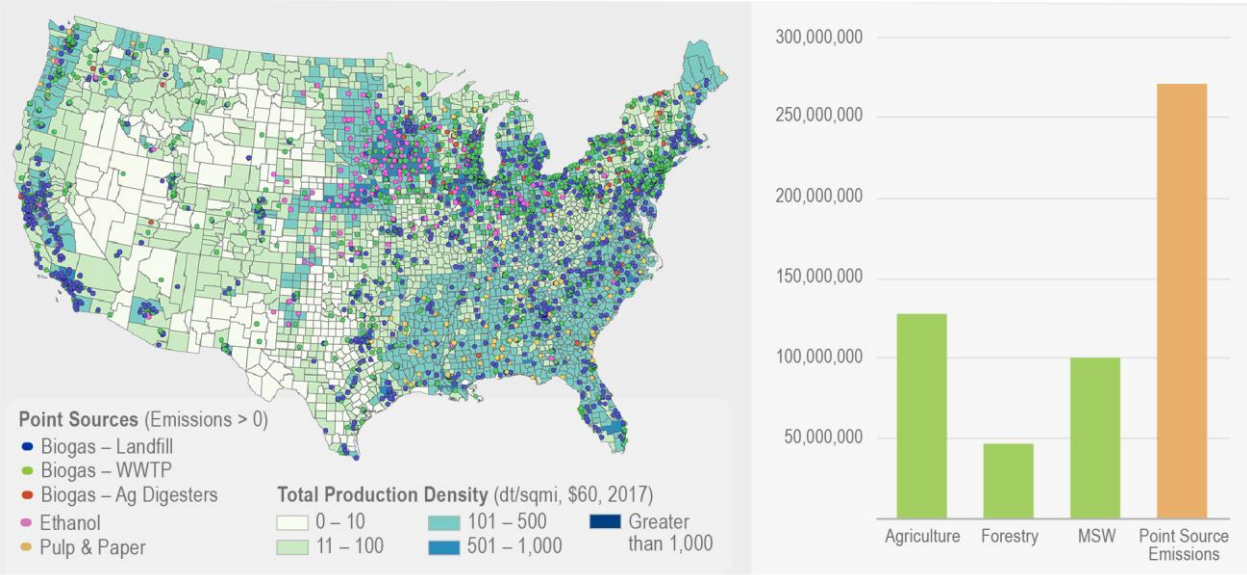

Figure 5. *(A) (Left) Spatial distribution of BiCRS-relevant near-term biomass resources (relevant to 2025 scenario) from forestry (logging residues and forest management), agricultural residues (e.g. corn stover), and wastes (e.g. municipal solid wastes and food processing wastes), in addition to biogenic CO_2 point sources. Data drawn from the Billion Ton Report.* **(B)** *(Right) Preliminary scale of biomass and biogenic point source CO_2 equivalents for 2025 BiCRS scenario (excluding pending data from pacific northwest forest restoration biomass). The total CO_2 resource (when biomass carbon is converted to CO_2 equivalents and added to biogenic point source emissions) is greater than 0.5 Gt.*

Analysis Boundaries

Given the broad scope of BiCRS and time urgency, we have defined a set of technological, cost, and impact boundaries for inclusion in our analysis. First, we will quantitatively assess only pathways that have sizeable impacts: >1% of the 1 Gt CO_2/yr removal goal (10 million t CO_2/yr removal capacity). In some instances, a specific feedstock may not meet these constraints but can be combined with other co-located feedstocks and a suitable technology to reach this threshold. We will not perform original technoeconomic analysis (TEA) of BiCRS-relevant technologies for our quantitative analysis of cost and carbon/energy balances. Therefore, we will rely on technologies for which literature data are available from pilot studies (typically TRL 7 or higher). We will also exclude biomass-technology pathways for the 2025 scenario that we project to cost significantly more than most estimates of DAC costs today (approximate >$500/t CO_2). A major benefit to BiCRS is its potential for intermediate cost *and* durable CO_2 removal; therefore, we will only include pathways in which CO_2 durability is projected to be greater than 80% carbon retained over 100 years. In some cases (e.g., biochar), durability may be dependent on specific conditions. In all our analyses, we will endeavor to state our assumptions but will not explicitly analyze BiCRS pathway carbon removal durability. BiCRS-relevant biomass is incredibly heterogeneous in its physical forms, spatial distribution, and composition, as well as in its temporal variability. Outside of assuming certain biomass storage costs and decomposition rates, we will not model economic impacts of biomass seasonality. Similarly, given the wide range of potential products available from BiCRS, we will not analyze product distribution costs or logistics (*past the plant gate*). Finally, our analysis is squarely focused on understanding the most impactful and lowest cost BiCRS pathways in the United States as a critical contributor to removing 0.5 Gt CO_2/yr by 2050. We will not explicitly analyze biomass supply and conversion technologies in the context of decarbonization goals or the impacts of optimized BiCRS pathways on rates of decarbonization or the tradeoffs between

the two. We will report quantities of energy/fuel produced through BiCRS pathways and relate to current and projected fuel needs, showing the impacts of BiCRS pathways on decarbonization.

Research and Development Needs

Priority research needs can be grouped according to three primary themes:

5. Process modeling and technology development are needed to address BiCRS technological implementation gaps. These include: adapting thermochemical processes (e.g., gasification with CCS) to (variable) biomass feedstocks, understanding scaleup and deployment bottlenecks and barriers of BiCRS technologies, and scaling and process integration of CO_2 capture technologies specifically for BiCRS.
6. Empirical data are needed to guide land-use decision toward maximized carbon benefit (standing carbon stocks, soil carbon) in BiCRS-relevant bioenergy crop production and land selection for biochar application.
7. Data and analyses are needed to address uncertainties around BiCRS feedstock costs, including costs incurred during collection, storage, and due to degradation. We note that economic and sustainability costs of providing municipal solid wastes for BiCRS are particularly uncertain.

GEOLOGIC STORAGE

Geologic storage is the key secondary step for both DAC and BiCRS. While the highly prospective subsurface areas are relatively well studied and understood, establishing the existence or lack of viable storage in parts of the country with sparse data will require additional characterization efforts.

Early Insights

Suitable geologic storage is available in many parts of the country where biomass methods can be used for removal, and storage capacity is much greater than any potential demand. While many highly prospective areas are already relatively well studied and understood, establishing the existence or lack thereof of viable storage in parts of the country with sparse data will require additional characterization efforts. For the areas of the country where viable storage is not available locally, CO_2 transportation to viable areas is generally possible. Concerted development, mainstreaming, and standardization of monitoring and characterization technologies will assist in the broad deployment of geologic storage in the United States.

Methodology

Storage of supercritical phase fluid CO_2 may need to be deployed in areas where capture and geologic storage from existing point sources has not been previously considered and, as such, the suitability of the subsurface for storage is not well understood. We are re-evaluating storage feasibility in conventional deep saline formations (DSF) using a series of recently updated national databases. We have produced a new map (**Figure 6**) that screens out those parts of the subsurface where these five criteria are not met and that shows the distribution of rock volumes that are prospective for further evaluation. In our future work, we will combine, rectify, and document available, previously complied data from multiple storage databases. We will produce a county-level quantitative assessment covering the continental United States, Alaska, and Hawai'i. We will highlight regions of the United States where subsurface DSF storage criteria are not met and will illustrate the distribution of rock volumes that are prospective for further evaluation. After combining our new analysis with previously complied data, we will further annotate where storage potential is high (prospective DSF are both thick and permeable) and moderate (prospective DSF are thinner and/or less permeable).

In the future, we will combine our initial results with location-specific data and will (1) remove inconsistencies and fill data gaps, (2) conserve complete data, (3) formally score uncertainty in each data coverage, (4) generate storage supply curves at the county scale, and (5) provide data in downloadable ARC files with metadata.

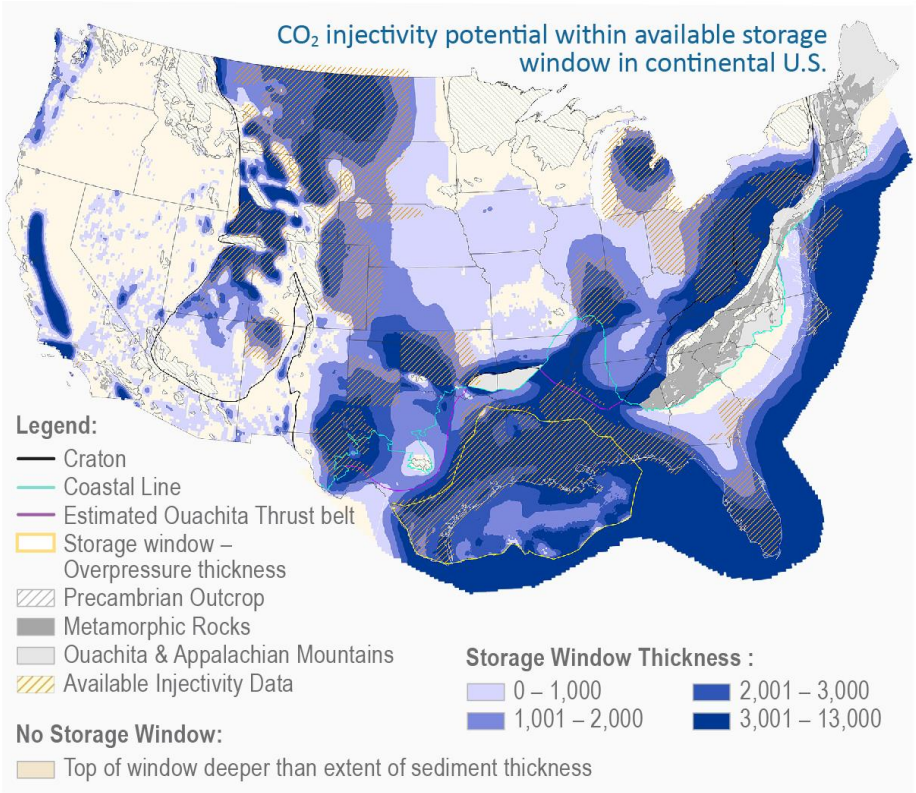

Figure 6. *Geologic storage window thickness map derived from sedimentary thickness, digital elevation model (DEM), and depth-to-groundwater data as a raster file.*

Analysis Boundaries

Our assessment focuses only on well-established sedimentary-rock geologic storage and will not include more experimental techniques, such as storage in basalts or coal seams, as these are not yet mature enough for broad deployment. The geographic boundaries of the assessment include the lower 48 states, Alaska, and Hawai'i.

Research and Development Needs

Based on our preliminary analyses, we have identified the following key research needs to improve our understanding of available geologic storage potential:

- For establishing geologic storage resource viability with more confidence:
  - *Improve quantification of storage resource in areas where availability may be a limiting step*
  - *Define rate limiting steps such as pressure interference in sedimentary formations*
  - *Increase storage resource distribution and availability throughout the Nation by increasing confidence and developing a permitting process for storage in mafic rocks, such as basalt*
- For increasing confidence in geologic storage permanence:
  - *Demonstrate the viability of a variety of methods for managing unacceptable induced seismicity*
  - *Further characterize leakage-risk associated with existing wellbores and strategies to mitigate that risk*
  - *Develop reliable and inexpensive leakage monitoring methods that are readily deployable in a multitude of settings*

ENVIRONMENTAL JUSTICE

Every method of CDR we will analyze has the potential to benefit communities with environmental justice concerns, if intentionality and community involvement are combined. As such, environmental justice (EJ) "the fair treatment and meaningful involvement of all people regardless of race, color, national origin, or income, with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies"[31] is a critical aspect of our analysis. All citizens of the United States have a right toprotection from environmental and health hazards. However, there are inequalities between the demographics of citizens living in polluted conditions and those living in non-polluted conditions, as well as those forecasted to be disproportionately exposed to climate change–related risks.[31] The nationwide implementation and deployment of CDR methods must be conducted in a just manner, and where possible, rectify historical environmental injustices.

Early insights

Environmental justice will be a major constraint on the large-scale endeavor to achieve 1Gt CO_2/yr removal because this effort touches so much of our land, people, and economy. The large number of available CDR options makes it more possible to find individualized solutions that profit the environment, jobs, and communities of our Nation.

EJ analyses will investigate the intersection of environmental (e.g., air and water quality), community (e.g., land use and traffic), demographic, and socioeconomic (e.g., job opportunities in fossil fuel-dependent counties) variables associated with CDR to highlight regions of interest for each method. As an example, we analyzed CDR methods that could reduce nitrate pollution in the groundwater of our nation's poorer communities. Our results point to benefits of two complementary strategies: cover cropping and BiCRS. In a national assessment of corn-soy rotational cropland (**Figure 3**), poverty rates and groundwater nitrate concentrations were assessed in the top 50% of corn-soy farming counties, where the greatest soil carbon sequestration potential exists due to land area. High (>11.4% of the national average) poverty rates and nitrate concentrations above the Environmental Protection Agency (EPA) drinking water standard (10 mg/L) overlap near the western Kansas-Oklahoma border, central Illinois, eastern Kentucky-Tennessee border, and eastern North Carolina (**Figures 7 and A14**). Since one potential EJ risk in cover cropping is the further concentration of wealth in the hands of white farm owners, it is important to also assess where farms are operated by non-white citizens (**Figure 7**). Through this lens, it is clear that if a stakeholder aims to improve cover-cropping implementation to reduce nitrate loading in the groundwaters of poorer communities by investing in black-operated farms, eastern North Carolina would a place to focus initial efforts.

BiCRS, in contrast, may be slower to initiate than cover cropping, due to industrial and infrastructural needs. However, it stands to potentially remedy nitrate pollution in the Nation's most contaminated aquifer: the California central valley, which poverty rates are double the national average (**Figures A13 and A14**). Concentrated animal feeding operation (CAFO) manure lagoons are strongly associated with nitrate pollution in the Central Valley.[32] BiCRS could divert this manure from polluting lagoons to an anaerobic digester, and produce biogas for liquid fuels and carbon storage. Via this BiCRS process, methane and nitrous oxide emissions from lagoons would also be avoided, yielding a secondary climate benefit. In our national assessment of black-operated farms (**Figure 7**), 2-4% of farms in this region are black-owned, thereby offering opportunities to encourage investment in diversity among farmers. In our final version of this analysis, we intend to expand the dataset to include other ethnicities of farm operatorship as well (e.g., Hispanic and Asian Americans).

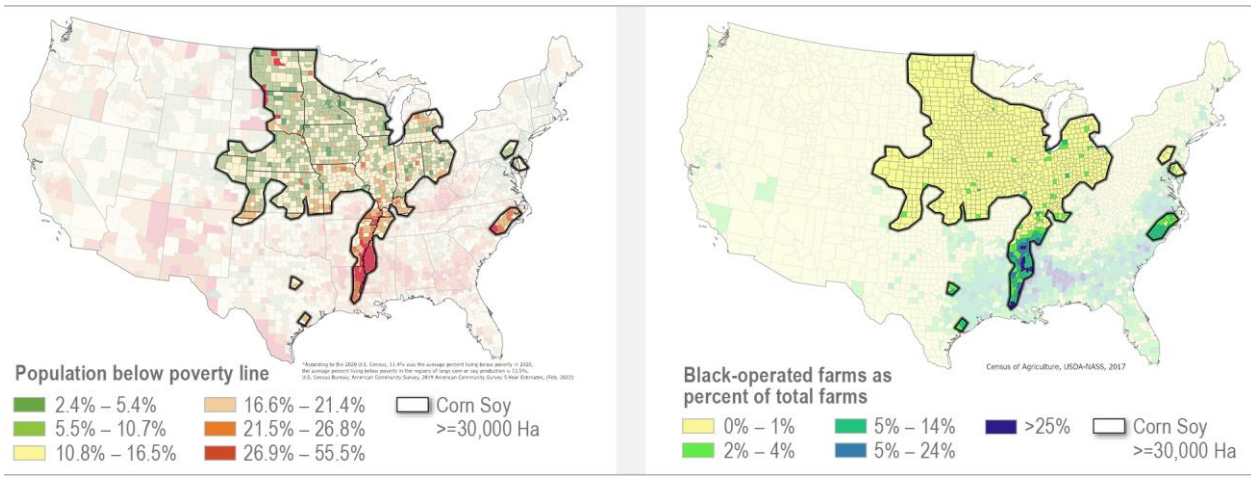

Figure 7. (Left) *Overlay of US population below the poverty rate from the 2020 US Census within the top 50% of corn-soy rotational farming lands. (Right) Black-operated farms as a percent of total farms, organized by county, within the top 50% of corn-soy rotational farming lands. We will evaluate the potential for each CDR pathway to make a positive environmental impact and use demographic data to highlight regions where socioeconomic risks are minimized and*

Methodology

To assess the potential for EJ co-benefits and potential risks, we are undertaking an interdisciplinary analysis of cultural, historical, environmental, socioeconomic, and demographic data to outline next best steps for CDR in the 'Just Transition.' Our goal is to outline where CDR can be used as a tool for correcting environmental injustices, emphasize where it may risk exacerbating inequities, and highlight regions that may benefit the most individuals. Our EJ analysis methodology has four parts: (1) recognition of indigenous practices, (2) identification of current environmental injustices relevant to CDR, (3) a tradeoff analysis of potential benefits and risks that CDR may represent to communities with EJ concerns (Table A4 in the Appendix), and (4) a summary of best practices for implementation of 1-2 CDR methods that overlap with each technical chapter of the report (particularly indigenous forest management, afforestation, urban forestry, cover cropping, BiCRS and DAC facilities, and geologic carbon storage (Table A4 in the Appendix)).

Analysis boundaries

The list of variables and scenarios connecting CDR to EJ is vast, and we have necessarily established a series of "in-scope" and "out-of-scope" boundaries. For example, if job-creation estimates existed for each CDR method, then a cursory jobs estimate might be feasible. However, many CDR technologies and strategies have not been deployed widely enough to make reliable estimates and, therefore, job creation/loss estimate will only be discussed qualitatively. However, we will add regional overlays of projected fossil fuel job loss[33] and BiCRS/DAC/geologic carbon storage opportunities for a regional perspective. Age-related demographics are prone to more rapid changes than other social dimensions that we will address (e.g., race, unemployment, poverty rates), and we have opted not to include them. Water resources are difficult to quantify, particularly for highly novel CDR technologies, and will only be discussed qualitatively. Currently, we do not intend to discuss EJ concerns regarding pipeline placement unless this topic becomes focal for other technical chapters of our report. Due to slow development/repurposing timelines for Superfund sites relative to the speed with which CDR needs to be deployed, we will not be assessing Superfund site development opportunities, although we recognize this may help alleviate CDR land-scarcity pressures. Lastly, this report solely aims to present data and analyses for stakeholders, including those who have the expertise to use the information to enact effective policies or legislative actions. Our report will not recommend specific policies or strategies for the democratization or just implementation of CDR.

APPENDIX 1: METHODOLOGY

SUMMARY

In our national carbon dioxide removal (CDR) analysis, we will provide a supply curve based on a multi-pathway county-level assessment of the scale, cost, regional considerations, and opportunities for CDR in the US with the national goal of reaching at least 1 Gt CO_2/yr removal capacity by 2050. The CDR strategies we will evaluate include 'Engineered Solutions' (Biomass Conversion with Carbon Storage (BiCRS), Direct Air Capture (DAC)) and 'Ecological Solutions' (Soil Sequestration, Forest Sequestration). Long-lived carbon products will also be considered as a separate means of permanent storage. Our analysis of Environmental Justice (EJ) facets and cross-cutting interactions integrate across all the CDR strategies. We will evaluate each strategy for negative emissions at the county level wherever feasible, with an emphasis on current cost and performance, R&D pathways to future cost and performance, and the volume of CDR possible.

Each of these removal strategies has intrinsic limits on the amount of CO_2 removal. For instance, biomass methods are limited by the amount of material available without impacting other important activities such as providing food or feedstocks for necessary biofuels. One approach is to assume a price for a feedstock and then use equilibrium models to calculate how much will be available at that price. However, this can predict too little feedstock at a low price (and failure to reach the removal goal), or too much use and feedstock switching at high prices. Both must be avoided to generate a supply curve that represents the true CDR capacity of the Nation. Feedstocks, storage and transportation are key CDR limits for all pathways.

In our approach, we will first identify the limiting item, e.g., biomass supply, available agricultural land, waste materials, managed forests, geologic storage availability, land availability for DAC and renewable energy required to power it, impacts on disadvantaged communities and populations, and the intrinsic costs of transporting either raw material or CO_2 for storage. Source material for these limits will be collected from existing databases or modeled based on county-level information and will be collected as uniformly as possible. EJ assessments will take advantage of existing DOE, EPA, state, and tribal resources and will merge empirical technical maps for CDR with demographic and environmental quality data.

With limits identified and quantified at a county level, we will next calculate the best use of the limited resources to remove CO_2 without other negative impacts. Two key negative impacts would be assuming too much biomass usage to permit production of needed jet fuel or using renewable electricity for DAC without considering the needs of a fully decarbonized grid. We will construct the primary supply curve, at a county level, by choosing the lowest cost for carbon removal per ton using the available resource. Alternate supply curves can be constructed for other desired scenario analysis, such as increased biofuel supply or assumed ease of CO_2 pipeline construction.

Thus, our top-level methodology is as follows:

8. Identify the key limits for each of the considered CDR approaches
9. Quantify those limits to the degree possible
10. Distribute the limited resources to CDR approaches with costs that can reasonably be estimated at large scale
11. Estimate the costs of those approaches at the most efficient scale available within transportation cost limits
12. Consider the cross-cutting limits (such as not using land for two incompatible uses)
13. Sum all the CDR processes based on increasing cost and capacity (note that some resources may appear in approaches with different costs if their use is limited by a cross-cutting factor, such as the availability of permanent storage)

Below, we provide detailed descriptions of our methodology for each topic area.

I. GEOLOGIC STORAGE

TEAM: Susan Hovorka, George Peridas, Briana Schmidt, Alex Bump, Ramon Gil Egui, Edna Rodriguez Calzado

Introduction and Analysis Scope

Storage of **dense (supercritical) phase** CO_2 may need to be deployed in areas where capture and geologic storage from existing point sources has not been previously considered and, as such, the suitability of the subsurface for storage is not well understood. To enable this prospect, we are re-evaluating conventional deep saline formation (DSF) storage feasibility using a series of recently updated national databases (detailed below). The quantitative assessment we will produce will be at scales more granular than the county level and will cover the continental United States, plus Alaska and Hawai'i. Our assessment will focus on well-established sedimentary-rock geologic storage and will not include more experimental techniques, such as storage in basalts or coal seams, since these are not yet mature enough for broad deployment.

Methods

Storage Criteria

Large-volume DSF storage requires the following criteria to be met in order to be permittable and feasible:

14. Layered sedimentary rocks (both injection and confining zones)
15. A depth of at least 750 m below the top of the saturated zone so that the CO_2 will be stored as efficient dense phases (supercritical or, in a few cases, liquid)
16. A depth below regulatorily protected (defined as >10,000 ppm total dissolved solids or "TDS") underground sources of drinking water (USDWs)
17. Depth in the normally pressured section above the top of overpressure
18. Above low permeability rocks at depth (defined as crystalline basement, low- to high-grade metamorphic rocks, or deeply buried (>4 km) sediments in which porosity has been lost by compaction)

We have produced a new map that screens out those parts of the subsurface where these five criteria are not met and that shows the distribution of rock volumes that are prospective for further evaluation. In our future work, we will combine, rectify, and document available previously-complied data from the DOE-National Energy Technology Laboratory (NETL)-funded University of Texas Bureau of Economic Geology brine database (https://www.beg.utexas.edu/gccc/research/brine-main[34, 35]), the US Geological Survey CO_2 storage assessment units inventory (https://pubs.usgs.gov/ds/774/[36]), and the National Carbon Sequestration (NATCARB) database (https://www.netl.doe.gov/coal/carbon-storage/strategic-program-support/natcarb-atlas[37]), which overlay and add detail to the feasibility database. These data will be used to further annotate where storage potential is high (prospective DSF are both thick and permeable) and moderate (prospective DSF are thinner or less permeable). Future work to be completed in the coming months includes making underlying data on DSF consistent and comparable, filling gaps, and expressing uncertainties and the state-of-knowledge.

We will use a DOE NETL-funded dynamic capacity estimator, Enhanced Analytical Simulation Tool (EASiTool) V4.0 (https://www.beg.utexas.edu/gccc/research/easitool).[38, 39] EASiTool produces a fast, reliable estimate of dynamic (rate-based) storage capacity for any geological formation. The closed-form analytical solutions behind the EASiTool are cutting-edge models that incorporate effects of rock geomechanics, evaporation

of brine near the wellbore, and deployment of brine extraction in the field to enhance storage capacity. A net present value (NPV)-based analysis has been implemented to devise the best field development strategy to maximize the stakeholder's profit by optimizing the number of injection/extraction wells.

Mapping Storage-Window Thickness

For the first stage of this project—generating a storage-window thickness map—we have used a top-down analysis to locate sedimentary rocks within the "storage window" (**Figure A1**). Previous approaches (such as the NETL NatCarb atlas, the BEG brine Database, and USGS storage assessment units) have used a bottom-up approach. However, the bottom-up approach has limits in that 1) it does not include all the storage potential (only selected storage units), 2) various study-area and state-line boundaries and other artifacts are prominent, and 3) data density and content is uneven.

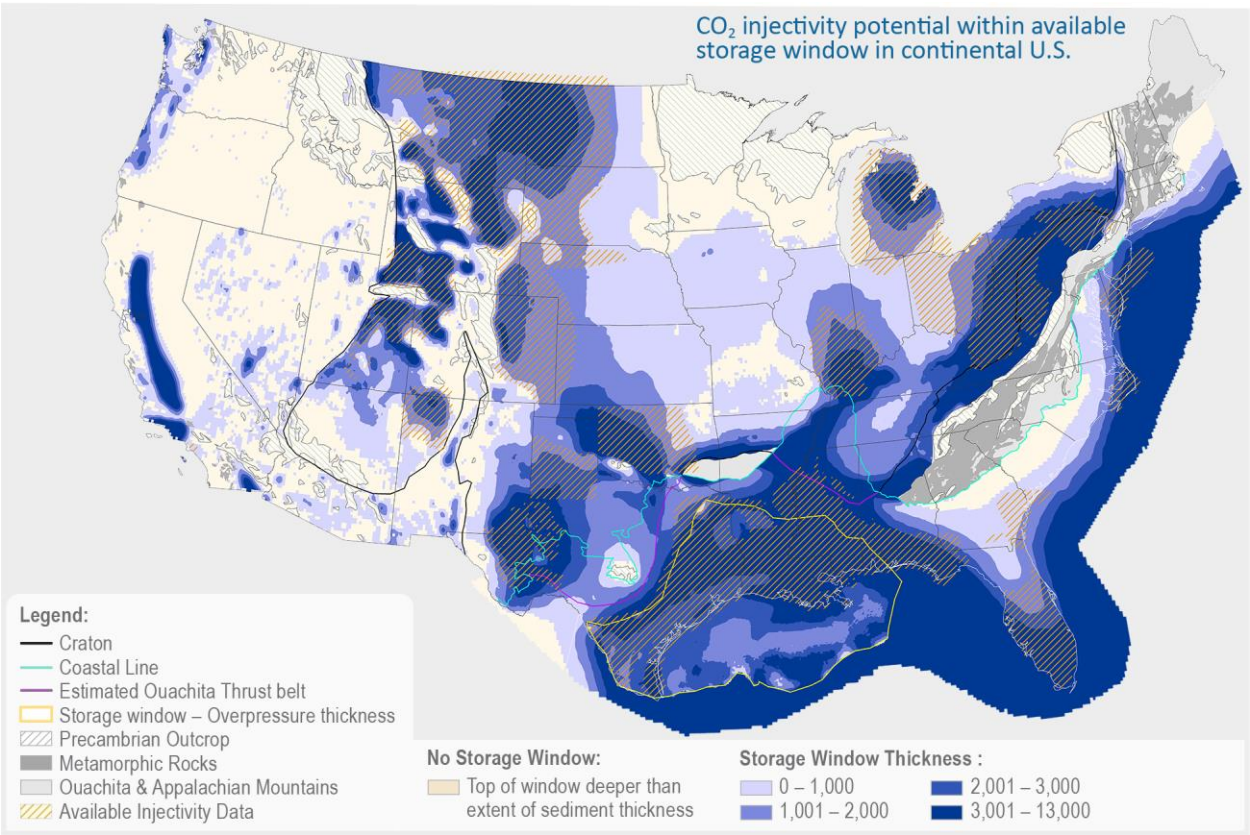

Figure A1. *Storage- window thickness map derived from sedimentary thickness, digital elevation model (DEM), and depth-to-groundwater data as a raster file.*

For our study's CO_2 capture applications (primarily BiCRS and DAC), we assume that local injection of small volumes may be of overall higher value than storage that can accept large volumes at high rates but is distant from optimum capture location. We therefore produced a broadest "feasibility" map.

In our future work, we will add the bottom-up data collected by previous storage-resources estimation efforts. We plan to rank these somewhat de-risked "storage fairways" into three or more categories based on what is known about the rate at which CO_2 can be injected on a per-well basis.

In the future we will 1) remove inconsistencies and fill data gaps, 2) conserve complete data, 3) formally score uncertainty in each data coverage, 4) generate storage supply curves at > county scale, and 5) provide data in downloadable ARC files with metadata.

To create the storage-window thickness map (**Figure A1**), we used the following data sources:

19. US-wide sediment thickness map: A compilation of data from three sources [40-42] delineating different regions in the US (Western US, Middle US, Eastern Coast US) were used and modified to create a sediment-thickness map. To merge all three sources, contour lines were created from each data source and then rasterized with ArcGIS's topo-to-raster interpolation tool. The Western US sediment thickness map covers the western coastal states and continues east to the Precambrian basement craton edge.[40] The Middle US database by Shah et al. 2018[41] provides depth to the top of the Precambrian basement, so a US-wide digital elevation model (DEM) dataset[43] was used to create a sediment-thickness map. For the US East Coast, contour lines were edited to avoid overlap with data from the Middle US. The Western US thickness map covers sediment thickness up to the top of the Mesozoic basement.
20. Depth to the top of groundwater [44]
21. US Land digital elevation model (DEM) data [43]
22. Depth to the top of overpressure [45]
23. Bathymetry DEM data [46]

To delineate the top of the storage window, we removed depths too shallow to maintain CO_2 in a supercritical state. We accomplished this removal by taking the depth-to-top of groundwater raster data[44] and adding 750 m in depth to the raster data. Then, we subtracted depth-to-top of the storage window from DEM data to create a surface-to-top-of-storage-window thickness dataset. Finally, having created this thickness dataset, we can subtract it from the US-wide sediment thickness data[40-42] to create a US-wide storage-window thickness map. The bottom of the storage window is set at the top of the Precambrian or Mesozoic basement rocks for most of the US, except for the Gulf of Mexico, where we utilized depth-to-overpressure data (0.70 psi/ft).[45] To obtain overpressure thickness, we subtracted the depth-to-overpressure data from land and bathymetry DEM data[43, 46] to cover both onshore and offshore overpressure data. To improve the extent of storage window thickness, we will identify additional shallow over-pressured areas and remove any fresh water areas (up to 10K ppm) that are over 750 m in depth.

II. DIRECT AIR CAPTURE (DAC)

TEAM: Simon Pang, Nathan Ellebracht, Elwin Hunter Sellars, Peter Psarras, Hélène Pilorgé

Introduction and Analysis Scope

Direct Air Capture (DAC) removes CO_2 from ambient atmospheric air, so it theoretically can be built anywhere. This flexibility means that DAC facilities can be sited as close as possible to suitable geologic sequestration sites or other end uses of CO_2. However, DAC is energy-intensive and energy availability is an important consideration for deployment. Buildout of new low-carbon energy will be prioritized for electrical grid decarbonization to meet the Biden administration's goal of 100% clean electricity by 2035, requiring that energy for DAC developments be provided by additional dedicated renewable energy facilities. Our analysis will attempt to identify locations around the Nation that are likely to be best for deploying DAC, quantify the feasible amounts and costs, and describe the infrastructure needs that will accompany such deployment.

Methods

Our approach to understanding the best locations for DAC considers currently available DAC technologies, nominally liquid solvent and solid sorbent approaches (Figure A2). Considering that supply of future low-carbon energy is likely to be dominated by renewable electricity, we will evaluate the cost, energy use, and land-area requirements for complete electrification of these two DAC processes for comparison with their fossil-driven counterparts. To perform these analyses, we will draw upon published literature for the solvent and sorbent processes and prepare cost evaluations of building and operating DAC facilities from established methodologies, including capital equipment, operating, and energy costs.

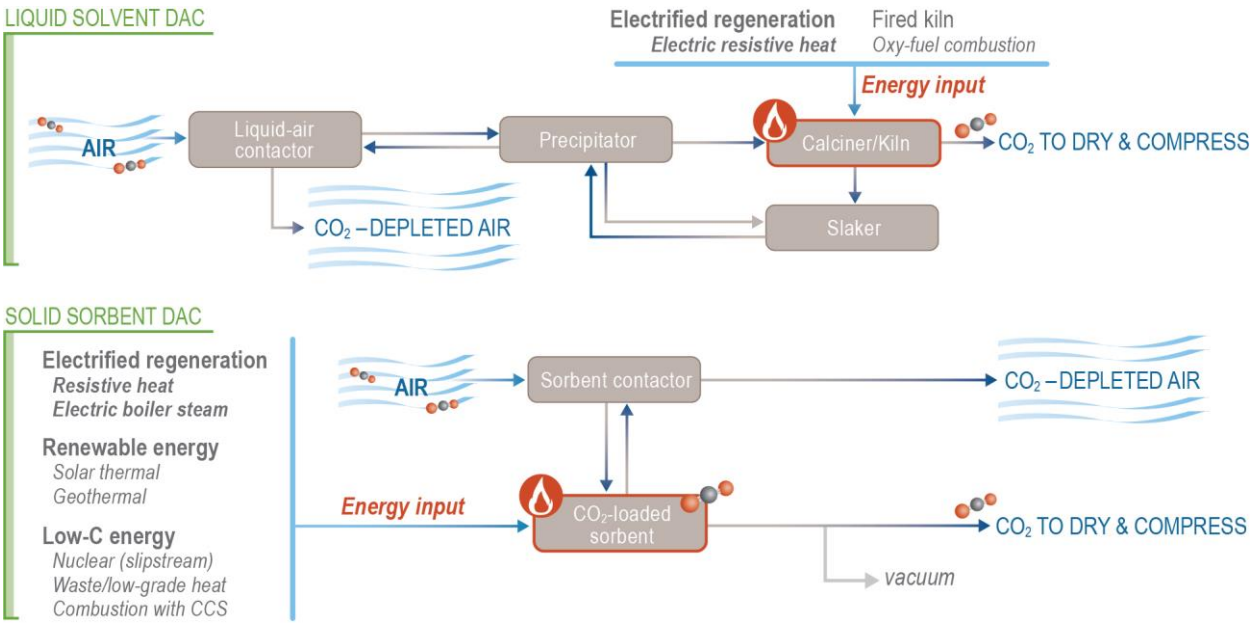

Figure A2. *Process schematics of liquid solvent and solid sorbent DAC integrated with low-carbon energy sources.*

Our work here will build upon prior analysis performed as part of a report on achieving carbon neutrality in the state of California[47] and on published literature examining pairing DAC with low-carbon thermal energy in the United States.[48] From a cost-analysis perspective, the work here is distinguished from prior

analyses in that it will consider dedicated build-out of low-carbon renewable electricity in conjunction with DAC buildout, first accounting for prioritization of renewable electricity for grid decarbonization, rather than being limited to waste heat from geothermal and nuclear sources. This approach potentially allows more regions of the country, which may not have access to geothermal or nuclear energy but may have solar and wind resources, to participate in DAC deployment. This approach also necessitates developing process and cost models for electrically driven DAC processes.

Near-term scenarios will use existing low-carbon electricity or renewable thermal sources and smaller DAC facilities at the 10-100 kt CO_2/yr-scale, whereas in long-term scenarios we will assume construction of dedicated low-carbon electricity and/or thermal power to power larger DAC facilities at the 100-1000 kt CO_2/yr-scale. We will draw costs for construction of energy facilities from the literature, whereas we will adapt costs for the DAC facilities from published literature using standard scaling relationships to account for the differences in facility size. We will consider technology-learning scenarios for low TRL components, including sorbents and modular and unique equipment that do not have scaled production costs.

We will identify resources for estimating the cost of renewable energy generation as a function of total generation capacity. We will prioritize clean electricity first for decarbonization of the electrical grid and other sectors of the economy. This could mean that the "best" locations for producing solar and wind electricity may be unavailable for powering DAC. We may also need to make considerations for long-distance electrical transmission in the event that additional clean electricity production sites are not located near suitable sequestration sites. Therefore, we expect that clean electricity specifically for DAC will come with an additional cost—we will factor this into our location-based cost estimates. We will use established models, such as the Renewable Energy Potential (reV) Model from NREL, to assess the geographic technical potential for future solar and wind generation.[49]

To identify the best locations for deploying DAC, we use a mapping approach, looking at the intersection of suitable sequestration, available land for both the DAC facility and the renewable energy and/or other low-carbon energy facilities, CO_2 transportation networks, and the local average temperature and humidity. We also consider urban and protected regions, such as tribal lands or wilderness areas, to avoid disturbing local wildlife or communities. Potential co-benefits and risks for environmental/social justice and inclusion will be evaluated in collaboration with the EJ team.

DAC Scenarios

We will consider two scenarios: near-term deployment of DAC in 2025 and long-term deployment of DAC in 2050. The 2025 scenario considers early deployments, in the range of 10-100 kt CO_2/yr per facility, the best initial locations based on regional characteristics, and methods for using these initial deployments to help accelerate technology development and quickly reduce cost. We will consider the impact of the carbon intensity of the local electrical grid on the net carbon removed by the DAC process and the impact on net removal cost. The goal for the 2050 scenario is to develop a supply curve for DAC deployment in the United States, within the bounds of other decarbonization goals, land-area usage, and energy supply. The long-term scenario may also include cases where DAC is paired with low-carbon renewable natural gas (RNG) or hydrogen for providing thermal or electrical energy, as there may be cases to reduce the overall system cost using novel system integration.

Currently we do not plan to deeply evaluate DAC processes differentiated by different methods (moisture swing, electro swing, pH swing, or calcium-looping), due to a combined lack of demonstration facility or published data about the economics and durability of complete processes using these methods. However, as new data are made publicly available, we may consider including one or more of these approaches in future analysis, as there are potential regional benefits for using some of these types of DAC. Exclusion of

particular DAC technologies from this analysis does not necessarily indicate that it does not have promise but rather that a lack of publicly available data makes a rigorous analysis impossible.

DAC Costing Data Sources

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- Lackner, K. S. & Azarabadi, H. Buying down the Cost of Direct Air Capture. *Ind. Eng. Chem. Res.* **60**, 8196–8208 (2021).
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- Sabatino, F. *et al.* A comparative energy and costs assessment and optimization for direct air capture technologies. *Joule* **5**, 2047–2076 (2021).
- Sadiq, M. M. *et al.* A Pilot-Scale Demonstration of Mobile Direct Air Capture Using Metal-Organic Frameworks. *Advanced Sustainable Systems* **4**, 2000101 (2020).
- *Capital Cost and Performance Characteristic Estimates for Utility Scale Electric Power Generating Technologies*. US Energy Information Administration. https://www.eia.gov/analysis/studies/powerplants/capitalcost/pdf/capital_cost_AEO2020.pdf (2020).
- *Cost and Performance Characteristics of New Generating Technologies, Annual Energy Outlook 2022*. US Energy Information Administration. https://www.eia.gov/outlooks/aeo/assumptions/pdf/table_8.2.pdf (2022).

Renewable Electricity Availability and Cost Data Sources

- NREL reV: The Renewable Energy Potential Model. https://www.nrel.gov/gis/renewable-energy-potential.html
- NREL Annual Technology Baseline: Electricity. https://atb.nrel.gov/electricity/2021/index
- US Energy Information Administration: Renewable & Alternative Fuels. https://www.eia.gov/renewable/

Mapping Data Sources and Methodology

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- Land usage: Multi-Resolution Land Characteristics Consortium (MRLC), "National Land Cover Database (NLCD) 2019" [Online]. Available: https://www.mrlc.gov/data/nlcd-land-cover-conus-all-years. [Accessed: 20-Dec-2021]
- Land classes: Cress et al., "Terrestrial Ecosystems—Land Surface Forms of the Conterminous United States: US Geological Survey Scientific Investigations Map (2009)". Available: https://pubs.usgs.gov/sim/3085/ [Accessed: 18-Feb-2022]
- Saline aquifer: National Energy Technology Laboratory (NETL), "CO_2 Storage Formations" in "NETL Carbon Storage Atlas, 5th Edition", Available: https://www.netl.doe.gov/coal/carbon-storage/strategic-program-support/natcarb-atlas, [Accessed: 12-Jan-2022]
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- Existing geothermal power plants: National Renewable Energy Laboratory (NREL), "NREL Geothermal Prospector." [Online]. Available: https://maps.nrel.gov/geothermal-prospector/. [Accessed: 30-Dec-2021]
- All mapping will be carried out using open-source software 'QGIS', (https://qgis.org/en/site/index.html)

24. Designation of 'high injectivity regions' for land usage/ land classes:
    Using a vector layer of 'Injectivity' (Mtonne/yr well) digitized from images in Baik et al.[50] the regions with injectivities ≥ 1 were selected as 'Mask layers'. The land-usage/land-class raster layers were then cut to these mask layers. A similar process was carried out for the Alaska database, using the on-shore saline aquifer regions as a mask layer. This assumes the DAC facilities will be located directly on these sequestration regions. Changes to the mask layer can be made at a later date to 'expand' the available region (e.g., to within 50 miles of sequestration regions).
25. Calculation of 'Potential DAC' using waste heat from geothermal/nuclear sources: These calculations are based on the work by McQueen et al.[48] who use approximations for the hot fluid flow (i.e., steam for nuclear, geothermal fluid for geothermal) and fluid temperature to calculate the amount of heat that can be supplied to the solid sorbent DAC process to meet thermal energy requirements. This assumes: relatively low (~100 °C) temperatures for regeneration of the sorbent. The primary assumptions for these calculations are as follows:
    - An energy requirement of 1600 kWh per ton of CO_2 captured
    - 85% energy efficiency
    - 330 operating days per year
    - An 'inlet' fluid temperature of 275 °C and 100 °C for nuclear and geothermal, respectively, and an 'outlet' fluid temperature of 186 °C and 70 °C for nuclear and geothermal, respectively

26. Environmental justice/protected areas: The Protected Areas Database was used to add vector files for 'protected' regions across the United States. These regions were grouped by governing body, and no further analysis has been completed at this time.

III. BIOMASS CARBON REMOVAL AND STORAGE (BICRS)

TEAM: Chad Hellwinckel, Corinne Scown, Daniel Sanchez, Dermot Hayes, Andrew Wong, Ethan Woods, Hanna Breunig, Hannah Goldstein, Jerome Dumortier, Joe Sagues, Mark Mba-Wright, Matthew Langholtz, Phil Robertson, Sarah Baker, Wenqin Li, Whitney Kirkendall

Introduction and Analysis Scope

Biomass with carbon removal and storage (BiCRS) is a class of carbon removal pathways where biomass is processed so that its carbon, which originated from CO_2 in the air, can be sequestered, either geologically or through production of durable carbon products like biochar. BiCRS pathways can be tailored to produce electricity or liquid, gaseous, and hydrogen fuels and can therefore contribute to decarbonization (fossil-fuel emission reductions) *and* meet CDR goals. Because of the large diversity of geography, local climate, population density, prevailing industry, agriculture, and geologic storage resources in the United States, our assessment of BiCRS opportunities will be tailored to US regions that we define to have distinct BiCRS opportunities and impacts. For example, our assessment of the scale of opportunity will include regional supply curves for biomass and CO_2 (resolved at the county level), as well as understanding other impacts such as air quality, avoided landfill disposal, creation of new carbon-negative biofuels industries, and other cross-cutting ecosystem impacts, such as soil health, forest carbon stocks, and biodiversity. We will also include quantitative technology assessments when the data are available and provide insights into appropriate technologies for feedstock, region, distance to geologic storage/carbon sink, and biomass transportation and logistics. Necessarily, our BiCRS analysis will cross-cut other major analyses in this report, including impacts on soil carbon, higher resolution geologic storage maps, impacts on forestry and biomass carbon sinks, and environmental justice impacts.

Methods

Our BiCRS analysis is broadly divided into two scenarios. We classify the two scenarios as "current," based upon a 2025 time horizon, and "mature," or the potential removal opportunities available in 2050. This distinction provides a useful context for understanding current opportunities and future potential, in terms of biomass availability, technology development, and the impacts of supporting infrastructure. The "current/2025" scenario assumes current waste biomass supply and biogenic CO_2 emissions and does not include purpose-grown energy crops. It focuses on currently available BiCRS technologies at TRL 7 or higher where technoeconomic and carbon efficiency/life cycle data exist from pilot-scale demonstrations and assumes only current CO_2 pipeline infrastructure. The "mature/2050" scenario includes bioenergy crop potential according to four "conservative" to "maximum potential" sub-scenarios, including an electric vehicle–focused scenario, described below. Additionally, the mature scenario will describe opportunities and research needs (e.g., bio-oil carbon sequestration in asphalt for regions with no geologic storage opportunities) around emerging BiCRS biomass feedstocks and technologies that are not yet mature enough for robust technoeconomic analysis (TEA). Finally, the mature scenario will include consideration of future climate impacts (CMIP6 SSP2-4.5) on biomass availability, will assume a CO_2 pipeline network, and will discuss impacts of other supporting infrastructure, such as CO_2 and H_2 hubs, that may serve to reduce pathway costs and logistical hurdles.

2025 Biomass Availability Assessment:

For the current/2025 scenario, we will primarily draw biomass and biogenic CO_2 point-source availability data from the 2016 Billion-Ton Report (BTR)[30] and the National Wet Waste Inventory[51] and will draw point-source data from the Renewable Fuels Association, EPA AgStar, and LMOP databases and from the JBEI BioSiting tool[52] and other literature sources.[53, 54] The taxonomy and data sources for each biomass type for the 2025 scenario are shown in **Figure A3**.

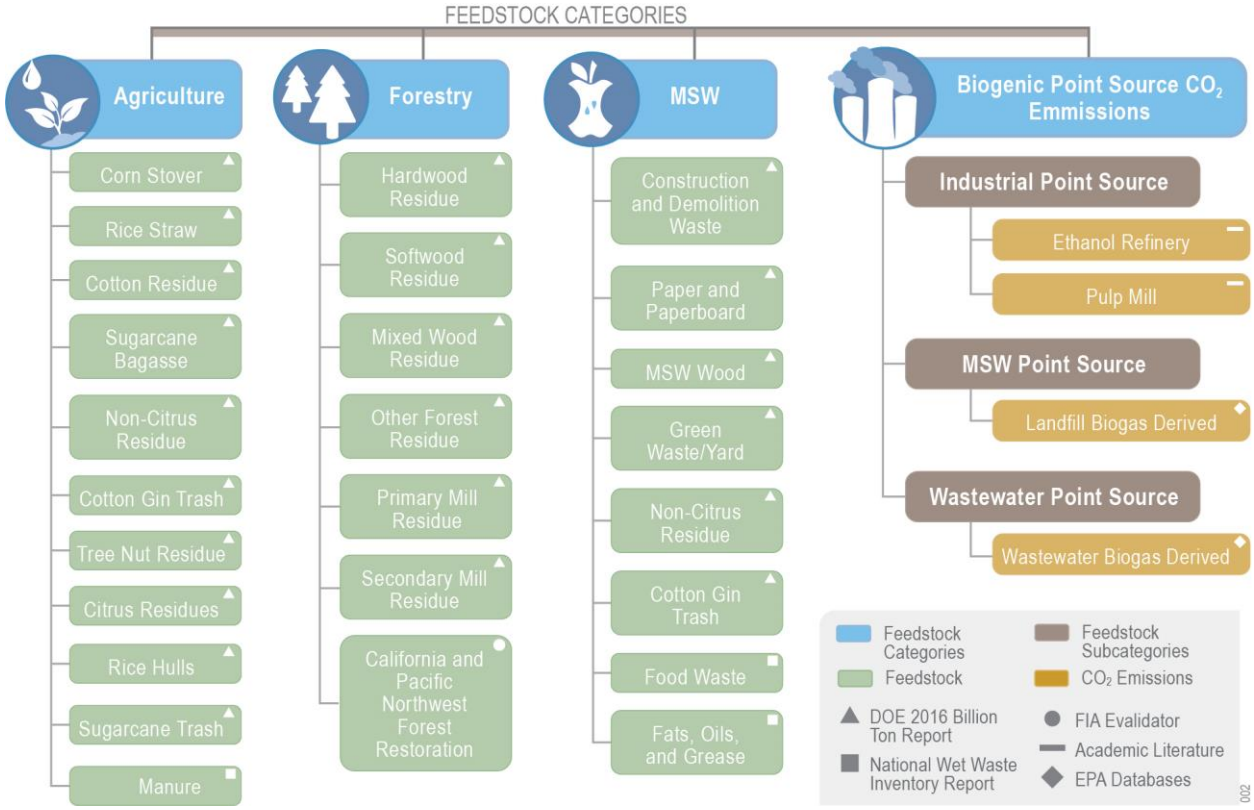

Figure A3. *Taxonomy of biomass/CO_2 sources and associated data sources used in 2025 scenario.*

Billion Ton Report (BTR) Methodology

The BTR is our primary source for 2025 biomass availability data, with additional data sources and biomass listed below. Near-term resources include municipal solid wastes, food-processing wastes, agricultural residues, logging residues, and small-diameter trees from forest management.

The forestland and agricultural resources in the BTR are modeled in partial-equilibrium economic models that account for competing demands for food, feed, fiber, and exports and include detailed environmental sustainability constraints. Forestland resources are constrained to timberlands within 1 mile of existing roads on slopes <40 degrees, where net growth exceeds harvests, and where logging residue removal is constrained for soil conservation. Agricultural residue removal is limited to not exceed the tolerable soil-loss limit of the USDA Natural Resources Conservation Service and to not allow long-term reduction of soil organic carbon. Modeling of environmental sustainability constraints are described in BTR chapters 3-4. The potential economic availability (supplies as a function of price) for the forestry, agricultural residues, and wastes from the BTR feedstocks relevant to our 2025 scenario are shown in **Figure A4**.

Additional Biomass Supplies and Data Sources

Building on previous analyses, our BiCRS analysis will explore harmonization with other datasets and modeling approaches, e.g., the National Wet Waste Inventory,[51] alternative forest biomass availability from forest fuel load management for fire reduction, and biogenic industrial emissions, such as from pulp and paper, ethanol, and biogas production.

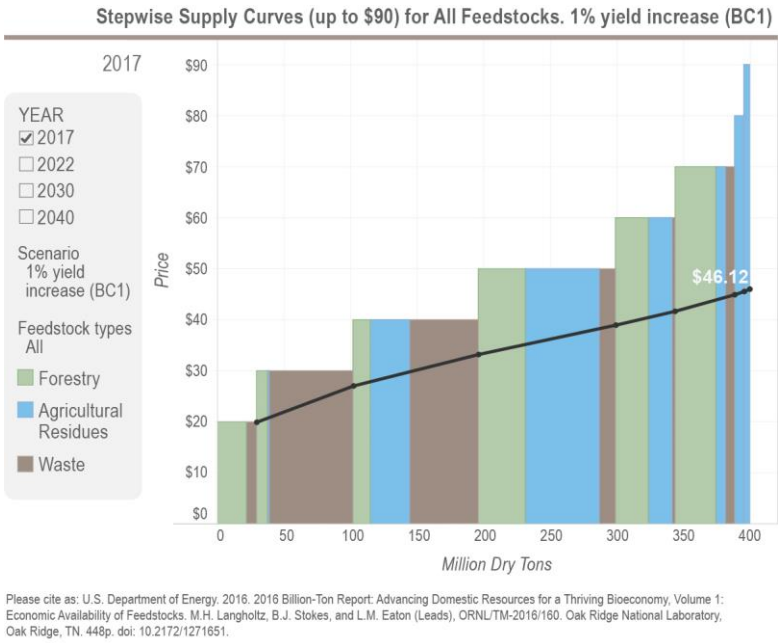

Figure A4. *Estimated near-term biomass resources from forestry (logging residues and forest management), agricultural residues (e.g., corn stover), and wastes (e.g,. municipal solid wastes and food-processing wastes) as a function of price (includes collection costs but excludes transportation costs, in 2014 $). Supplies shown as estimated for supplies in 2017 from BTR.*

Forest Treatment for Wildfire Prevention

We will estimate near-term forest residue availability for 2025 based on forest restoration treatment quantities proposed by the USFS 2022 10-Year Wildfire Crisis Strategy on USFS lands (20 million additional acres on top of 20 million currently being treated) and other federal, state, tribal, and private lands (30 million acres). Our efforts will focus on the American west and include the following states: California, Idaho, Nevada, Oregon, Washington, New Mexico, Arizona, Wyoming, Utah, and Colorado. We will select a total of 70 million acres to be treated over 10 years based on wildfire hazard[55] by identifying the highest risk counties in the states selected. We assume 7 million acres will be treated in 2025 and will calculate biomass availability accordingly. We will use published data sourced from the Forest Inventory and Analysis (FIA) EVALIDator tool, a custom-query database that allows for segmentation, exploration, and summary of current carbon stocks in the United States. To select and quantify biomass availability based on limiting criteria and/or assumptions, we will submit a selection of custom queries to the EVALIDator tool to report and record results on a county level. We will limit availability based on distance to road, slope, and land designation (non-reserved land). Biomass availability will be determined through overstocking status and consequent thinning to 80% full stocking.

2050 Biomass availability assessment:

Our 2050 biomass availability assessment will include additional economic analysis of potential supply from purpose-grown perennial energy crops, such as switchgrass (within constraints of the CMIP6 SSP2-4.5 climate projections). We will also describe other emerging feedstocks, such as micro and macro algae.

Algae as a Feedstock in BiCRS 2050

We will include an assessment of the role of micro- and macroalgae cultivation with other biomass feedstock conversion pathways in our 2050 scenario analysis. Our initial assessment of microalgae biomass supply potential and cost indicates that 10s-100s of millions of tons of CDR is available, at costs ranging from $450-2000/metric ton. Microalgae can be cultivated in oblong racing ponds on topographically flat locations cited near concentrated CO_2 sources (must be biogenic sources for carbon removal); the predominant cost components for this CDR source include the racing pond capital cost (e.g., lined vs.

unlined ponds) and CO_2 cost from local sources. According to the 2017 Algae Harmonization Report,[56] if fully deployed around the United States, freshwater ponds can produce 104 MM tons ash-free dry weight (AFDW) biomass/yr at around $472/ton AFDW, while saltwater ponds can produce 235 MM ton AFDW/yr, at around $655/ton AFDW (ash-free dry weight:CO_2, 1:1.98). Similarly, the BTR suggests minimum future microalgae costs at ~$500/ton biomass from freshwater sources, ~$550/ton biomass from minimally lined saltwater ponds, and ~$650/ton biomass from fully lined saltwater ponds; however, due to the constraint of co-location to CO_2 sources, to achieve >100 MM tons biomass/yr, production costs may exceed $2000/ton biomass.

Bioenergy Crop Supply Potential for BiCRS

In addition to near-term resources from wastes, forestry, and agricultural residues, the BTR includes the potential addition of biomass energy crops in the future. These resources are currently unavailable at scale but could expand in response to market demand. In the BTR, terrestrial biomass energy crops (e.g., switchgrass, mixed perennials, poplar, willow) are modeled in a national economic model that solves for land allocation to meet demands for food, feed, fiber, and exports before biomass is produced. The BTR base-case and high yield scenarios identify the potential for 411 and 736 million tons of biomass energy crops annually.[51]

2050 Bioenergy Crop Modeling Scenarios

For our BiCRS analysis, we assembled a cross-cutting team with expertise in soil carbon, impacts of bioenergy crop production on biodiversity and carbon stocks, agronomics, and biomass conversion technologies. We will use the following four bioenergy crop modeling scenarios for our 2050 bioenergy crop supply assessment with a range of constraints. Our objective in developing these scenarios is to show the range of biomass availability under different land-use scenarios while prioritizing carbon removal (avoiding leakage and soil/standing carbon loss) and biodiversity.

Scenario *1:* "Conservative" (CRP lands only)

We expect this scenario to be the most conservative because it assumes no current agricultural lands are converted to bioenergy crop production, avoiding any potential for carbon leakage while making Conservation Reserve Program (CRP) lands available for some bioenergy production. Lands enrolled in the CRP (**Figure A5**) provide wildlife, water quality, erosion prevention, and carbon benefits to the nation. A mature biomass energy market incentivizes landowners to drop out of the CRP program to either (a) harvest biomass for energy or b) plant other annual crops due to higher market prices induced by dedicated biomass competition nationally. A potential approach following CRP regulation for forage harvest is to allow lands that remain enrolled in CRP to be harvested for biomass every three years. The objective of the proposed policy is to produce biomass for energy while still maintaining the environmental benefits of enrollment in CRP. In this scenario, we will compare the land-use transition under a mature biomass market with (for lands that remain enrolled) and without (e.g., annual harvest for lands that are no longer enrolled) a 3-year harvest option. The results will give insight into whether a 3-year harvest option will lead to more or less biomass production on lands currently enrolled in CRP and into what extent the policy could maintain enrollment in CRP and preservation of environmental benefits. This analysis will use the same method developed in Hellwinckel et al. (2016).[57] This will allow higher resolution estimation of the yield potential of traditional commodities and dedicated biomass crops on existing CRP lands and, therefore, more accurate estimation of land-use transitions under a mature biomass energy

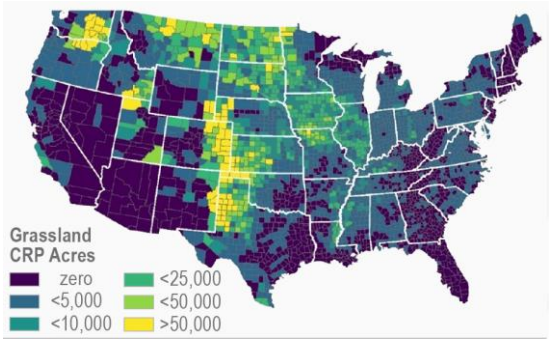

Figure A5. *Acres enrolled in the Conservation Reserve Program (CRP).*

market. We will simulate biomass prices from $30-100/dry ton to construct supply curves of biomass and associated sub-county CRP land-use changes with and without the 3-year harvest option.[57]

Scenario 2: "Intermediate" (Bioenergy + CRP lands)

In this scenario, we will estimate the impact of a mature biomass market on land-use, crop production, and crop prices *if biomass production was only permitted on non-arable former cropland and pastureland in addition to CRP lands*. The results will give insight into the value of stipulating specific land biomass can be grown upon to avoid displacement of the most productive cropland for food production. Comparison of the commodity-price impacts of producing a given quantity of biomass under the intermediate scenario to the maximum potential scenario will indicate if policies that target permissible biomass lands is of value in reducing indirect impacts on food prices. We will use the DOE Great Lakes Bioenergy Research Center (GLBRC) Atlas of US Bioenergy Lands to first define lands based on former cropland not now forested, as well as lands transitioning out of food crops due to drying aquifers (such as the Ogallalla aquifer in the southern Great Plains) and climate change. In general, we define bioenergy lands as lands that are not used for food crops, do not have carbon stocks in trees or soil that could be lost and thus create carbon debt upon conversion to bioenergy crops, and do not have high biodiversity conservation value. Next we will calculate the relative yield difference between marginal and non-marginal lands at the county level,[57] where the weighted National Commodity Crop Productivity Index (NCCPI) is estimated for county-level marginal and non-marginal lands. The NCCPI estimates are then used to differentiate and adjust crop yields from the reported county averages. With yields differentiated, we will use the Policy Analysis System (POLYSYS) model to simulate biomass prices from $30-100/dry ton to construct supply curves of biomass and associated sub-county marginal land-use changes. The model will also calculate the indirect impact of biomass production on commodity prices.

Scenario 3. "Future Electric Vehicle"

In our future electric vehicle scenario, lands made available due to declining demand for corn ethanol are added to the land evaluated in our "intermediate" scenario. Electric vehicle scenarios will be centered around the most recent version of the US Energy Information Administration's (EIA) Annual Energy Outlook (AEO). Specifically, we use the Reference Case (status quo policies and baseline macroeconomic projections), as well as four so-called side cases (i.e., low/high economic growth and low/high oil price) to project gasoline, diesel, and ethanol use under various EV market share scenarios.[52] We will then pick a reasonable EV scenario (e.g., 75% reduction in corn ethanol demand) and measure the change in corn prices associated with the reduction in ethanol demand. To avoid leakage, we will increase biomass prices so that corn prices do not increase. We will assume that ethanol prices remain stable with stable corn prices, meaning no change in ethanol exports. We will then model biomass supply curves at the county level using POLYSYS or the methodology found in Dumortier (2016) and Dumortier et al. (2017).[58, 59] The model will be deterministic (i.e., no uncertainty) to ease the computational burden. The model projects crop demand until 2050 and determines county-level area allocation, including switchgrass and CRP land, as a function of the biomass price. Based on the area allocation at the county-level, the biomass production and/or carbon supply curve will then be calculated.

Scenario 4: "Maximum Potential"

POLYSYS is a partial-equilibrium economic model that simulates the US agricultural sector. POLYSYS quantifies market equilibrium prices and production of agricultural commodities[60] and has been expanded to simulate potential biomass production in response to market demand. POLYSYS solves at the county level in response to national demand in an annual timestep. Recent national biomass resource assessments (e.g., BTR) have quantified potential future production of biomass energy crops in response to perfectly elastic demand (i.e., sustained biomass prices over time) while also meeting projected demands for food, feed, fiber, and exports of commodity crops and livestock. BTR identifies the potential to produce over 400

and 700 million tons of biomass per year, under a base-case or high-yield scenario, respectively, assuming a farmgate price of $60/dry ton (2014 $). A revised US DOE biomass resource assessment is in preparation, expected to be released by 2024. Maximum potential biomass production scenarios quantified in POLYSYS for this project will be held consistent for the US DOE national biomass resource assessment in preparation.

Biomass criteria for technology mapping

We have developed preliminary technology mapping criteria to assign biomass to specific BiCRS technologies. This mapping is based on the technical limitations and economic considerations of medium to high TRL technologies for biomass processing. The selected biomass criteria, including moisture, ash, lignin, holocellulose, and starch content, are described in Table A1.

Table A1. *Biomass criteria to determine the suitability of a biomass type for a given technology.*

Biomass Criteria	Feedstock	BiCRS Technology
Moisture content: >25 wt.% Ash content: >10 wt.%	Sewage sludge	Anaerobic digestion, hydrothermal processing
Moisture content: >25 wt.% Ash content: <10 wt.%	Energy sorghum, green waste/yard, citrus residue, food waste, manure	Anaerobic digestion, hydrothermal processing, fermentation
Moisture content: <25 wt.% Ash content: >10 wt.%	Rice straw, tree nut residue, citrus residue, rice hulls, sugarcane trash, municipal solid wastes, wood	Combustion
Moisture content: <25 wt.% Ash content: <10 wt.% Lignin content: <15 wt.% Holocellulose > 50%	Corn stover, switchgrass, sorghum, sugarcane bagasse, non-citrus residue	Hydrolysis + fermentation, gasification, pyrolysis
Moisture content: <25 wt.% Ash content: <10 wt.% Lignin content: >15 wt.%	Hardwood residue, softwood residue, mixed wood residue, other forest residue, primary mill residue, secondary mill residue, cotton residue, cotton gin trash, tree-nut residue, construction and demolition waste, paper and paperboard	Gasification, pyrolysis
Oil content: >30 wt. %	Algae; fat, oils, and grease (FOG)	Transesterification, hydroprocessing

Several biomass types can be processed by competing BiCRS technologies. We are investigating different approaches to allocating feedstock availability to similar biorefineries. These approaches include carbon removal potential–, economic-, and quota-based allocation strategies that balance maximizing carbon removal with economic and market demand considerations.

BiCRS Technologies:

Our BiCRS analysis will consider pathways with system boundaries that include feedstock, conversion technologies, products, and carbon sequestration in the two scenarios—2025 and 2050—as shown in Figure A6. Biomass feedstock will be allocated to biomass conversion technologies for different bioproducts production, while biogenic emissions from existing industries, such as fermentation plants, pulp and paper mills, and anaerobic digestion facilities, can be directly captured and sequestered for carbon removal. We match available biomass to technologies according to the suitability of the biomass following criteria such as moisture, ash, lignin, starch, holocellulose, or oil content as mentioned above. We consider a wide variety of biomass conversion technologies, including thermochemical conversion technologies such as gasification, pyrolysis, combustion, liquefaction; biochemical conversion technologies such as fermentation and anaerobic digestion; and mechanical treatment technology. We only consider quantitative analysis for high TRL technologies in 2025 but will qualitatively discuss low TRL technologies, such as bio-

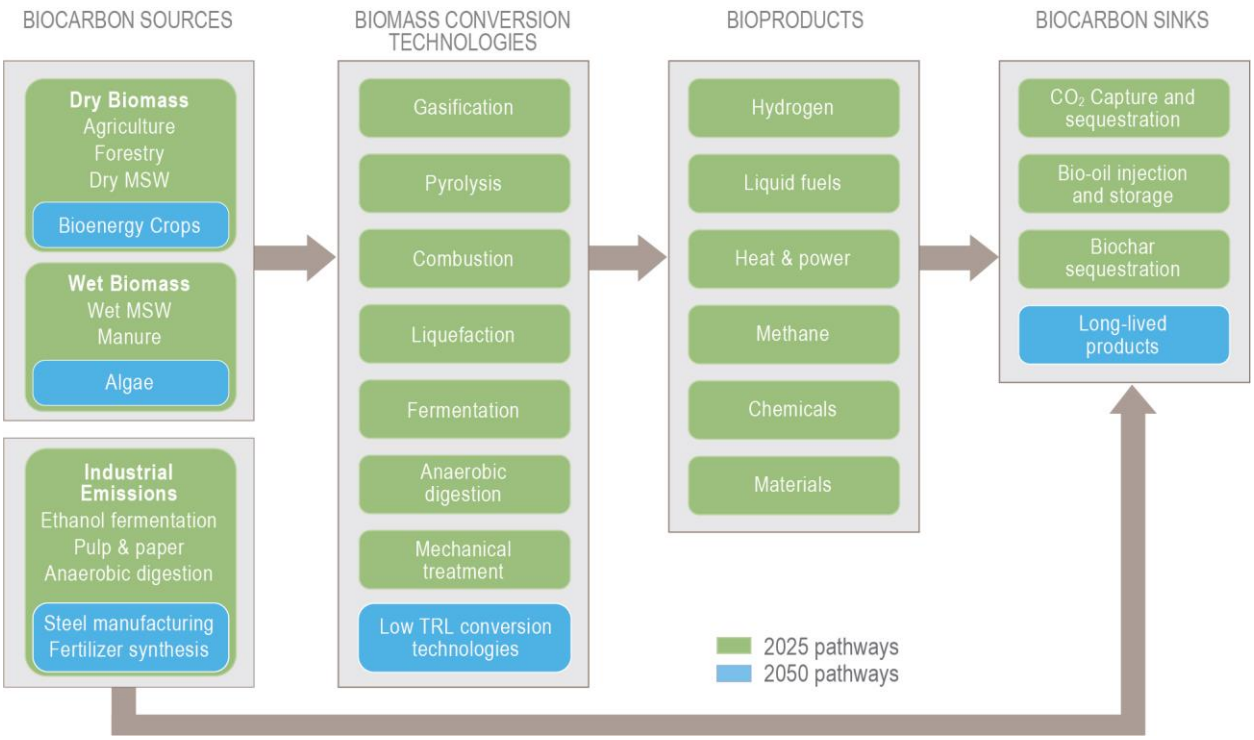

Figure A6. *Biomass conversion and carbon sequestration pathways in 2025 and additional options available in 2050 (in red). Potential long-lived products include building materials that sequester biogenic carbon.*

electrochemical conversion, dark fermentation, gas pyrolysis, etc., in 2050. For products, we mainly include hydrogen, liquid transportation fuels, heat and power, methane, biomaterials, and chemicals. We will consider the wholesale price of these bioproducts as revenue in our economic analysis. There are four primary potential biocarbon sinks to maximize CO_2 removal: carbon capture and storage (CCS), bio-oil injection and storage, biochar sequestration, and long-lived products (Figure A6). We will assess the overall carbon balance calculation for all the considered pathways based on their mass and energy balance, as well as on TEA of the cost/t CO_2 removal for each pathway.

Modeling BiCRS Biomass, Infrastructure and Transportation

Biomass collection, storage, and transport assessments

The Biofuel Infrastructure, Logistics, and Transportation Model (BILT) models the supply chain to analyze the use of biomass in the production of energy products. Developed in 2009 to analyze ethanol production and distribution, BILT has since been expanded to allow modeling of other products, including electricity, sustainable aviation fuel, biodiesel, and renewable natural gas. The spatial distribution of biomass provided by the BTR allows BILT to calculate estimates of both cost and emissions involved in biomass transportation. The geographic locations suitable for CO_2 storage are used to evaluate the benefits of siting production plants in locations where direct sequestration of CO_2 can be done.

The current version of BILT develops a series of mixed-integer programming problems to generate the cost of carbon avoidance curve by first calculating the maximum carbon that can be avoided, given a set of feedstocks and production plant types. Once this maximum attainable carbon avoidance value is determined, BILT then solves a series of cost minimization problems to determine the least costly solution to avoiding at least p% of the maximum CO_2 avoidance where p is [10, 20, 30, …, 80, 90, 99, 100]. (Values

for p are user-defined.) For each solution, BILT stores the types and locations of production plants chosen, as well as which feedstocks are used at each site and from where they are sourced.

We will adapt the BILT model for optimizing BiCRS across the US by considering six primary factors: 1) spatial distribution of biocarbon resources and associated costs, 2) whether to preprocess the biocarbon, 3) intermodal transportation systems, 4) siting, sizing, capex, and opex of biorefineries, 5) bioproduct market dynamics, and 6) siting and sizing of biocarbon sinks. The BILT model was developed by Ingrid Busch and Mike Hilliard at Oak Ridge National Laboratory (ORNL) as an optimization tool for bioenergy production pathways, including ethanol fermentation, gasification with Fischer-Tropsch (FT), and combustion for biopower. Recently, the model was adapted for bioenergy with CCS.[61] *Our team will adapt the model further by transitioning the primary objective from optimizing net CO_2 avoided via bioenergy to optimizing net CO_2 removed via biocarbon storage*. The adaptation of the model will require development of new features including point source biocarbon resources such as biogenic industrial emissions, several new biorefining pathways, consideration of bioproduct market saturation, accounting of new gate-to-sink transportation logistics, and several new end-of-life biocarbon sinks. The new features will require extensive TEAs and life cycle assessments (LCAs) to generate the data necessary for model expansion. The primary outputs of the modified BILT model will be region-specific and will include types and quantities of biorefineries sited and their associated biocarbon feedstocks, costs of carbon removal (Figure A7), and related outputs.

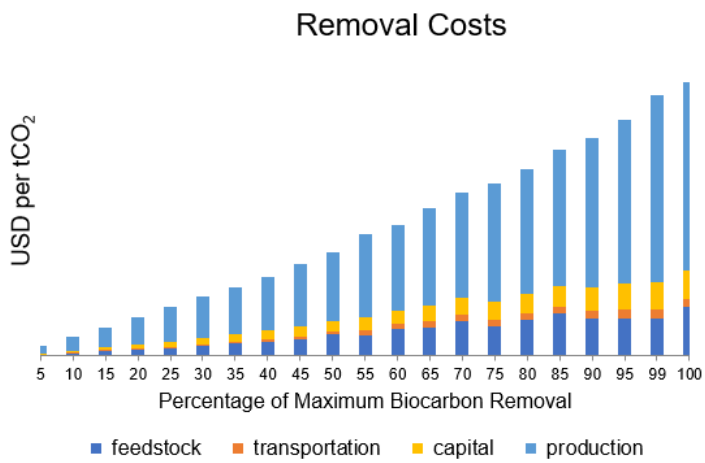

Figure A7. *Example of a region-specific output from the BILT model to achieve varying levels of biocarbon removal: the associated feedstock, transportation, capital, and production costs for the various biorefining pathways*

Defining Biomass Regions:

We have identified 2025 US BiCRS regions (loosely based upon USDA regions) and modified them based on the predominant biomass sources relevant to BiCRS and geologic storage resources (Figure A8).

Using the biomass data from the BTR at a price of $60/dry ton, we identified by county the predominant biomass type. We visualized the predominant biomass type geospatially and then manually drew boundaries for BiRCS regions around larger areas of the same biomass type. The biomass type categories included crop residues, concentrated animal feeding operation (CAFO) manures, municipal solid waste, secondary wastes, and timberlands. Similarly, to delineate feedstock regions, we selected a filter by county for the BTR 2017 data of $80/dry ton with a production density of greater than or equal to 50 dry tons/square mile. Once filtered, we displayed this subset of data geospatially and through a combination

of manual digitization and automated data processing–assembled feedstock regions. Geologic storage areas were developed separately by the geologic storage team.

While we intend to evaluate biomass supply curves at the county-level, we will also evaluate BiCRS pathways, considerations, barriers, and opportunities at the regional level. Our regional analysis will be both quantitative, in which we will calculate biomass and CO_2 supply curves for each region, and qualitative. Examples of qualitative analysis include matching regional biomass feedstock characteristics to beneficial technologies, products, and carbon sequestration methods based upon proximity to geologic storage and regional geography, agriculture, and industry. For example, a region with primarily woody waste biomass that is a significant distance from geologic storage locations may benefit most from conversion technologies that allow above-ground CO_2 sequestration (e.g., biochar). Identification of BiCRS benefits may also be qualitative and regional, for example, conversion of waste woody biomass to e.g. biochar may reduce wildfire risk and improve air quality in that region.

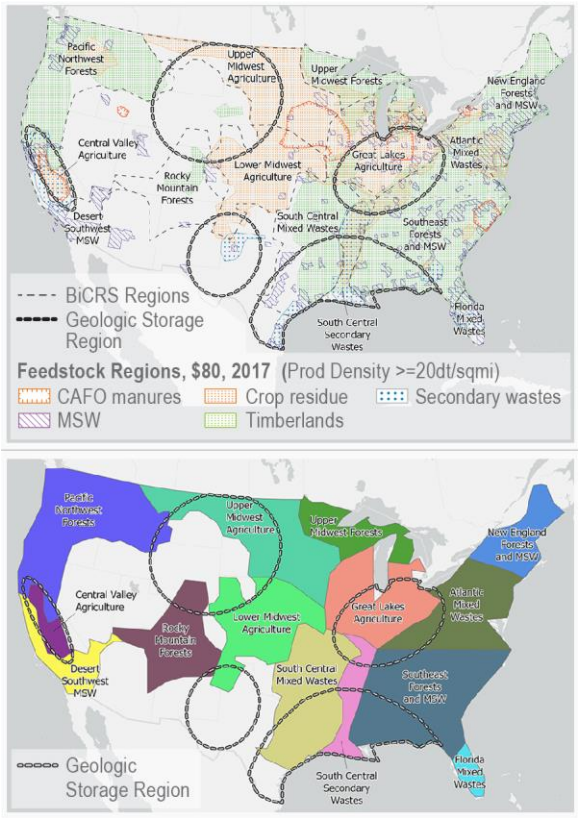

Figure A8. *2025 Biomass regions drawn according to predominant feedstock, (top) showing biomass distribution withing regions and (bottom) highlighting regions only for visual clarity.*

IV. SOIL SEQUESTRATION

TEAM: Eric Slessarev, Allegra Mayer, Katerina Georgiou, Jennifer Pett-Ridge, Keith Paustian, Yao Zhang, Amy Swan, Mark Layer, Crystal Toureene, Jerome Dumortier, Mark Bradford, Dermot Hayes, Lydia Price, Ames Fowler, Bruno Basso, Phil Robertson

Introduction and Analysis Scope

US agricultural soils have lost a significant fraction of their natural stores of organic carbon since the onset of cultivation.[6] Optimizing agriculture to restore some of this organic carbon can remove CO_2 from the atmosphere. If improved agricultural management practices were applied to a significant fraction (10%) of US croplands, soils could potentially sequester tens of millions of tons CO_2 over a 10-20-year period.[7–14] In addition to sequestering carbon, improving agriculture practices can reduce emissions of fossil CO_2 and the powerful greenhouse gases nitrous oxide and methane. These emissions reductions are a permanent climate benefit that may be comparable to gains from sequestering new carbon in soil. Consequently, soil carbon sequestration must complement broader efforts to reduce emissions from the agricultural sector, which currently accounts for 10% of US emissions.[15]

Methods

We have identified 1) land management practices that have a relatively well-demonstrated potential to increase soil carbon; and 2) areas for increased research and development investment. We will estimate carbon removal potential at the national scale with this first set of practices and will systematically evaluate the benefits and barriers to adoption for the second set of practices. We will consider four major categories of land management in our national-scale analysis:

27. **Cover cropping and agroforestry.** In most annual croplands, planting cover crops has a moderate to high potential for increasing soil carbon storage relative to conventional management.[9,10,16] Cover crops can be integrated into existing crop rotations and have considerable room for increased adoption in US croplands (**Figure 3**). In addition to cover cropping in annual croplands, we will model the effects of replacing bare soil with cover crops or saleable crop types in existing tree-crop systems (agroforestry).
28. **Conservation buffers**. We will also consider practices that establish perennial plant cover in the borders of conventional croplands. This family of practices includes windbreaks, shelter belts, and riparian buffer zones.[13] While these practices apply to a small fraction of agricultural land area, they may be cumulatively significant.
29. **Land set-aside.** Conversion of cropland to perennial cover (e.g., via restoration of prairie or wetlands) can yield increases in soil carbon. Land set-aside is supported under the USDA CRP. We will consider cost tradeoffs between bioenergy production and CRP (see BiCRS section), identify economically marginal croplands that are allocated to CRP versus bioenergy, and calculate associated soil carbon benefits.
30. **Perennial bioenergy**. Conversion of conventional cropland to perennial bioenergy crop production can sequester carbon in soil while supplying bioenergy feedstocks.[11,12,17] We will evaluate the amount of soil carbon that might be stored if bioenergy crops are planted in CRP lands or in actively managed cropland currently used to produce bioethanol. This analysis will extend the four scenarios defined in our analysis of BiCRS-based carbon removal to consider soil-carbon impacts.

Biogeochemical modeling

We will estimate the effects of these four broad groups of management practices on soil carbon and emissions of greenhouse gases. First, we will simulate the effects of land management using biogeochemical models. Specifically we will use DAYCENT/COMET[40] to model cover cropping and agroforestry, conservation buffers, and land set-aside using conservation practice standards defined by the USDA. Critically, we will adjust these practices to account for the assumptions made in the BiCRS analysis regarding crop residues (i.e., we will ensure that the soil carbon effects of removing crop residues from annually cropped systems for BiCRS are fully accounted for). For bioenergy crops, we will use the SALUS[41] model, which is better optimized for biofuel cropping systems; modeling of bioenergy cropping will extend the specific scenarios and bioenergy crop types defined for BiCRS to consider soil-carbon impacts and greenhouse gas emissions. We will use these models to simulate net soil carbon changes resulting from land management, correcting our estimates for any increases in emission of methane, fossil CO_2, and nitrous oxide.

In all management scenarios, carbon removal and reduced loss of soil carbon will be differentiated by modeling change in soil carbon stocks over time in a business-as-usual management scenario versus an improved management scenario. We will simulate soil management practices over the period 2030-2050 using climate inputs from CMIP6 model ensemble climate projections (scenario SSP2-4.5). Other environmental parameters (e.g., clay content) will be obtained from USDA geospatial products (e.g., SSURGO). Models will be run at multiple points sampled across US Major Land-Use Areas (MLRAs) and results will be summarized at the MLRA level (e.g, [42]). Model predictions will be validated against publicly available syntheses of soil carbon sequestration rates from agricultural experiments.[43,44] We will develop Monte Carlo–based statistical approaches to propagate uncertainty estimates from the validation process onto soil carbon supply curves.

Economic modeling

The biogeochemical model simulations will yield a predicted response of soil carbon and crop yields to management in different MLRAs. We will integrate these predictions with an economic model purpose-built for this analysis (see BiCRS section) to simulate land-use decisions across a range of carbon and crop prices. We will initially use the land-use decision model to map lands converted to bioenergy crops. We will then develop a sub-model to map the extent of cover cropping and agroforestry, conservation buffers, and land set aside within residual cropland not allocated to bioenergy production. The cost parameters required for this sub-model will be drawn from the literature (e.g., [45]). The economic model will incorporate the cost to the landowner of 10-20-year contracts for accruing and maintaining soil carbon stocks (our approach will be similar to CRP contract modeling). Ultimately, we will account for the medium-term costs of maintaining soil carbon and the risks of reversal at the national scale by assuming that a fixed number of soil carbon contracts occur through 2050. Additionally, while we will not track overall land-use patterns beyond this time horizon, we will conduct additional model simulations under different climate change and land-use assumptions over a 100-year period to characterize the durability of sequestered soil carbon to changes in management and environmental conditions.

We will bound the economic analysis with exogenous land-use constraints. For instance, we will exclude ecologically vulnerable lands (e.g., wetlands) from development of perennial cropping systems. Cropping systems will also not expand at the expense of forests, and land-use projections will be held consistent with afforestation/reforestation scenarios (see Forestry section). The structure of our analysis dictates that cover cropping will not be modeled where perennial cropping occurs. We will also coordinate with the BiCRS team to ensure that crop residue demands for BiCRS are consistent with the management scenarios we model.

Our overall workflow is depicted in **Figure A9**, which shows the iterative structure of our analysis. Biogeochemical model predictions will establish the potential carbon sequestration rates achievable over US croplands. We will then use these potential rates to inform the economic decision model and generate projections of land use as a function of carbon price. Finally, we will re-combine these maps with the biogeochemical modeling results to estimate the quantity of sequestered carbon as a function of total investment in intensifying crop rotations and perennial cropping, building a set of soil carbon supply curves for different practices.

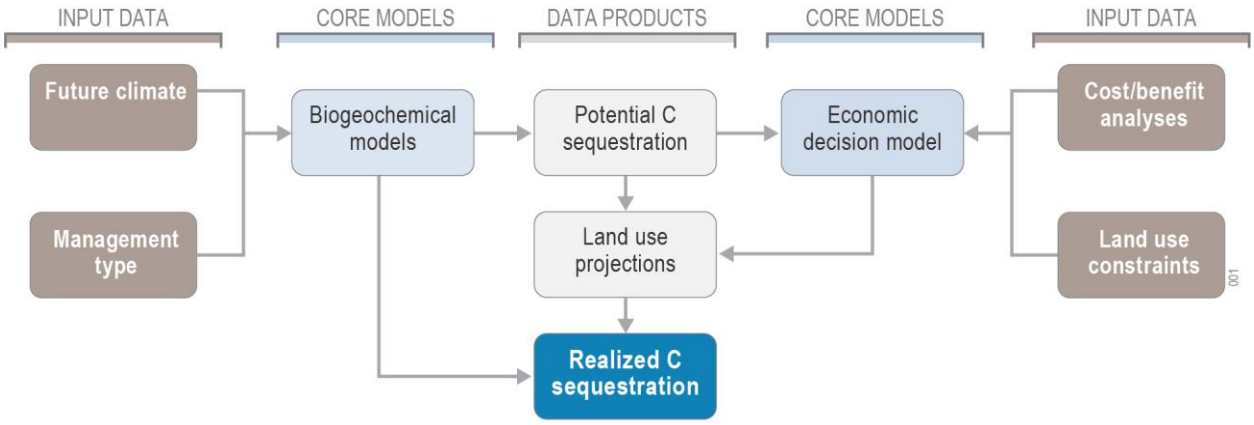

Figure A9. *Workflow of soil-carbon modeling. Biogeochemical models will be used to predict potential soil carbon sequestration rates. These will determine land-use decisions, yielding land-use projections and realized sequestration.*

V. FOREST SEQUESTRATION

TEAM: Mark Bradford, Mark Ashton, Sara Kuebbing, Reid Lewis, Mark Ducey, Dan Sanchez, Sasha Ponomareva

Introduction and Analysis Scope

The goal of our analysis of Forest Sequestration is to quantify the biophysical potential for change in forest management practices, wood products, and wood-product fate to achieve negative CO_2 emissions from forest lands. Because of inherent biogeographic, ecological, and socio-economic differences in forest ecosystems around the US, we must suggest prescriptive management practices that are broad enough to create economies of scale but also specific enough to be ecologically and economically relevant to local forest ecosystems and the people living within them. For this reason, all our analyses and recommendations will be tailored to specific forest regions.

Given the wide array of intervention options relating to management of existing lands and fates of forest products, there appears high potential to dramatically increase carbon sequestration rates and reduce atmospheric carbon emission rates associated with existing forest lands. Improved forest management practices—such as reducing stocking densities in high fire risk areas, lengthening rotations, and routing of timber to long-lived forest products—have the potential to increase forest carbon stocks and decrease forest carbon emissions by promoting tree growth while still supplying critical wood products for market. Such practices could, conservatively, reduce atmospheric carbon by an additional 0.1 Gt CO_2/yr for operations on existing forest lands (**Figure A10**).

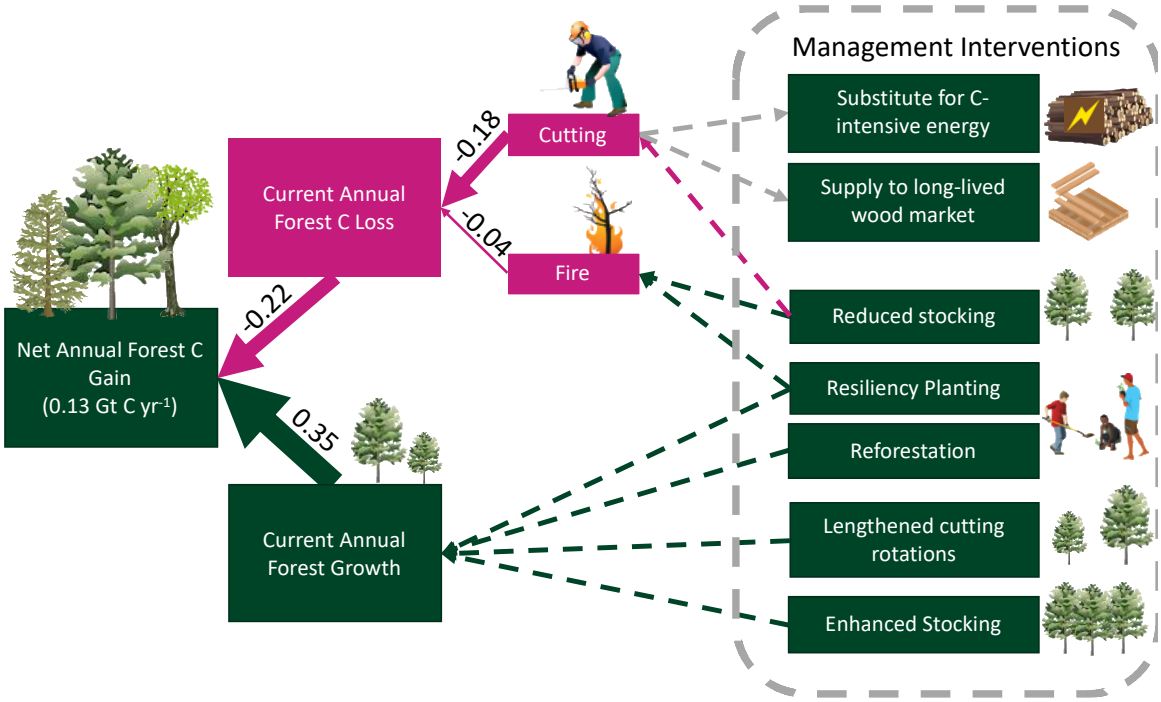

Figure adaptation from Woodall et al. 2015, USFS; Images Images Integration and Application Network (ian.umces.edu/media-librar

Figure A10: *Wide array of management interventions (depicted by green and gray dashed lines) can dramatically increase current sequestration rates and reduce atmospheric carbon emission rates, leading to increased net annual forest carbon gains.*

Methods

We see four major areas of research and synthesis that will inform our goal. First, we must estimate current forest carbon stocks to derive a baseline value of standing carbon stocks and annual carbon flux rates from forested ecosystems in the US. Second, we must assess the potential natural and anthropogenic drivers of forest carbon-stock changes through 2050. These drivers include both 'threats' to forest carbon-stock loss that might erase any negative emission gains and 'opportunities' for altering forest sequestration rates or increasing carbon storage in long-lived wood products that are regionally viable management practices. Importantly, identifying projected threats to forest carbon stocks (in the absence of new interventions) and the current 'business as usual' forest management practices provide a baseline "business as usual" scenario for carbon sequestration, loss, and storage in forested ecosystems through 2050. Estimating a "business as usual" baseline is a critical and necessary step for building confidence that new forest management interventions meet additionality criteria (that any negative emissions calculations are in addition to forest carbon gains already built into greenhouse gas accounting budgets). Third, once we have identified regional opportunities for improved forest management practices and/or wood-product markets and wood-product storage, we will estimate the implementation costs of each practice. Finally, once we have derived these input data, we can build spatially explicit models to identify forested ecosystems with high potential for negative emissions accrual, low potential for large carbon loss (i.e., higher permanence), and specific management practices that would enhance negative emissions and avoided emissions for these forests.

Estimating current forest carbon stocks

We will synthesize current estimates of forest carbon stocks using a variety of publicly available data products (Table A2) to produce an estimated range of current forest carbon stocks. Most of the current forest carbon estimates use a combination of satellite and aerial remote-sensing data and USDA Forest Service Forest Inventory Analysis (https://www.fia.fs.fed.us) but differ across a few key dimensions, including the carbon pools and fluxes measured for total forest carbon estimates, forest attributes included in the analysis, and the model structures used to estimate forest carbon stocks. We will produce a comparative table of estimates of forest carbon stocks for each major carbon pool for all counties in the US that demonstrate the range of values arising from current models. We will assess our degree of certainty in each model through a qualitative confidence score and a quantitative measure of uncertainty provided from models, following the format of the IPCC Assessment Reports.[62] These values will form our baseline carbon stock values for county-level models.

Table A2: *Proposed datasets for estimating current standing forest carbon stocks*.

Name	Owner	Spatial Scale	Stocks Measured	Citation
National Forest Carbon Monitoring System	DOE ORNL	30-m pixel	Stocks Measured: AGB, CWD, Total Live Biomass, NEP;	Williams et al. 2020
Carbon Monitoring System (CMS): Stocks, Emissions, Net Fluxes for CONUS	DOE ORNL/NASA	100-m pixel	AGB, BGB, Dead Wood, litter	Hagen et al. 2016
Carbon Monitoring System (CMS): Carbon Pools Across CONUS Using MaxEnt Models	DOE ORNL/NASA	100-m pixel	AGB (living and dead), BGB (living and dead), litter, SOM	Yu et al. 2021
USFS Forest Carbon Stocks of the CONUS	USFS	250-m pixel	AG, BG, down dead wood, litter, standing dead wood, SOC	Woodall et al. 2015

Name	Owner	Spatial Scale	Stocks Measured	Citation
Carbon Monitoring System (CMS): Terrestrial Carbon Stocks, Emissions, and Fluxes for CONUS (2001-20160	ORNL DAAC/NASA	0.5 degree	Labile carbon, foliar carbon, fine root, woody carbon, litter carbon, SOC [GPP, NPP]	Yang and Saatchi 2020
Forest Carbon Removals, Emissions, Net Change	Global Forest Watch	30-m	AGB, BGB, dead wood, litter, SOC	Harris et al. 2021
Global Forest Carbon Database (FoC)	Smithsonian	Field measurements	various	Anderson-Teixeira et al. (2016, 2018).

We will consider two primary drivers of forest carbon stock changes in our models. First, "threats" to forest carbon stocks, which can take the form of natural disturbances that include fire, pests and pathogens, drought, and windstorms, conversion of forests to other land-uses, and unsustainable timber harvest practices that deplete forest carbon stocks and long-term potential for forest carbon gain. Second, forest management and wood-product market "opportunities" that can enhance carbon sequestration into forest carbon pools, store carbon in long-lived wood products, or provide wood substitutes for other carbon-intensive products or energy sources. The importance of forest carbon threats and opportunities will vary considerably across the United States because of biogeographic differences in climate and forest composition and socio-economic differences in land ownership, current forest management practices, and existing wood-product markets. We have currently identified the leading regional 'threats' and 'opportunities' for forests within the 8 USFS Forest Regions in the conterminous United States. We will include Alaskan and Hawaiian forests in future work. We will also consider urban forested natural areas, since they can also store large amounts of carbon[4] and improved management of city forests may lead to increased sequestration rates and many co-benefits (biodiversity, reduced urban heat island effects and associated building cooling costs, decreased flooding and storm-water runoff, and improved human health through decreased air pollution and increased access to natural areas).[5]

Assessing Regional Drivers of Forest Carbon Stock Changes

Estimating Management Costs

We will conduct a literature review to assess per hectare costs of altered forest management practices in US forests. From literature we will extract information on the forest management strategy, region, forest type, current forest condition, current forest management practices, and forest ownership. We will derive cost estimates for management practices, most likely by region, to inform CDR supply-curve estimates.

Modeling Avoided and Negative Emission (CDR) Potentials

Using our regional analysis of threats to forest health and opportunities for forest management and wood product markets, we will source quantitative models for each identified forest carbon threat or opportunity (**Table A2; Figure A11).** We have already identified spatially explicit datasets that can quantify the historical or current impact of threats and opportunities in the lower 48 US states (**Table A3**), and we will conduct further literature and database reviews to add to these sources for regionally specific threats (for example, pest or pathogen outbreaks). For each identified threat or opportunity, we will assess available models based on their spatial resolution, how recently they have been updated, and structural and parameter assumptions. We will determine which single model—or composition of multiple models—is best for estimating the potential carbon gain or loss magnitude. For models assessing altered land-management practices or wood-product markets, we will also assess implementation costs. The spatial resolution of

these estimates will fluctuate based upon the underlying model(s) and data used; we will estimate at as fine a spatial resolution as the underlying data permit. We will combine these different component estimates to create a unified estimate of forest carbon change by county. We will add case studies that exemplify the challenges and opportunities that a given region's forests face. These case studies will add a level of nuance at the regional scale that would be challenging to capture in models that have such large spatial output.

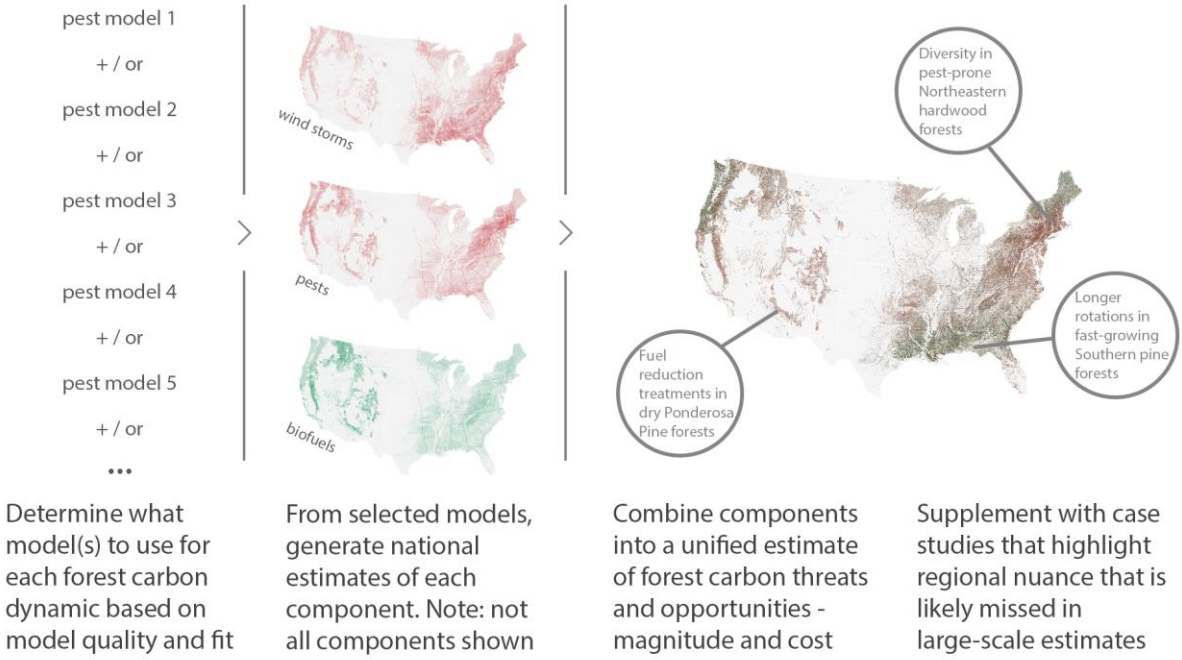

Figure A11: *Proposed workflow for modeling net forest carbon sequestration potentials using multiple spatial data layers of threats to forest-carbon loss and increased atmospheric emissions and opportunities for improved management to increase forest-carbon gain across the United States.*

Table A3: *Proposed datasets for assessing historical and predicted drivers of forest carbon stock change.*

Name	Owner	Spatial Scale	Driver	Citation
USA Development Risk	Natural Resource Ecology Lab (CSU)	1-km pixel	Conversion of forest to other land uses	Theobold et al. 2008
Wildfire Hazard Potential for the United States (2020)	USFS	270-m	Fire	Dillon and Gilbertson-Day 2020
National Insect and Disease Risk and Hazard Mapping 2013-2027 (NIDRM)	USFS	240-m	Pests & pathogens	Krist et al. 2014
Forest Damage Agent Range Maps	USFS	County	Pests & pathogens	Various; https://www.fs.fed.us/foresthealth/applied-sciences/mapping-reporting/damage-agent-range-maps.shtml
Monitoring Trends in Burn Severity (MTBS)	USGS, USFS, DOI, USDA	30-m	Fire	https://www.mtbs.gov
Storm Prediction Center Severe Weather GIS	NOAA	N/A (shapefiles)	Tornado, wind, hail	https://www.spc.noaa.gov/gis/svrgis/
National Hurricane Center and Central PAcific Hurricane Center	NOAA, NWS	N/A (shapefiles)	Hurricanes	http://www.nhc.noaa.gov/gis/
National Land-Cover Database (NLDC)	Multi-Resolution Land Characteristic Consortium	30-m	Conversion (land-cover change)	Dewitz and USGS 2021
US Drought Monitor	National Drought Mitigation Center, Univ. of Nebraska-Lincoln, USDA, NOAA	N/A (shapefiles)	Drought	https://droughtmonitor.unl.edu/CurrentMap.aspx
Map of Forest Ownership in the Conterminous United States [Scale 1:7,500,000]	USFS	250-m	Forest ownership	Nelson et al. 2010
Timber Product Output Studies	USFS	State	Timber sales by state	https://www.fia.fs.fed.us/program-features/tpo/

VI. ENVIRONMENTAL JUSTICE

TEAM: Kimberley Mayfield, Alex Stanley, Jackson Chirigotis, Ramon Gil Egui

Introduction and Analysis Scope

The nationwide implementation and deployment of CDR methods must be conducted in a just way but will ideally also rectify historical environmental injustices whenever possible. How CDR can be deployed in a way that its placement is centered on environmental justice, with a focus on its potential harms and co-benefits, was highlighted in the CDR Primer[63]. Our EJ analysis (**Figure A12**) will build on this research, with an expanded trade-off analysis (**Table A4**—compare to Table 1.4 in CDR Primer) and regional assessments that highlight regions with maximum EJ potential with minimal risk for each CDR pathway.

Our EJ assessments will take advantage of existing DOE, EPA, state, and tribal resources and will merge empirical technical maps for CDR with demographic, socioeconomic, and environmental quality data. This analysis aims to serve as a resource to CDR stakeholders by evaluating social dimensions in regions identified in this report to be ideal for CDR (e.g., **Figure A13**), gathering/reporting insights into CDR from indigenous representatives (federally and state-recognized Native Americans, Native Alaskan, and Native Hawaiian), and analyzing CDR-relevant and EJ-relevant data alongside one another to provide a regional understanding of potential trade-offs (**Figure A14**).

Methods

Our EJ analysis methodology can be broken down into five parts: recognition of indigenous practices, identification of current environmental injustices relevant to CDR, an assessment of potential benefits and risks that CDR may represent to communities with EJ concerns, and a summary of best practices for implementation of 1-2 CDR methods, which will overlap with each of the other technical chapters in our analysis (**Figure A12**). Beginning with a recognition of indigenous practices that sequester carbon follows the ideal of "giving credit where credit is due." By including interviews with indigenous representatives across the United States that discuss methods of forest management and agriculture, within the context of carbon sequestration, our EJ analysis can give a voice to an often-marginalized community. These interviews also aim to elucidate indigenous beliefs relevant to geologic carbon storage, which is of utmost importance as the nation recognizes the outsized role that geologic storage of carbon will have in our energy transition.

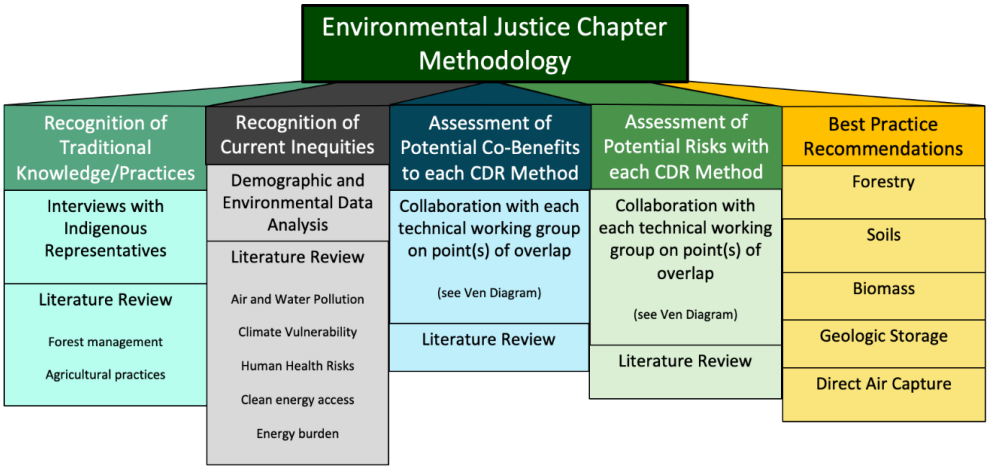

Figure A12. *Outline of methodological approach to our EJ analysis.*

Table A4*: Robust trade-off analysis of potential benefits and risks for each CDR method*.

CDR Method	Duration of C Storage (years)	Socioeconomic Risks to Permanence	Biophysical Risks to Permanence	Potential Co-Benefits to Communities with EJ Concerns	Potential Risks to Communities with EJ Concerns	References
Soil Carbon Sequestration	1 - 100 [1]	Duration depends on ongoing maintenance of land use practices and governance regimes; economic incentives to change land management [1]	Warmer temperatures may increase decay rates of soil organic matter and drought may decrease cover crop yields and associated carbon sequestration [2,3]			[1] CDR Primer, Table 1.4
Cover Cropping				Decreased nitrate pollution in water resources [4]; Reduced air particulate pollution due to wind erosion [5]; Improved soil tilth [5]; Improved crop yields [5]	Funds may go to predominantly (97%) white farmland owners and not tenants [6]; Increased operating costs in the short-term for farmers [5]; Potentially increased herbicide usage [5]	[2] Stockmann et al., 2013; [3] Melillo et al., 2017; [4] Preza-Fontes et al., 2021; [5] Mannering et al., 2000; [6] Gilbert et al., 2002
Forest Carbon Sequestration			Wildfire, drought, and insect-related tree mortality risks increase with changing climate [7]			
Improved Forest Management				Reduced forest fire risks [7,8]; Recognition of indigenous forest management practices [9]	Increased vehicular traffic and associated on-road emissions that reduce air qualtiy due to woody biomass transport [10]	[7] Anderegg et al., 2021; [8] Omi et al., 2002; [9] Findlay, 2021; [10] Anderson et al., 2018
Afforestation and Reforestation				Incentivized reforestation offers alternative for marginally productive lands [11]; Habitat restoration may increase wildlife populations and hunting opportunities [11],	Land competition for alternative uses by the local community [12]	[11] Shabman et al., 2009; [12] Sacco et al., 2021
Urban Forestation				Reduced air conditioning needs from increased shade [13]; Reduced airborne particulate pollution [13]; Reduced stormwater runoff hazards [14].	Exacerbated water scarcity in arid and semi-arid cities; Increased vehicular presence for tree maintenance; Tree abandonment aesthetic and safety risks	[13] Nowak & Greenfield, 2017; [14] Phillips et al., 2019; [15] Petri et al., 2016; [16] Esperon-Rodriguez, 2022
Bioenergy Carbon Removal & Storage (BiCRS)	1,000+ [1]	Mismanagement of geologic storage sites [1]	Supply of biomass could decrease or change spatially with climatic changes [7]	Improved air quality from less biomass burning [17]; Alternative to landfilling for municipal solid waste [18]; Job transition opportunities for communities in fossil fuel production regions [19]	Land competition for alternative uses by the local community [12, 20]; Increased industrial presence [10]; Competition for clean energy [20]; Deincentivizes alternative uses for biomass (e.g. mulching) [20]	[17] Skiles et al., 2018; [18] Pour et al., 2018 [19] Snyder, 2018; [20] Fuss et al., 2018
Direct Air Capture (DAC)			Reliable renewable energy supply for DAC could change with climatic changes [21]	Opportunity to phase out some idle oil wells in favor of geologic storage [22]; Job transition opportunities for communities in fossil fuel production regions [19]	Land competition for alternative uses by the local community [12, 20]; Competition for clean energy [20]; Uncertain emissions, dependent on DAC pathway	[21] Ucal & Xdis, 2020; [22] Syed & Cutler, 2010

Data description

Our EJ analysis will combine demographic, socioeconomic, and environmental data together with our other CDR pathway data products to produce an understanding of the CDR-EJ intersection. Data and maps produced by our teams working on specific CDR approaches will be used to improve the EJ chapter's analyses in an iterative fashion. All of our analyses will involve US Census and EJ Screen (US EPA) data. In general, the complementary data products and maps intended for use in this chapter include:

- **Forestry:** Urban forestry maps (US Forestry Service), Heat island data (US EPA), Tribal Land Maps (Bureau of Indian Affairs), Climate vulnerability assessment (US EPA)
- **Soils:** Land tenure (USDA), Corn-soy hectare data (USDA), Surface water and groundwater quality data (USGS)
- **BiCRS:** Air quality indices (US EPA), Fossil fuel job dependence by county (Snyder, 2018)
- **DAC:** Brownfields locations (US EPA), Energy Burden (DOE), and Low Income Energy Affordability Data tool (DOE)
- **Geologic storage:** Fossil fuel job dependence by county (Snyder, 2018)

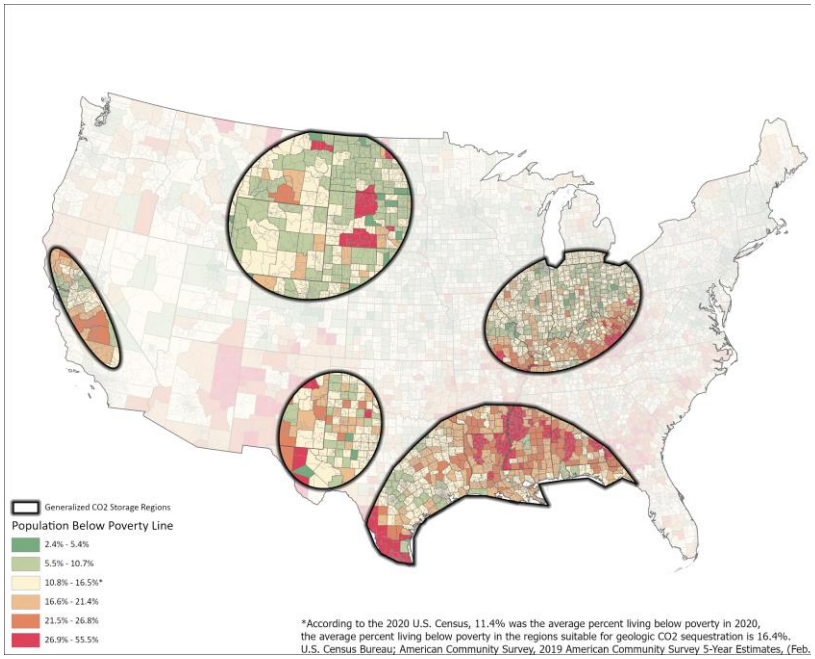

Figure A13. *U.S. Census 2020 percent individuals living below the poverty line overlay within generalized geologic carbon storage regions.*

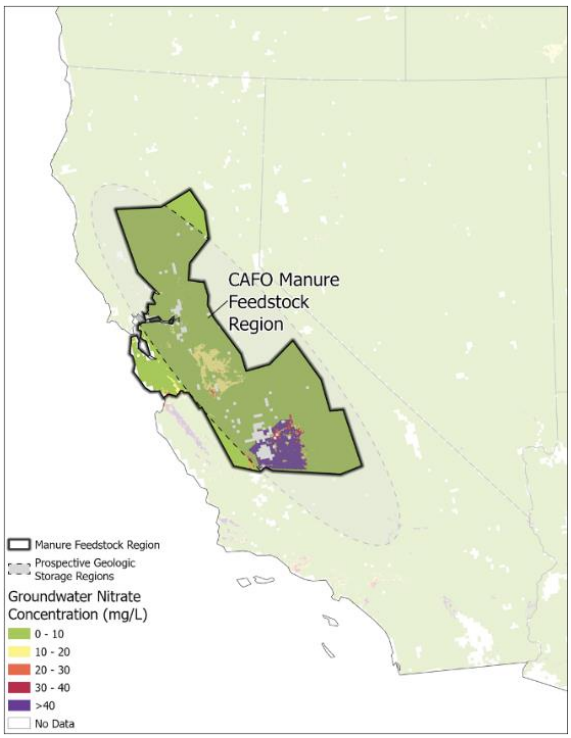

***Figure A14**. USGS nitrate modeled data in groundwater for the western US within the top 50% of corn-soy rotational growing regions. (California zoomed map). Groundwater nitrate concentrations within CAFO manure feedstock region, atop prospective geologic storage region.*

VII. CROSS-CUTTING ANALYSES

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Introduction and Analysis Scope

In the upcoming phase of our National Getting to Neutral project, we will integrate the single CDR pathway results generated in Phase I to develop cross-cutting strategies. Through this process, we will identify and quantify tradeoffs between the primary CDR pathway and related resource competition, opportunities for co-location, and other potential synergies between the primary CDR pathways. Issues of interest in the cross-cutting analyses include (but are not limited to) agricultural land management strategies that supply waste biomass and sequester carbon in soils, low-GHG energy demands of DAC and other energy-intensive sectors, geospatial alignment of CO_2-producing processes and geologic storage sites, expected supply of biochar and other soil amendments based on biomass availability, and expected conversion routes. To tackle these cross-cutting topics, we will employ geospatial analysis, LCA, and systems analysis methods to ensure that the report culminates in comprehensive CDR strategies, while accounting for potential co-benefits or unintended adverse consequences. Issues we will address include the following:

- **DAC phase-in and regional tradeoffs:** The DAC deployment scenarios we generate will be put into the context of US economy–wide decarbonization scenarios. Specifically, the anticipated load profiles will be compared to a range of US electric sector capacity expansion projections produced in prior DOE-sponsored reports and other reputable resources. This is expected to result in recommendations for geographic regions that are more vs. less suitable for DAC deployment, for example, due to potential curtailment issues (and thus low-cost electricity to flexible users like DAC) or transmission investment requirements.
- **Soil-carbon synergies/enrichment:** We will identify land with high potential for soil carbon accrual (marginal land) and develop land/soil management strategies that may include different cropping systems and soil amendments.
- **Competing land-uses:** A critical function of the cross-cutting team is to identify competition for, or complementary uses of, land for DAC, biomass supply, soil carbon sequestration, and forestry. Using regions and strategies identified by the individual teams, the cross-cutting team will develop a framework for allocating land among competing approaches where necessary. The team will also review scenarios for increased production of solar and wind energy to ensure that the CDR scenarios do not hinder deployment of renewable energy production.
- **Water requirements and wastewater management:** Although biomass supply will rely only on rainfed crops, some industrial facilities will require process and cooling water. The cross-cutting team will assemble an inventory of freshwater needs, including separate accounting of consumption and withdrawals. Areas where water scarcity or drought risk are of concern will be flagged and scenarios may be updated to mitigate water-supply risks. Wastewater production will be tracked separately and needs for treatment and disposal of liquid waste streams will be evaluated to identify any additional infrastructure needs to properly handle these streams.
- **Air quality implications:** InMAP or an alternative integrated assessment model (such as APEEP or EASIUR) will be used to evaluate the potential human health impacts of any new pollutant-emitting facilities (e.g., biomass processing facilities) to be cited as part of the broader CDR strategies put forth in this report. Air pollutants of interest include fine particulate matter ($PM_{2.5}$) and precursors to secondary $PM_{2.5}$ (SO_x, NO_x, NH_3, and VOCs). These results will be analyzed on

the basis of their distributional impacts to understand how burdens may vary across different demographic, economic, and racial/ethnic groups.

- Eutrophication impacts: Based on the estimated net impacts on fertilizer application as a result of biomass production scenarios, the team will identify and analyze any concerns associated with excess nitrate and phosphorous releases to water bodies and update scenarios to account for land-management strategies capable of mitigating these concerns.
- Geologic storage sites: Based on locations of geologic storage and potential CO_2 sources requiring sequestration, we will evaluate the cost and energy implications of CO_2 storage and transport and evaluate the possibility of revising CDR scenarios to reduce these costs in cases where tradeoffs exist between extending transportation distances for inputs/feedstocks (e.g., biomass) versus transporting CO_2 to available injection sites. Any co-benefits or unintended impacts of specific injection sites, such as idle/orphaned oil wells, will be assessed and quantified where necessary.
- Impacts on urban energy demand: If CDR scenarios result in substantial increases in urban forests, significant impacts on air quality and urban energy demand will be evaluated and quantified using integrated assessment models and published values for reduced heat island effects on building energy use.

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