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WORKING PAPER

CARBONSHOT: FEDERAL POLICY OPTIONS FOR CARBON REMOVAL IN THE UNITED STATES

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EXECUTIVE SUMMARY

Highlights

- The United States needs to make large-scale investments in carbon removal in the coming years if the country is to achieve carbon neutrality by midcentury.
- This working paper identifies a consolidated set of high-priority, near-term, federal policy options for advancing terrestrial carbon removal.
- These options would require up to $6 billion per year in federal funding over the next 10 years, with the lion's share in this first decade dedicated to restoring trees to the landscape. We expect the need for public funding to increase, especially for technological pathways, to support scaled deployment beyond 2030.
- Compiled deployment scenarios through 2050 illustrate needs and trade-offs to achieve a 2 $GtCO_2$ per year benchmark by 2050—an illustrative but ambitious objective for the carbon removal portfolio and roughly commensurate with the emissions left unabated by 2050 in the U.S. Mid-century Strategy for Deep Decarbonization.
- Advancing a broad set of natural carbon capture and technological carbon removal pathways can significantly reduce the total expected cost of carbon removal, mitigate the risk that some fail to scale to the levels needed, and increase cumulative removals through 2050.

CONTENTS

Working Papers contain preliminary research, analysis, findings, and recommendations. They are circulated to stimulate timely discussion and critical feedback, and to influence ongoing debate on emerging issues. Working papers may eventually be published in another form and their content may be revised.

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Background

Avoiding the worst impacts of climate change will require not only steep reductions in emissions but also the removal of carbon dioxide (CO_2) from the atmosphere at a massive scale (aka, carbon removal). Global climate models leave little ambiguity regarding the critical importance of carbon removal alongside deep emissions reductions to reach and sustain global carbon neutrality—a central requirement for stabilizing global temperature rise to 1.5°C or even 2°C above preindustrial levels (IPCC 2018).

A wide range of carbon removal pathways can augment the net removal of carbon from the atmosphere to plants, soils, the built environment, and underground geological formations. This includes low-tech natural carbon capture methods like tree restoration and agricultural soil management, high-tech methods like direct air capture, and emerging concepts like enhanced mineralization. Carbon removal is distinct from measures that reduce anthropogenic emissions to the atmosphere, such as carbon capture and storage (CCS) with fossil energy, avoided land use conversion, and cropland nutrient management. Carbon removal is also distinct from solar radiation management, which seeks to reflect incoming sunlight to reduce warming rather than remove carbon from the atmosphere.

Dedicated federal investment is needed to realize substantial untapped opportunity for natural carbon capture and to close a gap between current capabilities for technological carbon removal and the estimated need. Realizing the carbon removal potential in the natural pathways will require public funding to close the gap between total costs and the value of generated co-benefits. Technological pathways will require sustained investments in research and development as well as commercialization support.

About This Working Paper

The purpose of this working paper is to provide a consolidated set of high-priority, near-term federal policy options to advance carbon removal capabilities and deployment in the United States (Table ES-1). This paper is the fourth installment of a World Resources Institute (WRI) publication series, CarbonShot: Creating Options for Carbon Removal at Scale in the United States. This series presents findings from a WRI-led assessment of needs for scaling terrestrial-based carbon removal in the United States. This paper focuses on prioritized federal policy options across the carbon removal portfolio.

We group pathways into four categories—Staples, No Regrets, Speculative Bets, and Supplemental Pathways—based on shared characteristics relating to potential scale, cost, uncertainty, and co-benefits. Carbon removal pathways in the first three categories represent priorities for advancement. For these pathways, the paper puts forward policy options that are designed to address key barriers to deployment or deployment readiness and achieve rapid scale-up while maximizing public return on investment. The assessment looks to past successful climate policies for models and relies heavily on policy needs posited by the National Academies of Sciences, Engineering, and Medicine (hereafter, the National Academies) and others. We also point to key components of a strong enabling environment for scaling carbon removal.

Notably, the pathway-by-pathway policy design approach taken in this assessment is a departure from past attempts at federal deployment policy, which would have used cap-and-trade to activate a broad set of practices and technologies together rather than tailoring policy incentives to individual pathways. This assessment focuses on pathway-by-pathway policy design to enable more modular approaches to policymaking. This reflects a strategic judgment that narrower policy proposals have been underappreciated and may be more politically feasible.

Prioritized Federal Policy Options

We group pathways into four broad categories based on shared characteristics:

- **Staples.** These pathways are essential components of the carbon removal portfolio. Potential may be politically uncertain but is reasonably clear technically and outsized relative to other pathways—either in terms of annual removal rates or achievable cumulative removal through 2050.
- **No Regrets.** The potential of these pathways appears to be meaningful but subject to higher technical or economic uncertainty than the Staples pathways. Relatively low costs (<$50 per ton) and the prospect of significant co-benefits make the case for investment despite that uncertainty.

- **Speculative Bets.** These pathways require further development before they can be deployed. The upper-bound potential of these pathways is outsized relative to other pathways, but plausibly achievable potential is poorly understood due to technical or economic unknowns. Additional research and development is needed to clarify potential.
- **Supplemental Pathways.** The upper-bound potential of these pathways is relatively clear and relatively modest—generally less than 200 MtCO$_2$ per year. There is also no upside potential—to the contrary, actual potential is likely to be more limited due to unknown technical or economic constraints. Deployment challenges combined with high costs and/or a relative lack of co-benefits diminish the case for prioritizing these pathways. However, together these pathways could make a meaningful contribution to a broader portfolio.

Staples in the carbon removal portfolio

1. Tree restoration campaign
   - The opportunity in the United States to restore trees to the landscape in various forms ("tree restoration") appears to be significant. A new tax credit, direct payment program, and/or state grant program to underwrite tree restoration in targeted areas over the next 20 years could be one of the most powerful carbon removal measures through 2050. We estimate that tree restoration on one-third to two-thirds of suitable acres can remove **180–360 MtCO$_2$ per year** on average without displacing agricultural land uses (upper bound: 540 MtCO$_2$ per year). Tree restoration can provide over **7 GtCO$_2$** in cumulative removals by 2050, more than any other pathway.
   - As a first step, allocating **$1–2 billion per year** to federal subsidies for tree restoration would capture low-hanging fruit opportunities, build critical implementation experience, and serve to improve characterization of the scale of opportunity and full funding need.

Table ES-1 | **Summary of Prioritized Federal Policy Options**

POLICY OPTION	CATEGORY	PROPOSED AVERAGE ANNUAL FEDERAL INVESTMENT (2020-30)	PLAUSIBLE CARBON REMOVAL BY 2050 (MTCO$_2$ PER YEAR)
Tree restoration campaign	Staples	$4–4.5 billion	180–360
Federal direct air capture technology development program, including an expanded 45Q tax credit	Staples	$633 million	190–1,400
10-million-acre farm innovation program	No Regrets	$500 million	100–200
Foundational research program for carbon mineralization	Speculative Bets	$25 million	Negligible–410
Accelerated development of enhanced root crops	Speculative Bets	$40–50 million	0–185
BECCS	Supplemental Pathways	Not prioritized	Negligible–180 (plus possibility of displaced fossil emissions)
Wood waste preservation	Supplemental Pathways	Not prioritized	Negligible–<90
Extended timber rotations	Supplemental Pathways	Not prioritized	Negligible–25

Source: Author calculations based on estimates in the literature and assumed rates of deployment; see "Tree Restoration" chapter through "Supplemental Pathways" chapter for more information.

- Fully capturing the identified upper-bound potential would require an estimated **$4–4.5 billion** per year over 20 years. This estimate is sensitive to the degree to which landowners will require financial incentive to compensate for “hidden costs” associated with tree restoration, including transaction costs, monitoring costs, and the opportunity cost of land use. Additional funding could accelerate the pace of tree restoration.

- Priority areas for restoring trees to the landscape include reforesting disturbed or abandoned nonagricultural land in areas that are ecologically appropriate for trees, restoring stocking levels in existing private and public timberlands, expanding urban tree cover, and integrating trees into agricultural systems. While the federal government itself manages extensive areas of forestland, the vast majority of potential to restore trees to the landscape is on nonfederal lands, predominantly under private ownership.

- Several design elements will have significant bearing on the effectiveness and efficiency of a tree restoration subsidy—especially how the value of the subsidy is determined, whether third-party implementers are eligible recipients of federal funding, and how program safeguards are designed to ensure ecological appropriateness, additionality, and tree survival.

2. Federal direct air capture technology development program

    - A dedicated technology development effort singularly focused on driving down the cost of direct air capture is critical for the accessibility of this eminently scalable carbon removal pathway. Direct air capture could plausibly provide **more than 1 GtCO_2 per year** in removals toward midcentury but is unlikely to provide meaningful levels of carbon removal until well after 2030. Depending on the pace of scale-up, cumulative removals by 2050 may be anywhere from **2 to 7 GtCO_2**.

    - Publicly funded technology development driven by the Department of Energy is critical for developing and pilot testing novel components and systems, facilitating their commercialization, and ensuring that lessons learned and data from these efforts are shared with labs, universities, and engineering companies in the nation’s broader innovation ecosystem.

    - Spurring private sector innovation and deployment experience is also a critical complement to a public technology development program. Several amendments to the 45Q tax credit are required to kick-start private investment to the needed scale, including extending the commence construction deadline, lowering the minimum capture threshold, and increasing the credit value for direct air capture.

    - This program will require **$150 million per year** on average over the next 10 years for basic and applied research, pilot testing, and a larger-scale demonstration of promising systems. The funding need in the first years is closer to $60 million per year but will increase over time. An additional **$360 million** in tax expenditures would be needed **per year by 2025** to support the scale of deployment envisioned, increasing to **$1.3 billion** by 2030, with further increases as the technology scales. In comparison, 2018 tax expenditures totaled $8 billion for solar and wind power and over $3 billion for fossil fuels (Sherlock 2019).

    - Subsidizing direct air capture deployment with direct subsidies like the 45Q tax credit is far more cost-efficient than subsidizing synthetic fuel derived from air-captured CO_2—until the cost of converting CO_2 to fuel is reduced substantially.

No Regrets

3. 10-million-acre farm innovation program

    - Agricultural soil carbon management is a No Regrets pathway in that practices that enhance soil carbon can also yield other benefits, including reduced water runoff and erosion, improved water quality, and in some cases farm profitability.

    - While soil management efforts have historically centered on deploying just a few practices—such as no-till farming and cropland retirement—a program that incorporates a broader array of innovative soil management practices will be better positioned to scale up across the heterogeneous land base of U.S. agriculture with less risk of undoing carbon removal gains through practice reversal or leakage. Some practices, like cover cropping, have well-established carbon removal benefits and could reasonably be implemented on agricultural lands throughout much of the United States; other practices are less ready for scaled deployment due to scientific uncertainty or infrastructure requirements but could provide significant carbon removal benefits in the longer term following initial investments in research and demonstration.

- Agricultural soil carbon management could plausibly remove **100–200 $MtCO_2$ per year** by 2050, consistent with adopting soil management practices on between one-third and two-thirds of agricultural acres nationally (upper bound: 300 $MtCO_2$ per year). This estimate is subject to considerable uncertainty due to widespread variation in the viability and efficacy of different soil management practices. However, deploying shovel-ready soil management practices at scale offers the prospect of significant cumulative carbon removal through 2050—over **2 $GtCO_2$**.
- Combining federal cost-share and technical assistance with on-farm research and monitoring will accelerate adoption of agricultural soil management practices while advancing understanding of their potential benefits and limitations. This policy would be a natural extension of existing Farm Bill Conservation Title programs. It would require up to **$500 million per year** to reach and maintain a 10-million-acre enrollment threshold, which would enable statistically robust inferences from monitored results and proof points to underpin further scaling. The program would likely need to run for 10 years and then transition to scaling up adoption of soil management practices.
- Lessons learned from this program can inform targeted scale-up of financial and technical assistance for the most promising soil management practices in a cost-effective manner that seeks to maximize persistence of practice adoption.

Speculative Bets

4. Foundational research program for carbon mineralization
    - Scaling carbon removal through surficial (aboveground) mineralization will require utilizing abundant but challenging underground source material like basalt, rather than readily available and more reactive but ultimately limited material like alkaline industrial waste. Orienting public research around mineralization approaches that can utilize these abundant source materials and, ideally, produce commodities like aggregate with some economic value, will clarify opportunities to scale surficial mineralization as a carbon removal pathway. Promising in situ (underground) concepts that provide not only storage but also removal from the atmosphere are just emerging.
    - Surficial approaches have the potential to store **410 $MtCO_2$ per year**, assuming one-third penetration of the U.S. market for aggregate, or **2–3 $GtCO_2$** cumulative through 2050, assuming linear scale-up from effectively 0 $MtCO_2$ per year in 2040.
    - Roughly **$25 million per year** in federal research and development funding would likely be adequate for a well-targeted program until approaches warranting public incentive are demonstrated.
    - Validated approaches would progress to field-testing and demonstration while others are discontinued. Research should also examine potential environmental and social impacts.
5. Accelerated development of enhanced root crops
    - The prospect of developing new and enhanced root crop varieties—through either selection or gene editing—with deeper and more robust root systems to increase soil carbon without sacrificing yields is enticing but requires additional research to understand the practical feasibility.

- Estimates of potential remain highly theoretical but point to storage potential on the order of **185 $MtCO_2$ per year** or 1 $GtCO_2$ cumulative through 2050, assuming linear scale-up from 0 $MtCO_2$ per year in 2040.

- A significant increase—**$40–$50 million per year**—in current efforts by the Department of Energy's Advanced Research Projects Agency–Energy (ARPA-E) in this area would need to be sustained over a decade or longer to accelerate development of new or enhanced varieties of major crop types. An initial time-bound investment to achieve proof of concept may be appropriate before continuing such a program.

Supplemental Pathways

- Several pathways are unlikely to be the difference-makers on their own, given relatively limited upper-bound potential, but together they may add up to a meaningful contribution in a carbon removal portfolio.

- Several applications of bioenergy with carbon capture (BECCS) can reduce emissions to the atmosphere by displacing fossil energy—although the full life-cycle effects depend heavily on the source of the feedstock. Some forms of BECCS can also provide net carbon removal. The clearest opportunity for net carbon removal is to utilize biomass that would otherwise decompose and return carbon to the atmosphere—effectively adding permanence to carbon removal that occurs naturally already. By utilizing available forestry and agricultural by-products in the United States, BECCS could provide an estimated **180 $MtCO_2$ per year** in net carbon removal assuming typical losses in conversion, with the possibility of significant additional carbon gains (up to 125 $MtCO_2$ per year in the power sector) from fossil energy displacement. However, practical potential is likely lower given competing demands for these feedstocks, significant competitive disadvantages in the power sector, and only partial capture in the use of BECCS for most fuels. Other feedstocks can be used but are unlikely to provide net carbon removal given emissions associated with harvest and forgone sequestration (whole tree biomass), or indirect land use change effects (dedicated energy crops).

- Wood waste preservation would effectively extend the carbon removal benefit of past forestry activities and harvested wood products but is limited to **less than 90 $MtCO_2$ per year** assuming full preservation of wood in municipal solid waste and construction and demolition waste in the United States.

- Extended timber rotations would provide clear localized carbon gains by temporarily reducing timber harvest and boosting average sequestration rates in managed timber stands. This pathway would need to be phased in to avoid disrupting U.S. timber markets. Extending rotations on up to 1 million acres per year would maintain U.S. timber production within 10 percent of recent levels. We estimate that total U.S. potential from this phased approach—accounting for likely significant leakage of timber production to other areas—is roughly **25 $MtCO_2$ per year by 2050** (upper bound with safeguards, assuming no leakage: 50 $MtCO_2$ per year).

Creating a Strong Enabling Environment

Several investments in infrastructure, technology, markets, and data systems can directly or indirectly facilitate the scaled deployment of one or more carbon removal pathways. These needs tend to be cross-cutting. They are also not unique to carbon removal, and several may advance for reasons having little to do with carbon removal. However, all are critical for carbon removal. We profile each of the components of a strong enabling environment. While we do not prioritize policies for the enabling environment, we identify clear needs especially as they relate to carbon removal pathways and lay out several federal actions that would support a strong enabling environment for carbon removal (Box ES-1).

- **Low-cost carbon-neutral energy.** Rapid expansion of renewable and other low-carbon energy is critical not only for decarbonizing major emitting sectors but also to power the carbon removal engine. Several carbon removal pathways will rely on abundant carbon-neutral energy, and the cheaper the better. Direct air capture is particularly energy-intensive. Mineralization will require low-carbon energy for mining, processing, and transporting alkaline material. BECCS actually produces energy, but at much higher cost than renewable energy and fossil CCS. Direct air capture, BECCS, and fossil CCS will benefit from the cheap production of hydrogen to facilitate various forms of CO_2 utilization.

- **Credible life-cycle assessment.** Life-cycle assessments provide full accounting of greenhouse gas removals and emissions over the life cycle of a process or product. Robust life-cycle assessment is critical to the entire enterprise of scaling carbon removal, utilization, and storage. Technology developers, investors, regulators, and legislators all need standardized ways to measure and validate claims about the full life-cycle impacts of carbon removal and utilization pathways. Leadership in this arena by government agencies with technical expertise would be valuable if the process can be properly insulated from political influence.
- **CO_2 pipelines**. An expanded CO_2 pipeline network may be needed to connect direct air capture, BECCS, and fossil CCS facilities to storage reservoirs and utilization endpoints. There may be a federal role in pipeline mapping, scenario planning, and/or potentially in providing federal finance to oversize pipelines in anticipation of larger future demand.
- **Safe and effective geological storage of CO_2.** Geological sequestration of captured carbon is already occurring in the United States without incident. Nonetheless, investing in improved methods to facilitate rapid site selection and improve monitoring effectiveness would allow for more rapid scaling of CO_2 sequestration and build public confidence. The National Academies identify $250 million per year in needed federal research and development over the coming 10 years to improve storage methods.
- **Technology and markets for CO_2 utilization.** Spurring markets for the utilization of CO_2 in products and commodities can facilitate deployment of both carbon removal and emissions reduction pathways that yield concentrated streams of CO_2. Research and technology development will be needed in this arena, along with procurement and product standards to kick-start a new carbon economy.
- **Natural carbon sink monitoring systems.** The federal system for monitoring carbon stock changes above- and below-ground is the underpinning for any policy effort to safeguard and grow the natural carbon sink. Yet major deficiencies in the accuracy, timeliness, and spatial granularity of this monitoring system frustrate efforts to confidently track progress

Box ES-1 | Concepts for Federal Action to Support a Strong Enabling Environment for Carbon Removal

1. Establish a federal authority charged with ensuring the development of a wide range of on-grid and off-grid low-carbon energy sources to power a carbon removal and utilization economy.
2. Establish an independent governmental or quasi-governmental scientific commission to conduct credible life-cycle assessment and provide accounting frameworks for government regulations.
3. Extend and enhance the CarbonSafe program to continue to build the scientific and engineering knowledge to facilitate safe and effective geological storage operations—including saline aquifer storage and in situ mineralization (NAS 2018a).
4. Review permitting requirements for CO_2 injection and storage in saline aquifers (Class VI well permits) to ensure both adequate safeguards and workability for industry.
5. Strengthen the 45Q tax credit for CCS to incentivize storage in saline aquifers.
6. Assess requirements for CO_2 pipelines to enable scale-up of direct air capture and BECCS and consider public-private partnerships to develop and size CO_2 pipelines to service a deep decarbonization future with significant carbon removal.
7. Invest in technology development for CO_2 utilization technologies.
8. Establish federal procurement programs for products and commodities that utilize captured CO_2.
9. Boost technical and financial resources provided to states to develop and implement state programs for natural carbon capture.
10. Integrate remote sensing tools, including light detection and ranging (LiDAR), into the Forest Inventory and Analysis (FIA) program to sharpen the nation's forest carbon monitoring system.
11. Reinstitute soil carbon sampling in the National Resources Inventory (NRI) field plots.
12. Improve the accessibility of U.S. Department of Agriculture (USDA) data to academic researchers to facilitate scientific advances in soil carbon sequestration while protecting privacy and confidential business information.
13. Provide grants or incentives to states and communities that implement smart growth plans to prevent conversion of natural forests and grasslands.
14. Invest in research, development, and demonstration (RD&D) for agricultural productivity and rural broadband to support adoption of existing technologies like precision agriculture.

toward climate goals, evaluate the efficacy of past policies, and identify new policy interventions. Federal investments are needed to expand sampling networks, integrate field data with remote sensing tools, establish landscape-level monitoring systems for carbon removal, and build out data platforms to facilitate data-sharing and transparency.

- **Increased efficiency in the use of land.** Measures to limit conversion of natural forests and grasslands, continued increases in agriculture and forestry productivity, and broader efficiency improvements in the food and agriculture system like reducing food loss and waste and adopting plant-rich diets with a smaller land footprint are all important in combination to maintain existing forest cover and facilitate additional opportunities to restore natural ecosystems. For example, due to indirect land use change effects, increasing agricultural productivity by 6 percent on a given acre can provide comparable net carbon gains to planting cover crops on the same acre (Widmar 2018; Searchinger et al. 2019; Berry 2011; Poeplau and Don 2015). Public research and development for agricultural productivity—an important climate strategy—has stagnated in real terms since the 1980s.

Visualizing Success

The scenarios below illustrate deployment of the portfolio of prioritized carbon removal pathways in the United States at the 2 $GtCO_2$ per year scale by 2050 (Figures ES-1a and ES-1b). Removals at this scale—a little more than 30 percent of total 2017 greenhouse gas (GHG) emissions in the United States—would make a substantial contribution to the broader mitigation portfolio. Based on estimates of total potential and plausible deployment time frames, it also represents an ambitious objective for the carbon removal portfolio. It is also likely the United States will need carbon removal at roughly this scale by 2050 to reach and maintain carbon neutrality in line with limiting global temperature rise to 1.5°C. The U.S. Mid-century Strategy for Deep Decarbonization, for example, left roughly 2.55 $GtCO_2$ of gross annual emissions unaddressed in its benchmark scenario (White House 2016). The current U.S. land sink offsets roughly 720 $MtCO_2$ per year but is projected to decline through 2050 due to aging forests, forest disturbance, and forest conversion (Oswalt et al. 2019, 237). Similarly, Larsen et al. (2019) found a residual need for roughly 2 $GtCO_2$ per year in carbon removals to reach carbon neutrality by 2045. Considering a global need for as much as 10 $GtCO_2$ (or more) per year in carbon removals by 2050 and the clear importance of U.S. leadership in global mitigation efforts—and especially in technology development—the 2 Gt benchmark adopted here may be best viewed as a starting point rather than an endpoint for U.S. investment in carbon removal.

Deployment scenarios

For each pathway, we bound deployment between a low and high scenario. Scenarios constrain the timing and pace of deployment for each carbon removal option to account for various requirements and assumptions related to time frames for policy investments and adoption. In the near term, we impose a $50 per ton constraint that limits deployment from technological pathways. Between 2030 and 2040, we relax the cost constraint to $150 per ton, reflecting an expectation that the social cost of carbon—and the public's willingness to pay for carbon removal—will increase toward midcentury. All estimates of mitigation potential are additional to carbon removal occurring already through ongoing practices like reforestation and cover cropping, as these "baseline" rates of carbon removal are assumed to be factored into business-as-usual GHG emissions projections.

- **Tree restoration**: 180–360 $MtCO_2$ per year by 2040, sustained through 2050. This range represents tree restoration on one-third to two-thirds of suitable acres, given the possibility that landowner preferences may limit tree restoration in some portion of the available area.
- **Direct air capture**: 190–1,400 $MtCO_2$ per year by 2050. The scale-up rate assumes 20–30 percent annual growth from 2 $MtCO_2$ by 2025, broadly consistent with Larsen et al. (2019) through 2040. Between 2040 and 2050, direct air capture is treated as "last in" due to relatively high cost and is scaled to fill the gap in each scenario between other pathways and the 2 Gt target.
- **Agricultural soil carbon management**: 100–200 $MtCO_2$ per year by 2050. This range reflects plausible deployment of soil management practices on one-third to two-thirds of suitable acres, reflecting challenges in reaching all farmers through federal

policy and overcoming technical and cultural obstacles. Removal rates increase linearly from 2030 to 2050, following an initial 10-year "farm innovation" program that removes 5 $MtCO_2$ per year.

- **Carbon mineralization**: Negligible–410 $MtCO_2$ per year by 2050. The low end reflects the possibility that mineralization approaches may not provide meaningful removals at all due to technical and logistical constraints. The high end would require replacing one-third of the total U.S. market for aggregate with synthetic mineralized aggregate. Some demonstration-scale deployment occurs between 2030 and 2040; scaled deployment increases linearly between 2040 and 2050.
- **Enhanced root crops**: 0–185 $MtCO_2$ per year by 2050. The low end reflects the possibility that crop-breeding efforts may not successfully produce deep-rooted varieties that increase carbon sequestration while maintaining yields. The high end would require developing new crop varieties that mimic the root depth and distribution of perennial grassland species for major crop varieties. Distribution of deep-rooted varieties begins in 2040, and 100 percent replacement is achieved by 2050. Technical potential could be higher if all crop varieties, or even noncrop plants, are considered and/or if varieties are developed with root distribution that results in greater soil carbon input than perennial grasses provide.
- **BECCS**: Negligible–180 $MtCO_2$ per year by 2040, sustained through 2050—and with additional potential for emissions reductions by displacing fossil energy. The low end reflects the possibility that competing demands for available feedstocks limit deployment of BECCS in ways that provide meaningful net carbon removal. The upper bound would require full utilization of available forestry and agricultural by-products by 2040 at 50 percent conversion efficiency.
- **Wood waste preservation**: Negligible–90 $MtCO_2$ per year by 2040, sustained through 2050. The low end reflects the possibility that waste wood is diverted for other uses. The high end would require full preservation of all wood in municipal solid waste and construction and demolition waste in the United States by 2040.
- **Extended timber rotations**: Negligible–25 $MtCO_2$ per year by 2050, with continued growth thereafter. The low end reflects the possibility that timber companies and private timberland owners are unwilling to significantly reduce harvests, even in the presence of public subsidies. The high end assumes that rotations are extended on 1 million acres of timberland per year.

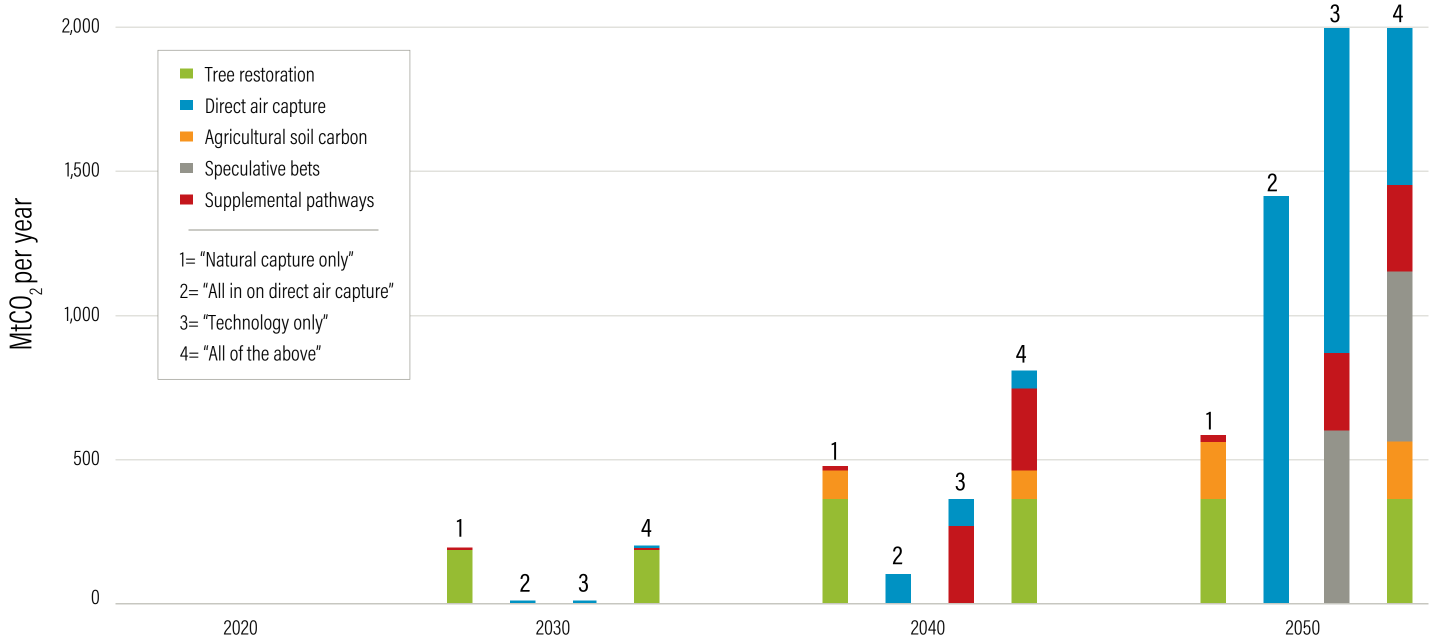
We plot the following scenarios through 2050:

- **Scenario 1. Natural Capture Only**: Ambitious achievement of potential in the natural capture pathways alone. No investment in technological pathways.
- **Scenario 2. All In on Direct Air Capture**: Full investment in direct air capture development and deployment. No investment in technologies other than direct air capture.
- **Scenario 3. Technology Only**: Broad-based and successful technology development and deployment. No realization of natural capture potential.
- **Scenario 4. All of the Above**: Full deployment of all pathways, reducing but not eliminating the need for direct air capture—which is assumed to be the highest-cost pathway.

Key insights

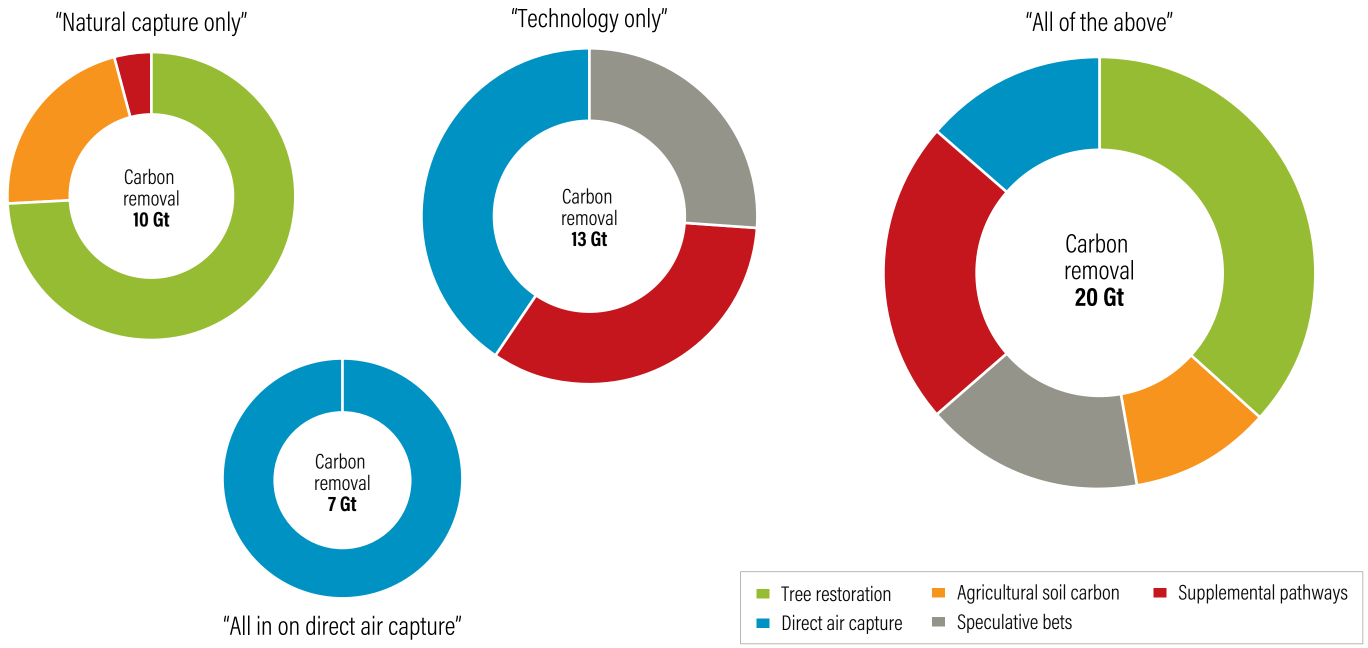
- **An all-of-the-above portfolio is the most robust.** Pursuing all pathways for carbon removal could enable considerably more cumulative carbon removal through 2050 than any other scenario. Natural carbon capture pathways alone are incapable of reaching a 2 $GtCO_2$ per year target. A technology-only or direct-air-capture-only portfolio could reach this level of deployment by 2050 (or shortly thereafter) but would yield considerably less cumulative removal over that period. An all-of-the-above portfolio is also the most risk-averse strategy because it creates the most options for achieving the 2 Gt target by 2050, should any single pathway fail to realize its expected potential. Assuming direct air capture remains the highest-cost pathway, the all-of-the-above portfolio is also the least-cost scenario. Because this scenario still requires aggressive development of direct air capture technology, this scenario positions direct air capture to scale beyond 2050.

Figure ES-1a | Carbon Removal Deployment Scenarios



Source: Author calculations based on estimates in the literature and assumed rates of deployment; see "Pathway-by-Pathway Deployment Scenarios" section for more information.

Figure ES-1b | Cumulative Carbon Removal in 2050 of Each of the Above Scenarios (GtCO$_2$)



Source: Author calculations based on estimates in the literature and assumed rates of deployment; see "Pathway-by-Pathway Deployment Scenarios" section for more information.

- **Natural pathways rack up cumulative removals.** Despite having lower annual removal potential than direct air capture, the natural carbon capture pathways can provide significant cumulative removals through 2050 because they can be deployed at scale much sooner. However, saturation rates will eventually diminish the contribution from natural pathways, underscoring the need for technological pathways.
- **Direct air capture is a requirement.** Achieving a 2 $GtCO_2$ per year carbon removal target—roughly the scale needed to achieve carbon neutrality—requires direct air capture no matter how successfully natural and other technological carbon removal pathways are scaled. Even the scenario with the least direct air capture deployment by 2050 would still rely on beginning aggressive technology development efforts in the coming years.
- **Investing now in carbon removal technologies is critical for harnessing significant removals by 2050.** The time required for technological development inhibits the total carbon removal that can be provided by emerging technologies prior to 2050.

ABBREVIATIONS

ARPA-E	Advanced Research Projects Agency–Energy
BECCS	bioenergy with carbon capture and storage
CCS	carbon capture and storage
CLT	cross-laminated timber
CO_2	carbon dioxide
CRP	Conservation Reserve Program
CSP	Conservation Stewardship Program
DAC	direct air capture
DOE	Department of Energy
EOR	enhanced oil recovery
EPA	Environmental Protection Agency
EQIP	Environmental Quality Incentives Program
FIA	Forest Inventory and Analysis
GEDI	Global Ecosystem Dynamics Investigation
GHG	greenhouse gas
GJ	gigajoules
GRACEnet	Greenhouse Gas Reduction through Agricultural Carbon Enhancement Network
$GtCO_2$	gigaton (one billion metric tons) of CO_2
ITC	Investment Tax Credit
LiDAR	light detection and ranging
LTER	Long-Term Ecological Research
MPa	megapascal
$MtCO_2$	megaton (1 million metric tons) of CO_2
NASA	National Aeronautics and Space Administration
NEON	National Ecological Observatory Network
NLCD	National Land Cover Database
NPV	net present value
NRCS	Natural Resources Conservation Service
NRI	National Resources Inventory
NSF	National Science Foundation
psi	pounds per square inch
PTC	Production Tax Credit
PVC	polyvinyl chloride
RCPP	Regional Conservation Partnership Program
RD&D	research, development, and demonstration
tCO_2	metric ton of CO_2
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey

INTRODUCTION

The Call for CarbonShot

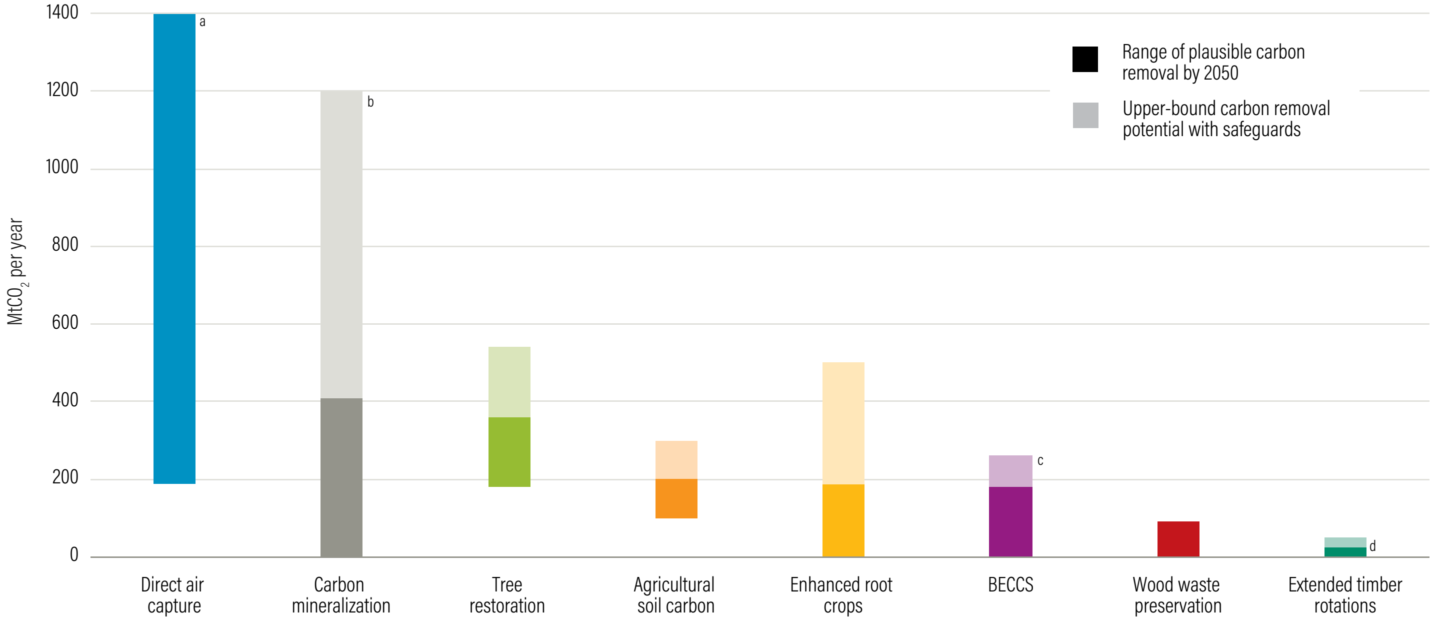
Over the past few years it has been well established that avoiding the worst impacts of climate change will require not only steep reductions in emissions but also the removal of carbon dioxide (CO_2) from the atmosphere at a massive scale (IPCC 2018; NAS 2018a; Minx et al. 2018; Mulligan et al. 2018b). Most global scenario planning models indicate the world will need to remove many gigatons ($GtCO_2$) from the atmosphere each year by 2050—as much as double the current annual emissions of the United States—in order to stabilize global temperature rise in the range of 1.5–2°C above preindustrial levels (Fuss et al. 2018).

The capabilities for carbon removal at this scale do not yet exist.

CO_2 can be captured naturally in forests, agricultural soils in grasslands and croplands, wetlands, and marine systems (Figure 1).[1] Natural carbon capture pathways are readily deployable and offer significant and generally cost-effective carbon removal potential. Yet considerable efforts—and public investment—will be needed to realize the untapped potential of natural carbon capture.

And still more will be needed. The estimated total need for carbon removal over the course of this century exceeds what natural carbon capture can provide (NAS 2018a). This gap necessitates the development of technological pathways for large-scale carbon removal. Several emerging technologies hold promise (Figure 1), but they will require significant and sustained policy investments in technology development to enable deployment at the needed scale.

Figure 1 | **Estimated Terrestrial Carbon Removal Potential per Year by 2050 Given Safeguards and Expected Constraints on Deployment**



Notes:

[a] Upper-bound potential for DAC is technically unlimited.

[b] Estimates for carbon mineralization are constrained by level of market penetration of economic products made via carbon mineralization processes.

[c] BECCS can also provide emissions reductions by displacing fossil energy. That potential is not reflected here.

[d] Estimate is constrained by feasible rate of scale-up and likely leakage effects.

Source: Author calculations based on estimates in the literature and assumed rates of deployment; see "Pathway-by-Pathway Deployment Scenarios" section for more information.

As challenging as this endeavor will be, it also offers real opportunity. Natural carbon capture has the potential to enhance productivity, profitability, and resilience in U.S. farms, forests, and rural communities (Oldfield et al. 2019; Abdalla et al. 2019; Vasievich and Alig 1996). Technological carbon removal offers the prospect of new industries, new employment opportunities, and global leadership in developing new technologies.

The federal government is a key player in technology development through investments in basic and applied science, demonstration-scale deployment, and commercialization support. The federal government also maintains an extensive policy and administrative infrastructure that heavily influences land management in both farms and forests—and is itself the largest landowner in the United States. As a result, the federal government has several critical roles to play in addressing barriers to natural and technological carbon removal.

Objectives of This Paper

The purpose of this working paper is to provide a consolidated set of high-priority, near-term federal policy options to advance carbon removal capabilities and deployment in the United States. This option set is not comprehensive—there is no shortage of good ideas for advancing carbon removal through federal policy. The options presented in this paper are the product of a set of design principles intended to highlight the most effective levers available to federal policymakers. These options are also not intended to be narrowly prescriptive—several variations of the same options could achieve similar results. Instead, they are intended to illustrate the application of key policy design principles. The best and most durable policy packages are the product of processes that cultivate multistakeholder dialogue and compromise. The options presented here are intended to serve as inputs to those kinds of processes.

Approach

This assessment seeks to identify a set of the most powerful policy options for carbon removal. We develop policy options for each carbon removal pathway in line with a set of prioritization principles. A series of deployment scenarios then illustrates the role and relative importance of each pathway in hitting a 2 $GtCO_2$ per year target in the United States by 2050. We also identify key components of a strong enabling environment for scaling carbon removal.

Defining pathways

Pathways are first defined drawing on practices and technologies commonly referenced in the literature. Individual practices or technology configurations that can be advanced together with a clear and coherent federal policy mechanism are grouped together into pathways for policy design. This ensures that the level of aggregation is commensurate with the potential achievable by clear federal actions. We assess the following pathways:

- **Tree restoration**: Establishing trees in historically forested areas through reforestation of undeveloped nonagricultural lands, restocking timber lands, agroforestry in croplands, silvopasture, and urban reforestation.
- **Agricultural soil carbon management**: Implementing practices like cover cropping, compost amendment, and grassland restoration that build soil organic carbon stocks in croplands and grazing lands.
- **Direct air capture (DAC)**: Capturing and concentrating CO_2 from ambient air using chemical reactions that bind CO_2 or potentially other engineered approaches that serve a similar function.
- **Carbon mineralization**: Emulating and accelerating natural reactions between reactive rocks and CO_2 in the air that result in capture and/or permanent storage of carbon by formation of carbonate minerals either at the earth’s surface or underground.
- **Enhanced root crops**: Developing crop varieties that have deeper, larger, and/or more recalcitrant roots that result in greater storage of carbon in soils and/or in the root tissues themselves.
- **Bioenergy with carbon capture and storage (BECCS)**: Cultivating biomass, which extracts CO_2 from the atmosphere as it grows, for combustion in power plants outfitted with carbon capture and storage technology, allowing for permanent storage of CO_2.
- **Wood waste preservation**: Preserving the embodied carbon in wastes from wood product disposal, construction and demolition, or other activities, for example by routing the wood to alternative landfills designed to slow decomposition.
- **Extended timber rotations**: Temporarily suspending timber harvests on natural forests, followed by a reinstatement of harvests with a longer harvest cycle.

More information on assessed pathways can be found in Table 1. Coastal and peat ecosystem restoration pathways, including peatland restoration, tidal restoration, and seagrass restoration, were also considered (as shown in Figure 1), but they were ultimately excluded from this assessment because the scale of potential referenced in the literature for these pathways is not significant in the context of a national carbon removal portfolio (Fargione et al. 2018).

Ocean-based carbon removal pathways are not included in the scope of this federal policy assessment. Other promising pathways like avoided land use conversion, fire management, and cropland nutrient management, which predominantly reduce anthropogenic emissions rather than actively drawing carbon out of the atmosphere, are also excluded. However, these measures can also play a significant role in a balanced portfolio of climate change mitigation measures and may be necessary in some cases to protect carbon removal gains from natural pathways.

Sizing up potential

A common approach to estimating the potential of a climate change mitigation strategy is to evaluate its maximum possible deployment given basic technical constraints on essential requirements like land or feedstock meeting certain suitability criteria. This approach belies political, economic, and social constraints as well as logistical challenges affecting the plausible rate of scale-up within a relevant time frame, but it avoids imposing arbitrary judgments on these factors, which are typically highly uncertain.

This assessment offers three estimates of potential for each pathway to provide broader perspective on possibilities and challenges:

- **Upper bound with safeguards.** This estimate limits potential based on technical factors only. We impose constraints to protect natural ecosystems and food production. This estimate is not specific to a time period and does not consider plausible scale-up rates. For pathways affected by biophysical uncertainty that has been quantified, this estimate is presented as a range.
- **2050 high scenario.** This estimate discounts the upper bound with safeguards to reflect several assumptions developed for each pathway to reflect technology development time frames, economic and logistical constraints on the rate of scale-up through 2050, and other likely barriers. This estimate reflects an optimistic view.
- **2050 low scenario.** This estimate reflects a less optimistic set of assumptions, relative to the 2050 high scenario.

The 2050 scenarios illustrate the possible implications of uncertainty and various practical constraints as well as the level of effort that would be needed in order to achieve a given level of deployment. All three estimates of potential for each pathway can be found in Table 1.

Portfolio development

Some pathways are more promising than others. A prioritized package of policy investments should advance a broad portfolio—hedging bets across pathways where different sets of technical, economic, or political unknowns could frustrate successful deployment at scale. Yet it is worth distinguishing among pathways on key metrics like potential, cost, and uncertainty.

Comparing pathways on standardized criteria is challenging due to uncertainty. Uncertainty affects all pathways but in different ways. For some pathways, achievable potential is highly uncertain due to technical unknowns. For others, achievable potential is highly uncertain due to political unknowns—for example uncertain prospects for large-scale and sustained public subsidy. Cost is uncertain for all pathways, but cost uncertainty is more consequential for some pathways than others. Natural pathways also face unique sources of uncertainty related to landowner interests and complicating dynamics of global markets for food and fiber that could ultimately constrain potential.

Instead of attempting to prioritize pathways on standardized criteria, the assessment settles pathways into categories:

- **Staples.** These pathways are essential components of the carbon removal portfolio. Potential may be politically uncertain but is reasonably clear technically and outsized relative to other pathways—either in terms of annual removal rates or achievable cumulative removal through 2050.

- **No Regrets.** The potential of these pathways appears to be meaningful but subject to higher technical or economic uncertainty than the Staples pathways. Relatively low costs (<$50 per ton) and the prospect of significant co-benefits make the case for investment despite that uncertainty.
- **Speculative Bets.** These pathways require further development before they can be deployed. The upper-bound potential of these pathways is outsized relative to other pathways, but plausibly achievable potential is poorly understood due to technical or economic unknowns. Additional research and development are needed to clarify potential.
- **Supplemental Pathways.** These pathways fail to meet any of the defining criteria of the above categories. The upper-bound potential of these pathways is relatively clear and relatively limited—generally less than 200 megatons (million metric tons) of carbon dioxide (MtCO$_2$) per year. There is also no upside potential—to the contrary, actual potential is likely to be more limited due to unknown technical or economic constraints. Deployment challenges combined with high costs and/or a relative lack of co-benefits diminish the case for prioritizing these pathways. However, together these pathways could make a meaningful contribution to a broader portfolio.

The assignment of pathways across these four categories is shown in Table 1.

Table 1 | **Carbon Removal Pathways at a Glance**

		UPPER-BOUND CARBON REMOVAL POTENTIAL WITH SAFEGUARDS	PLAUSIBLE CARBON REMOVAL BY 2050*	PLAUSIBLE COST**	OTHER CONSIDERATIONS
STAPLES	**Tree restoration**	540 MtCO$_2$ per year average over 20 years of tree growth, while preserving agricultural land uses and excluding afforestation in ecologically inappropriate areas (range: 310–1,090 MtCO$_2$ per year)	180–360 MtCO$_2$ per year (range: 210–730 MtCO$_2$ per year) 7.4 GtCO$_2$ cumulative through 2050, assuming linear scale-up over the next 20 years	$10 per ton (excluding transaction costs or other hidden costs)	▪ Deployment-ready at scale ▪ Environmental co-benefits ▪ Carbon removal potential may saturate after 2050
	Direct air capture	Limited only by available low-carbon energy inputs	190–1,400 MtCO$_2$ per year 2–7 GtCO$_2$ cumulative through 2050, assuming linear scale-up from 150 MtCO$_2$ per year in 2040 to full deployment, with negligible removals before 2040	$100 per ton	▪ Carbon removal potential can be sustained indefinitely and easily scaled ▪ Limited co-benefits ▪ Land footprint small when compared with BECCS (total footprint dependent on energy source)
NO REGRETS	**Agricultural soil carbon practices**	300 MtCO$_2$ per year (range: 200–400 MtCO$_2$ per year)	100–200 MtCO$_2$ per year 2.2 GtCO$_2$ cumulative through 2050, assuming linear scale-up from 2030 through 2050 after initial 10-year pilot program	$40 per ton, assuming $40 per acre cost-share, 0.5 tCO$_2$ per acre on average, and a one-for-one match with legacy acres (continued implementation after cost-share) and additional acres activated without cost-share through social influences or cultural shifts	▪ Some practices are deployment-ready at scale; others face technical or scientific uncertainties ▪ Scale requires sustained action by millions of landowners ▪ Environmental co-benefits

Table 1 | **Carbon Removal Pathways at a Glance (Cont.)**

		UPPER-BOUND CARBON REMOVAL POTENTIAL WITH SAFEGUARDS	PLAUSIBLE CARBON REMOVAL BY 2050*	PLAUSIBLE COST**	OTHER CONSIDERATIONS
SPECULATIVE BETS	**Carbon mineralization**	1.2 GtCO$_2$ per year, assuming 100% market penetration of the aggregate market	Negligible–410 MtCO$_2$ per year, assuming 33% penetration of the U.S. market for aggregate 2–3 GtCO$_2$ cumulative through 2050, assuming linear scale-up from 0 MtCO$_2$ per year in 2040	$50–$500 per ton	▪ Poorly understood logistical constraints ▪ Potential environmental risks
	Enhanced root crops	500 MtCO$_2$ per year, assuming enhanced crop varieties with root carbon input and depth on par with prairie grasses on cropland for major field crops in the United States (highly theoretical)	0–185 MtCO$_2$ per year, assuming enhanced crop varieties with 25% increase in root carbon input and 20% shift in root depth for eight major field crops 1 GtCO$_2$ cumulative through 2050, assuming linear scale-up from 0 MtCO$_2$ per year in 2040	Unclear but potentially under $2 per ton based on projected research and development needs, assuming that no deployment subsidies are required	▪ Little proof of concept ▪ Co-benefits for cropland resilience, erosion control
SUPPLEMENTAL PATHWAYS	**Bioenergy with carbon capture and storage (BECCS)**	260 MtCO$_2$ per year, assuming 50% conversion losses and excluding dedicated energy crops, currently used agricultural residues, and whole tree biomass	Negligible to 180 MtCO$_2$ per year, assuming some available feedstocks are used in other applications (e.g., compost, biochar, wood waste preservation) 1.8 GtCO$_2$ cumulative through 2050, assuming full use of available 2040 biomass from 2040 to 2050	$70–$100 per ton	▪ Likely constrained by available waste and by-product feedstocks, competing uses for those feedstocks, and conversion losses
	Wood waste preservation	90 MtCO$_2$ per year, assuming full preservation of all wood in municipal solid waste and construction and demolition waste	Negligible to <90 MtCO$_2$ per year, assuming some wood waste is not captured or diverted to other uses 900 MtCO$_2$ cumulative through 2050, assuming full preservation of available wood waste from 2040 to 2050	Unclear	▪ Constrained by total available wood in municipal waste and construction and demolition waste and competing uses for that biomass
	Extended timber rotations	50 MtCO$_2$ per year by 2050, growing incrementally for up to 300 years	Negligible to 25 MtCO$_2$ per year, assuming leakage reduces the net carbon benefit of reduced harvest by 85% 750 MtCO$_2$ cumulative through 2050, assuming linear scale-up	<$50 per ton in most cases	▪ Rate of adoption constrained by potential timber market impacts ▪ Upper-bound potential could continue to grow well beyond 2050 ▪ Willingness from private landowners to extend rotations is unclear

Notes: Estimates for plausible potential by 2050 assume a start date of 2020.

* Plausible potential is equivalent to the range between low- and high-deployment scenarios for each pathway. It considers economic, market, and social constraints that limit the portion of the technical potential that is realistically achievable in the United States.

** Reflects cost incurred by federal government—or by other entities by federal mandate—per ton of CO$_2$ removed.

Sources: Author calculations based on estimates in the literature and assumed rates of deployment; see "Tree Restoration" chapter through "Supplemental Pathways" chapter for more information.

Principled policy design

Lacking a discrete and comprehensive list of policy proposals to compare and prioritize for each pathway, we developed policy options in line with a set of prioritization principles:

- Address major barriers to deployment (financial, technical know-how) or deployment-readiness (cost, understanding). Tightly focusing on addressing major barriers helps isolate policy options that sit on the critical path to scaling. To the extent that pathways include multiple individual practices or technology configurations, policies focus on key barriers facing the pathway as a whole, rather than barriers unique to individual practices or concepts.
- Design for rapid scale-up rather than incremental gains. Although policy design for both incremental change and transformative change is strategically important, this assessment focuses on transformative change to demonstrate the scale of policy ambition required to meet the 2 $GtCO_2$ benchmark by 2050. For deployment-ready pathways, policies aim for full deployment within 20 years. For development-stage pathways, policies aim to ensure a good chance of deployment readiness within the next 20 years.
- Maximize return on public investment. This requires selecting policy mechanisms that are both most cost-effective and most effective at managing uncertainty. For natural pathways, this requires leveraging nonfederal investment where possible and striking a balance between transaction cost of implementation and ensuring that the program actually results in long-term sequestration that would not have otherwise occurred. For development-stage pathways, it requires sequencing investments such that key unknowns are addressed, or milestones achieved, prior to committing additional resources. Some nascent pathways require more modest investments in further research and field-testing to better understand their potential and cost, and to determine whether larger investments in their development are warranted. Policies are scoped to address barriers that are binding.
- Adopt and adapt existing policy models rather than create new ones. While this assessment does not explicitly consider political feasibility, this design principle allows for borrowing attributes from other policies that have been successfully adopted.

While the assessment draws heavily on policy needs posited by the National Academies and others, we apply these principles to screen out lower-priority policies and to identify others not yet considered in the literature. We also devote considerably more attention to policy design for Staples and No Regrets than for Speculative Bets and Supplemental Pathways.

Creating a strong enabling environment

Several investments in infrastructure, technology, markets, and data systems can directly or indirectly facilitate the scaled deployment of one or more carbon removal pathways. Promising areas of investment include

- abundant, low-cost carbon-neutral energy;
- rigorous life-cycle assessment;
- CO_2 transport and storage infrastructure;
- CO_2 utilization markets;
- natural carbon sink monitoring systems; and
- land use efficiency.

None of these needs are unique to carbon removal, and several may advance for reasons having little to do with carbon removal. However, all are critical for carbon removal. We profile each component of a strong enabling environment. While we do not prioritize policies for the enabling environment, we identify clear needs especially as they relate to carbon removal pathways.

TREE RESTORATION

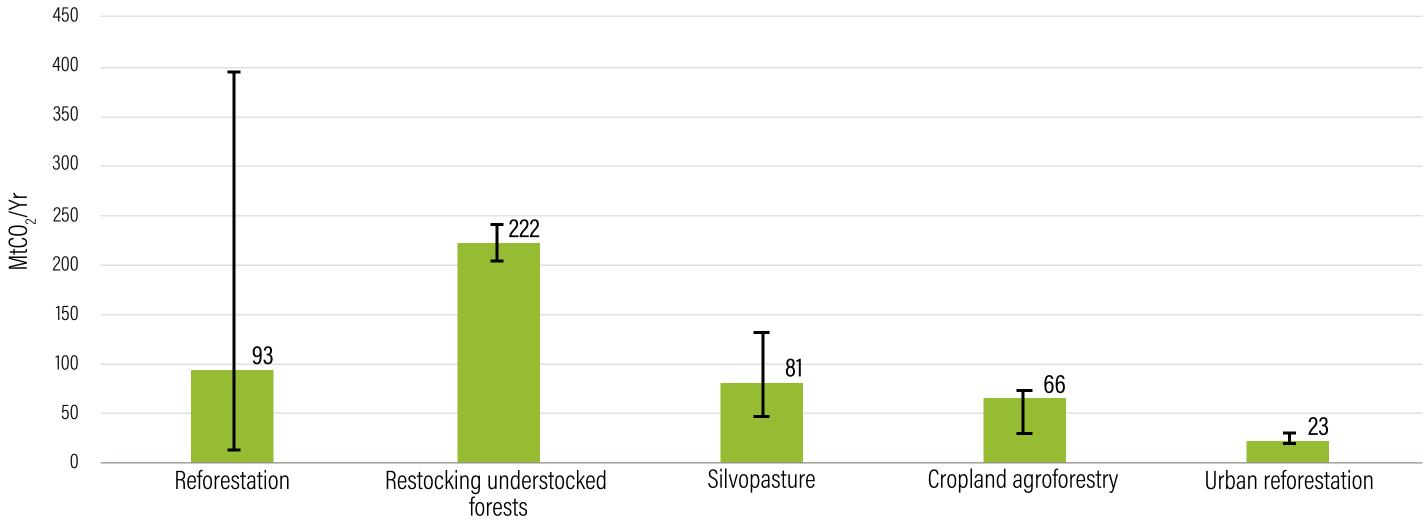
In Brief

- Restoring trees to the landscape (“tree restoration”; see Figure 2) could plausibly remove up to **360 MtCO$_2$ per year** in the United States through 2050, accounting for reversal risks from tree mortality and without displacing agricultural production (upper bound: 540 MtCO$_2$ per year; see Figure 3). The large majority of this opportunity is on private lands, while about 10 percent is on federal lands. In addition to carbon removal, tree restoration offers a variety of co-benefits with significant economic value.
- Allocating **$1–2 billion per year** to federal subsidies for tree restoration would capture low-hanging fruit opportunities for carbon removal at a modest cost, build critical implementation experience, and improve characterization of the scale of opportunity and full funding need. We estimate a need for up to **$4–4.5 billion** in annual federal funding to fully capture the estimated potential over a 20-year period (see Figure 4). The total need for federal funding might be lower if co-benefits of tree restoration can be monetized, or higher if landowners demand financial incentives above and beyond their direct costs (e.g., to reimburse them for the opportunity cost of other land use) to implement tree restoration.
- State and local governments can aid tree restoration efforts by channeling federal resources through agencies and programs customized to their specific circumstances, and by leveraging unique policy tools such as green growth plans and property tax incentives.
- Barriers to tree restoration are primarily financial, driven by high upfront costs for site preparation, planting stock and labor, and ongoing maintenance and long lag times before any financial and substantial carbon removal benefits accrue from tree restoration on working lands. Financial barriers are compounded in many cases by a lack of knowledge and/or capacity among many landowners to implement new land management regimes, and/or aesthetic and other preferences among landowners.
- Major uncertainties relate to the practicality of tree restoration on the areas identified as suitable via spatial analysis and literature review, the receptiveness of landowners to tree restoration, and the viability and potential value of monetizing co-benefits. Additional uncertainties pertain to specific approaches for tree restoration, such as uncertainty around baseline trends in forest restocking and impacts of agroforestry systems on crop or livestock yields. These unknowns all have significant implications for the total potential and public cost associated with pursuing tree restoration.

Figure 2 | **Tree Restoration Approaches for Carbon Removal**

Source: Authors.

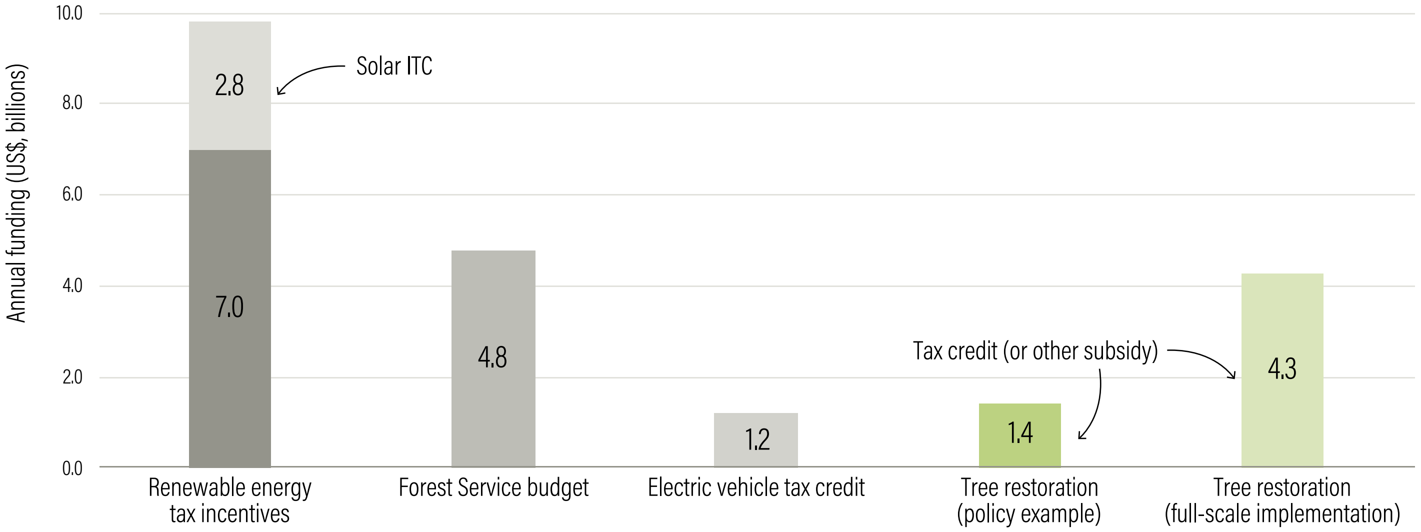
Figure 3 | **Composition of the Upper-Bound Potential for Carbon Removal from Tree Restoration in 2050 ($MtCO_2$/yr)**



Notes: Error bars reflect published or estimated standard error for the carbon removal rate associated with reforestation and restocking and published standard errors for both the available area and carbon removal rate for windbreaks (a component of agroforestry) and urban reforestation. For silvopasture, where an estimate of standard error was unavailable, the error was defined by the high and low carbon removal factors published in COMET Planner (Swan et al. 2015). For alley cropping (a component of agroforestry, along with windbreaks), where the published estimate was deemed inconsistent with findings in the source literature, the error was defined by extrapolating the minimum and maximum carbon removal rates found in the literature across the mean estimate of eligible acreage found by Fargione et al. (2018). Note that values may not sum exactly to total tree restoration potential due to rounding.

Sources: Reforestation, windbreak (agroforestry), and urban reforestation data from Fargione et al. (2018). Restocking data from Sohngen (unpublished); and Hoover and Heath (2011). Silvopasture data from Cook-Patton et al. (forthcoming); and Swan et al. (2015). Alley cropping (agroforestry) data from Fargione et al. (2018); Peichl et al. (2006); Bambrick et al. (2010); and Cardinael et al. (2015).

Figure 4 | **Relative Scale of Proposed Funding for Tree Restoration in Comparison to Other Funding for Green Technologies and Forest Management**



Note: Policy example represents a subset of the full federal funding need for tree restoration, which would be sufficient to capture low-hanging fruit opportunities for carbon removal at a modest cost.

Box 1 | What Is Tree Restoration?

We adopt the term *tree restoration* to encompass various forms of planting or naturally regenerating trees in areas that historically supported trees, or in other areas where trees can serve a beneficial ecological purpose (e.g., windbreaks in croplands and urban trees in cities). It includes the following key practices:

- Reforestation: Establishing forest cover on historically forested lands, including open areas in suburban and exurban landscapes, landscapes affected by wildfire or other disturbance, and other nonagricultural lands—with or without changing the prevailing land use.
- Restocking: Increasing the density of trees in existing forests while preserving or enhancing ecosystem functions, such as by actively replanting after harvest or controlling competition for regrowth from invasive species.
- Silvopasture: Integrating trees into pasture while maintaining livestock production.
- Cropland agroforestry (including alley cropping and windbreaks): Planting trees on cropland while maintaining crop production.
- Urban reforestation: Expanding tree cover within urban areas.

Tree Restoration 101

Restoring trees to the landscape represents the single largest near-term opportunity to deploy carbon removal at scale in the United States. Although the potential for tree restoration is constrained by competing demands for the use of land—especially for agriculture, which accounts for half of all GHG emissions from forest conversion (EPA 2019)—new analysis has identified significant opportunities for reforestation in suburban and exurban areas, postdisturbance forest landscapes, and other nonagricultural lands. Nationally, this analysis shows an opportunity to reforest an estimated 21 billion trees across 53 million acres, providing nearly 150 $MtCO_2$ in annual carbon removal potential (Fargione et al. 2018; Cook-Patton forthcoming).[2]

Restocking existing forests to increase tree density on land that the Forest Service considers less than fully stocked in the eastern United States could provide an even greater opportunity—contributing 220 $MtCO_2$ per year with 24 billion additional trees on 165 million acres of timberlands (Hoover and Heath 2011; Huang et al. 2004; Oswalt et al. 2014; Sohngen unpublished).[3] Opportunities for restocking arise from tree mortality—for example, due to poor harvesting practices like high-grading or selective logging, or natural disturbances like insects, disease, or wildfire—in instances where natural regeneration fails due to competition with other vegetation, herbivory, or continued natural disturbance (Vasievich and Alig 1996).[4]

Additionally, silvopasture, cropland agroforestry, and urban reforestation (see Box 1) together offer further potential of 170 $MtCO_2$ per year, based on planting 16 billion trees over 113 million acres (Fargione et al. 2018; Cook-Patton forthcoming; Swan et al. 2015). The potential estimate for silvopasture assumes that trees can be integrated into all pasture land in regions that have historically supported forest cover. For cropland agroforestry, the potential estimate includes alley cropping on 10 percent of all suitable cropland and windbreaks on 5 percent of cropland that would benefit from reduced wind erosion or snow accumulation (Fargione et al. 2018).[5] Finally, urban reforestation would entail a 7–11 percent increase in street trees and urban forest patches (Fargione et al. 2018).

Altogether, these opportunities would involve regenerating over 60 billion trees across 330 million acres, providing an average of 540 $MtCO_2$ per year of carbon removal over the next 20 years (with additional carbon removal continuing until the trees reach maturity). Figure 3 shows the distribution of the estimated upper-bound potential across these various approaches to tree restoration. Figure 5 shows the relative extent of these opportunities to current forest and woodland cover and historical forest conversion in the United States.

This carbon removal pathway is ready for deployment, and the majority of the identified potential can be realized cost-effectively at less than \$50 per tCO_2 (Fargione et al. 2018). However, there remains considerable uncertainty in the achievable scale of potential for tree restoration. Even in high-resolution spatial analysis, such as that conducted by Cook-Patton et al. (forthcoming), the land area available for tree restoration is difficult to identify precisely, especially potential conflicts with high-value land uses that are difficult to discern in national datasets. Some of the tree restoration practices described above are not currently employed at a significant scale, and landowners' lack of capacity or unwillingness to implement these novel practices—even with federal support—will inevitably preclude universal adoption of tree restoration. Additionally, some reversal of carbon removal gains due to tree mortality is unavoidable. In light of these challenges, we posit that the plausible carbon removal potential of tree restoration by 2050 is 360 $MtCO_2$ per year—two-thirds of the pathway's upper-bound technical potential.

The significant upfront planting costs and lack of near-term financial returns from monetizable co-benefits make tree restoration financially unworkable for many landowners, while knowledge gaps and technical challenges around complex land management practices present more hurdles. Tree restoration on federal lands, which appears to account for over 5 percent of the total area available for reforestation and restocking, is hamstrung by inadequate federal funding for forest management.

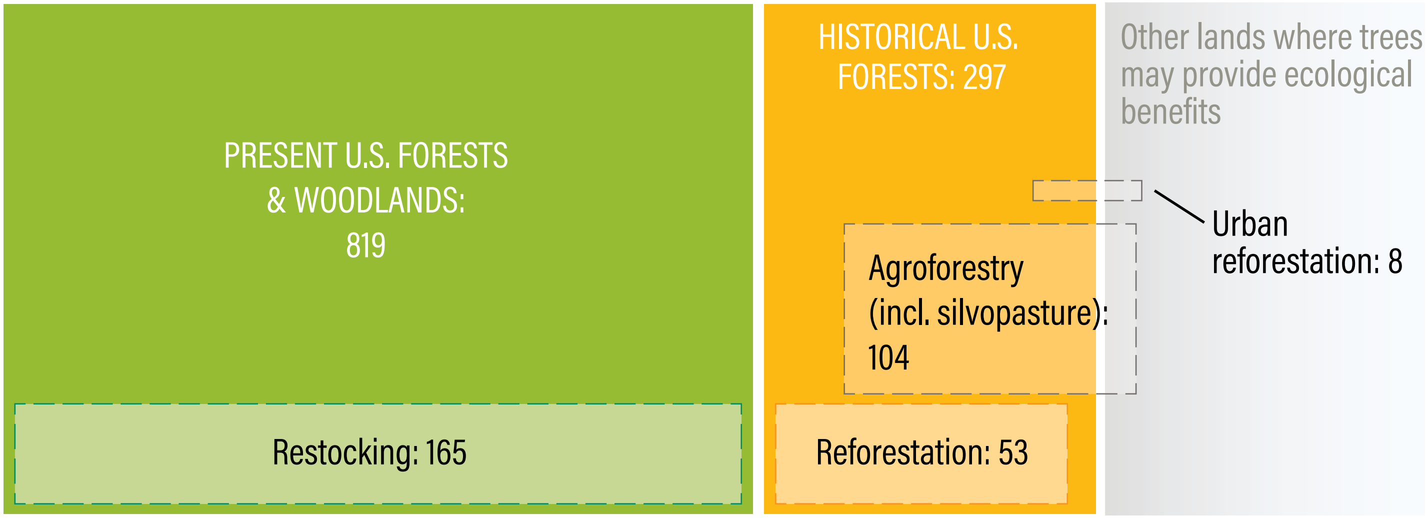
Co-benefits of tree restoration, including improved water infiltration, air purification, wildlife habitat, recreational opportunities, and production of biomass for forest products and energy, provide additional value to society beyond climate mitigation. Many of these co-benefits fail to translate into direct financial benefits for landowners, however. Landowners are therefore likely to engage in suboptimal levels of tree restoration considering the economic value of trees to society.

Given the size of the opportunity for carbon removal from tree restoration, the magnitude of the financial and technical barriers standing in the way, and the many co-benefits that trees provide, concerted action by the federal government is imperative to realize the full scale of potential for carbon removal through tree restoration.

Key Barriers to Tree Restoration

The financial requirements for private and public landowners constitute the primary barrier to tree restoration that can be addressed by federal policy. Although total economic benefits exceed total costs when fully accounting for public benefits like clean water, flood protection, and carbon sequestration (e.g., Lee et al. 2018; Vargas et al. 2007), few of those benefits accrue directly back

Figure 5 | **Potential for Tree Restoration Activities through 2050 in the Context of Present and Historical U.S. Forest Cover (Million Acres)**



Sources: Present U.S. Forests & Woodlands from Oswalt et al. (2014). Historical U.S. Forests from U.S. Forest Service (2001).

to landowners. Absent other sources of finance, landowners must meanwhile shoulder the entire cost of tree restoration, including upfront expenses for site preparation and planting along with recurring expenses for tree maintenance (surveys, management plans, pruning, invasive plant control, and/or fire safety measures).[6] Given the concentration of private costs and the diffusion of public benefits of tree restoration, public subsidies are warranted to achieve the socially optimal level of tree restoration in the United States.

Other barriers include transaction costs (especially on small parcels), a lack of landowner capacity to manage forests intensively, and landowners' time preference for money—since any revenues from monetizable co-benefits, like production of timber or other forest products, would not accrue for years or decades after planting. Overcoming these "hidden costs" will require an attractive financial incentive for either landowners or intermediary project developers.

As tree restoration activities scale up, economic barriers to continued expansion may grow. For instance, land prices may increase locally as more and more land that might otherwise be developed is restored to tree cover—thus increasing the cost of additional tree restoration projects in those areas. If the U.S. timber supply increases significantly due to widespread harvesting on lands used for tree restoration, timber prices could decline in global markets and make timber management less economically viable. These potential market impacts could be tempered to some degree if, for example, demand for fiber grows apace with the supply (see the "CO_2 Utilization" section).

It is also possible, however, that scaling up tree restoration activities will reduce the "hidden costs" of further expansion. Transaction costs, for example, may decrease as new business models arise that are adapted to implementing projects on small parcels. Landowner capacity for tree restoration may grow as landowners learn from other early-adopter tree restoration projects in their area. Because the net effect of these potential reductions in hidden costs and the aforementioned growing economic barriers is uncertain, periodic reevaluation and adjustment of federal tree restoration policies is important to ensure that they continue to provide carbon removal benefits cost-effectively.

Federal Policy Design for Tree Restoration

Effectively and efficiently restoring tree cover at the scale envisioned will require several key policy features: a subsidy that exceeds the net financial costs of tree restoration on nonfederal lands, safeguards for environmental integrity, the use of third parties to streamline implementation, technical assistance for landowners, and funding to federal land management agencies for tree restoration on federal lands.

Subsidy to address financial barriers to tree planting

SUBSIDY VALUE

We approximate an annual federal funding need based on the estimated total cost of tree establishment and maintenance over a 20-year window in areas that have been identified in recent literature and analyses as suitable for tree restoration (Bair and Alig 2006). Assuming that future timber harvest is likely in restocked forests, and that timber or other products of similar value will be harvested in cropland agroforestry and silvopasture systems, we reduce estimated total costs for these systems by the discounted value of future revenues in order to approximate federal funding need. Altogether, the estimated federal funding needed to achieve the estimated upper-bound potential with safeguards for tree restoration is $4–4.5 billion per year over 20 years.[7]

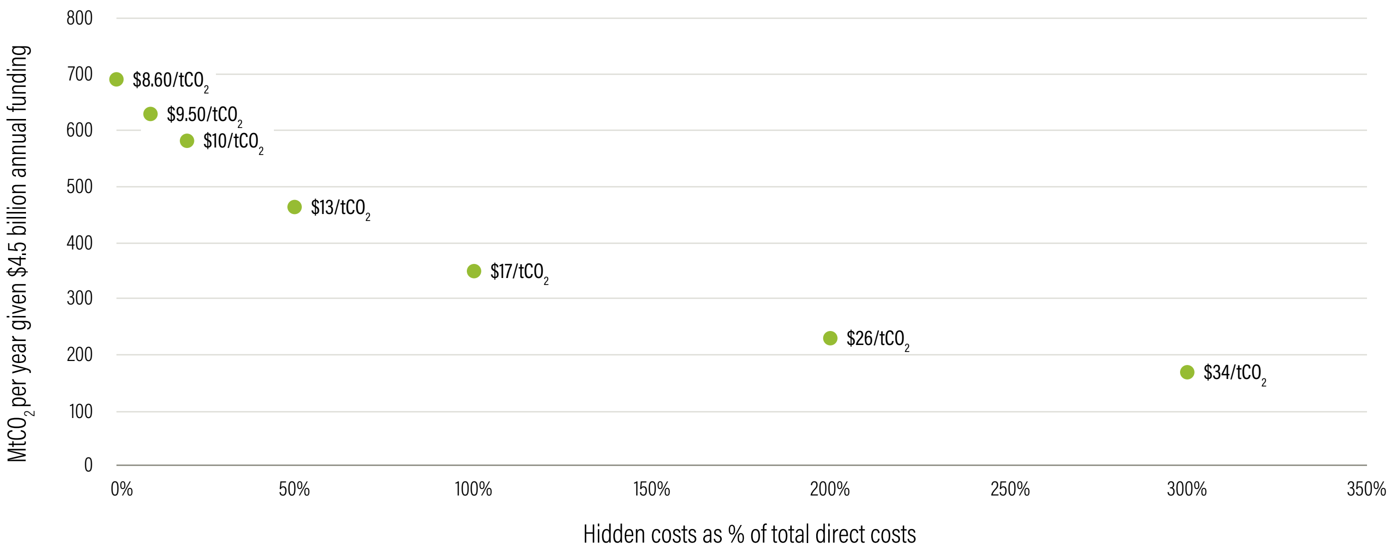
Additional "hidden costs"—like landowner aggregation and other transaction costs, opportunity cost of other land uses, and monitoring costs—could raise funding needs beyond the range estimated here. The makeup and magnitude of these costs are likely to vary significantly from landowner to landowner and practice to practice. There is very little basis in the literature to derive expectations for these costs across the composition of tree restoration opportunities examined here. For illustrative purposes, however, hidden costs may be broken down and assessed as follows:

- **Transaction costs** represent the costs incurred in the process of preparing tree restoration projects—for example, engaging landowners, conducting any necessary project design or study, and obtaining public and/or private finance. Transaction costs in other industries range from 4 percent of project cost in the passenger car industry up to 20 percent in the residential solar industry (Wesoff 2017). Tree restoration is likely to differ significantly from these other industries, however, with lower project costs and less specialized transactions, especially compared to solar panel installation.

- **Monitoring costs** represent costs incurred to demonstrate that the project is meeting its objectives as required to receive the federal subsidy. For a basic subsidy program, the main objective of monitoring would be to verify tree survival. Most literature on monitoring costs, however, relates to pay-for-performance carbon programs with more onerous monitoring requirements. For these projects, monitoring accounts for between 3 percent and 40 percent of the project cost, largely as a function of project size (Pearson et al. 2014).
- **Opportunity costs** represent the value, financial or otherwise, that a landowner forgoes by dedicating land to tree restoration. For example, these costs could reflect aesthetic preferences for open landscapes or forgone uses like playing fields. Opportunity costs could also include the lost value in moving from a profit-maximizing land management regime (e.g., selective harvesting) to a management regime that promotes tree restoration (e.g., uneven-aged harvesting coupled with active forest restocking). Phrased another way, the opportunity cost is equal to the additional financial inducement over and above direct costs that a landowner would require to establish a tree restoration project. Opportunity costs will likely vary widely based on a landowner's next-best use of land, management priorities, and other factors. Discovering these opportunity costs and attendant need for financial inducement would be a key benefit of an initial federal subsidy for tree restoration. For illustrative purposes, if opportunity costs are 100 percent of total direct costs, landowners would require a financial inducement of roughly $100–$500 per acre.

Conversely, monetizing co-benefits and economies of scale in seedling stock and equipment for site preparation and tree maintenance could reduce the amount of federal funding needed for tree restoration projects. These factors are likely to offset, but not overwhelm, the hidden costs described above. Figure 6 shows how a given level of federal funding would produce different carbon removal outcomes depending on the actual net impact of hidden costs and cost-reduction factors.

Figure 6 | **Impact of Hidden Net Costs on Carbon Removal Potential and Cost per Ton of Carbon Removal Associated with $4.5 Billion in Federal Funding for Tree Restoration**



Notes: Assumes annual federal funding is fixed at $4.5 billion per year and direct costs are $8.60/$tCO_2$. Per-ton costs account for costs and removals over a 20-year period. Since most costs are incurred upfront and trees continue to sequester carbon beyond year 20, actual total costs per ton are likely lower than represented here.

Source: Author calculations.

Hidden costs will increase the total cost per ton of carbon removal by tree restoration. If federal funding for tree restoration is fixed, these hidden costs will erode carbon removal achieved by a given policy. Figure 6 shows declining carbon removal levels corresponding to higher hidden costs. Under the most extreme assumption of hidden net costs that follows from available data, a given level of federal funding would result in one-quarter as much carbon removal as without hidden costs. Note, however, that even one-quarter of the carbon removal potential is still on par with the potential offered by many other pathways—and still at less cost (see Table 1).

Even with hidden costs considered, the public benefits of tree restoration clearly exceed the economic value of the subsidies proposed here. Assuming a relatively conservative sequestration rate of 1.5 tCO_2 per acre per year, the present value of the benefits to society from carbon removal alone would be five times as large as the net present value of hard costs for the median tree restoration scenario and significantly larger than the most costly scenario (see Appendix A).[8] Other public benefits, like increased water infiltration or biodiversity, could add to the economic value of tree restoration projects beyond the amount quantified here.

Total funding needs will also depend on the efficiency of the policy mechanism. Because the marginal cost of tree restoration varies by project type and regional conditions, applying a uniform cost-share rate across all acres would fail to fully activate some practices, while overpaying for others. How rates are set can therefore be highly consequential for the effectiveness of either a cost-share or tax-based subsidy.

Subsidy mechanism

Policy mechanisms that tailor federal subsidies to closely approximate the difference between total costs (both explicit and hidden) and potential private benefits—including copayment for these services by state, local, and private sector entities—will make more efficient use of federal resources than mechanisms to provide flat cost-share rates regardless of the circumstances. Policy options for tailoring subsidy rates include competitive bidding processes, tailored cost-share rubrics, and increasing rates over time to enable price discovery. For a full discussion of the options available to policymakers in structuring rates and the temporal distribution of subsidies for tree restoration, as well as more detailed information on the costs and benefits of project implementation, see Appendix A.

A federal subsidy for tree restoration could be administered through a **tax credit program** or a **direct payment program.** A tax credit program would be akin to other major federal climate policies enacted to-date—including the Investment Tax Credit (ITC) for solar, the Production Tax Credit (PTC) for wind, and the 45Q tax credit for carbon capture, utilization, and storage. In this structure, eligible project operators or sponsors would receive a credit for trees planted and maintained. Tax credits are administered by the U.S. Treasury Department. Much of the policy design for tax credits is done by Congress in legislation, rather than by implementing agencies. As a result, tax credits tend to be clunkier than administratively managed direct subsidy programs. However, tax credits provide a different avenue within Congress for policy adoption and are not subject to the annual appropriations process.

A direct payment program would be a natural extension of existing conservation incentives authorized under the Farm Bill and administered by the U.S. Department of Agriculture (USDA). Payments could be structured as either a cost-share or pay-for-performance program (or a hybrid of the two). **Cost-share** would entail USDA's issuing payments to landowners who restore trees on their land according to standardized rates and over a fixed contract period. Relative to the Environmental Quality Incentives Program (EQIP), which already provides cost-share for conservation practices by agricultural and nonindustrial forest landowners, this program would target an expanded set of landowner types—including urban, residential, commercial, state, and municipal—where there is opportunity for tree restoration. For lands where the cost of finance is the primary barrier to tree restoration, low-interest loans may be used instead as effective cost-share. Instead of or in combination with cost-share, a **pay-for-performance** system would entail payments from USDA for tons of CO_2 sequestered through tree restoration. This approach has both advantages and disadvantages for cost-effectiveness, depending on policy design, but it also poses challenges for administrative implementation (see Appendix A).

Safeguards for environmental integrity

Adhering to high standards of environmental integrity is critical to ensure that federal subsidies for tree restoration achieve real, lasting carbon removal benefits. An effective tree restoration policy must therefore include safeguards that address these key dimensions of environmental integrity:

- **Additionality**: Each year, 2 million acres are replanted following timber harvest, and several million more acres regenerate naturally (Oswalt and Smith 2014). Subsidizing these business-as-usual activities could significantly increase the cost of the program without delivering clear carbon removal benefits.
- **Minimal leakage**: Permitting reforestation of agricultural lands may cause other lands to shift from forest to agriculture in order to meet demand for food, thereby producing offsetting emissions from land use change.
- **Ecological alignment**: Planting trees may have negative impacts on ecosystem functions in areas that are maladapted for more trees—for example, “restocking” forests that are naturally sparse, like fire-adapted western forests, or afforesting native grassland areas like the Great Plains. The suitability of certain tree species on a landscape may also change over the trees’ expected lifespan as the climate changes.
- **Tree survival**: Tree mortality can reverse carbon removal gains achieved by a tree restoration program, especially if the dead trees burn or decompose rather than being turned into long-lived wood products.

These facets of environmental integrity could be embedded in a subsidy program through eligibility requirements or project reviews by independent verifiers, Natural Resources Conservation Service (NRCS) conservationists, or relevant state agencies to screen out projects that do not meet specific criteria. For instance, land that is not ecologically appropriate for forest growth could be excluded with eligibility requirements. Native tree species could be required of projects in key areas for biodiversity. Review by a third party or approval body might be employed to verify that areas in active timber rotations or ongoing natural regeneration are only subsidized in cases where additional management is necessary to increase tree density from understocking to full stocking. Land that has been used for agricultural production within a certain number of years might be eligible only if the farmer makes good-faith efforts to maintain production at similar levels after tree cover is established—effectively allowing agroforestry but ruling out full reforestation and the indirect carbon losses it may trigger through leakage.

Project review processes would allow for a more customized assessment of a project’s environmental risks but would also add to the administrative complexity and transaction cost associated with the program. In all cases, safeguards must balance environmental integrity with the barriers to entry associated with inflexible rules and administrative complexity.

Safeguarding against tree mortality could entail repayment obligations if planted trees do not survive or could require linking subsidy payments to benchmarks for tree survival over time. This approach may make it more difficult to access private capital to finance tree restoration.

Use of third-party intermediaries

Lack of knowledge and technical capacity among landowners, absentee landownership, transaction costs for landowners, and challenging economics of tree planting on small parcels can limit the effectiveness of a traditional subsidy paid directly to landowners. Third-party intermediaries—such as land trusts and other nonprofit organizations, private companies, or local or state governments—can serve multiple valuable functions:

- **Landowner engagement and burden shifting.** Aggregators can proactively solicit landowner participation—and facilitate that participation as needed by handling administrative aspects of program participation and even project implementation and reporting. This engagement would reduce the transaction cost for landowners of completing the necessary paperwork to apply for cost-share, a significant barrier to entry in existing programs that has disproportionately limited enrollment from small landowners (Bennett et al. 2014; Ma et al. 2012).
- **Project aggregation.** Intermediaries can package together and directly implement tree planting projects across many landowners, achieving economies of scale and making tree restoration more practicable on small parcels. Examples of economies of scale in this context include better access to private finance for larger projects; opportunities for optimizing seedling supply and use of machinery; and the possibility of using advanced technology like drone planters or organizing volunteer planting crews.

- **Expert implementation.** Intermediaries can place responsibility for tree planting and maintenance activities in the hands of qualified project operators, addressing the barrier posed by lack of knowledge and technical capacity among private landowners (Ma et al. 2012; Creamer et al. 2012). Intermediaries can even begin to address knowledge gaps in the communities where they operate.
- **Cofunding solicitation.** Intermediaries can solicit other sources of funding for large tree planting projects more easily than individual landowners.

Third-party intermediaries can be effective agents to reduce transaction costs and other barriers to entry for landowners, provided they maintain low overhead costs in recruiting landowners and processing subsidy payments (Boakye-Danquah and Reed 2019). To make a federal program attractive to intermediaries, the program must provide certainty through a clear payment timeline (i.e., one not influenced by changes in annual appropriations or legislative extension of the program) and transparently set subsidy rates. Third parties must be eligible to receive the subsidy for tree restoration activities conducted on behalf of landowners. Payment to the landowners and other arrangements would then be negotiated between the intermediary and the landowner. A minimum project size requirement would further shift implementation toward third-party intermediaries and facilitate any project review process.

The use of intermediaries would be a departure from existing Farm Bill incentive initiatives like EQIP and the Conservation Reserve Program (CRP), which require direct contracts between landowners and NRCS. However, intermediaries could be used in either a direct subsidy program or a tax credit program. Because many landowners may not have a sufficiently large tax liability to fully take advantage of tax credits, it would be important to structure a tree restoration tax credit like the ITC for solar energy development, under which the tax credit is transferable to financiers with greater tax liability than the landowners or project developers themselves. This transfer of tax equity comes with a cost, however, which has been estimated at 36 percent or more of the value of the wind power PTC (Bolinger 2014). Therefore, a tax credit approach may inherently favor larger landowners or project developers with sufficient tax liability to take full advantage of the tax credit themselves.

Role of state and local governments

State and local governments have an important role to play in a tree restoration campaign. State and local land use planning is necessary to restore trees on state and locally owned lands, which account for nearly 15 percent of the reforestation potential and over 10 percent of the forest restocking potential (Cook-Patton forthcoming; Oswalt et al. 2014; Hoover and Heath 2011). Tree restoration also returns myriad co-benefits to states and municipalities.

Delegating or sharing review and approval authority with state governments would allow states to integrate federal funding for tree restoration into state-level land use planning and ensure that funded projects are consistent with state natural resource objectives. In many cases, these funds could be integrated through existing channels for federal support to states—the Forest Service, for instance, runs programs that provide funding to states for forest planning, forest health treatments, and urban and community forestry.

States and local governments also have a different set of policy tools—such as green growth policies, property tax incentives, zoning regulations, and even hunting licenses—that could play a significant role in a tree restoration campaign. Involving state and local governments in project review processes would enable these jurisdictions to identify complementary policy measures. A portion of a national program for tree restoration could also be operationalized by awarding federal grant dollars to states that meet targets for tree restoration, using whatever set of policies they choose.

Technical assistance for landowners

Several forms of tree restoration require technical expertise that many private landowners lack. Restocking forests, for example, necessitates a location-specific understanding of appropriate forest stocking levels, accounting for risks like wildfire and overcrowding. Agroforestry requires production know-how for both annual crops and trees, and knowledge of specific practices has been linked directly to landowners' likelihood to adopt the practice (Valdivia and Poulos 2009). Access to information may even address some of the financial barriers to adoption such as finding markets for forest products (Strong and Jacobson 2005).

Third-party implementers are well positioned to act as technical assistance and education providers. Where landowners implement programs directly, federally directed technical assistance and education for landowners will likely be required above and beyond the technical assistance already provided to forest owners and agroforestry practitioners. These programs could build on initiatives run by NRCS conservationists, state forestry agencies supported by the Forest Service's State and Private Forestry Division, or the extension offices of local land-grant universities funded by the National Institute of Food and Agriculture.

Funding for federal lands

Federal land accounts for a small but important portion of the opportunity for tree restoration. About 700,000 acres of federal land were detected in a national spatial analysis of reforestation potential—over and above the area expected to regenerate without additional effort (Cook-Patton forthcoming).[9] Up to 18 million more acres of eastern timberland in the National Forest System may be available for restocking, assuming that current stocking patterns are similar to the rest of the region's timberlands (Oswalt and Smith 2014; Hoover and Heath 2011). These opportunities add up to potential carbon removal of around 25 $MtCO_2$ per year on federal lands.

Promoting tree restoration on federal lands requires a different policy approach than for private, state, and municipal lands, since the U.S. government manages the land itself. Rather than financial incentives and technical assistance, the biggest need for tree restoration on Forest Service land, much of which is disturbed forest land that has not regenerated naturally, is more funding. The Reforestation Trust Fund and supplementary funding sources currently only support some 200,000 acres of reforestation annually, which is just enough to keep pace with the annual growth in reforestation needs due to wildfire and disease mortality but cannot address the existing backlog of reforestation needs (U.S. Forest Service 2017). The vast majority of federal land in need of reforestation is backlogged because of additional resource needs for site preparation, replanting, and permitting requirements under the National Environmental Policy Act.

While the FY2018 Omnibus Spending Package took the first step by insulating the Forest Service's budget from firefighting cost escalations, additional funding is needed to adequately address the agency's reforestation backlog on a timely schedule. Going forward, the Forest Service must maintain a dedicated funding pool for reforestation that is commensurate with the need across all our federal lands. This pool would be an expansion of the Reforestation Trust Fund, which provides $24 million per year in project funding after accounting for indirect costs—about half of the total estimated federal funding available for reforestation efforts. In order to reforest all suitable federal land over 20 years, the Trust Fund would need an additional $10–20 million in annual funding.[10]

While the majority of the technical carbon removal potential on federal lands is associated with forest restocking, the implementation feasibility for this intervention on federal land is uncertain. Most federal forest lands are not currently managed and harvested for timber, and options for accelerating forest regeneration may be more limited than for smaller and more accessible tracts of private timberland. More research is needed to assess the extent of the restocking opportunity on federal lands and strategies for capturing it.

DIRECT AIR CAPTURE

In Brief

- Direct air capture is a chemical scrubbing process that directly captures CO_2 from the ambient air (see Figure 7). Captured CO_2 is then stored in products or underground in a geological formation. The technology must operate on low-carbon energy to provide net carbon removal (Minx et al. 2018).
- Direct air capture has large potential compared to other carbon removal measures—there is **no obvious upper bound to its technical potential**. In practice its scale of deployment as a carbon removal pathway will be closely linked to the pace of cost reduction and build-out of low-carbon energy inputs, as well as the availability of adequate public subsidy for operation (Mulligan et al. 2018c). All three of these factors represent risks to scaled deployment. Achieving and sustaining ambitious scale-up rates (20–30 percent per year) would yield 190–1,400 $MtCO_2$ per year by 2050 assuming a starting point of 2 $MtCO_2$ per year in 2025.

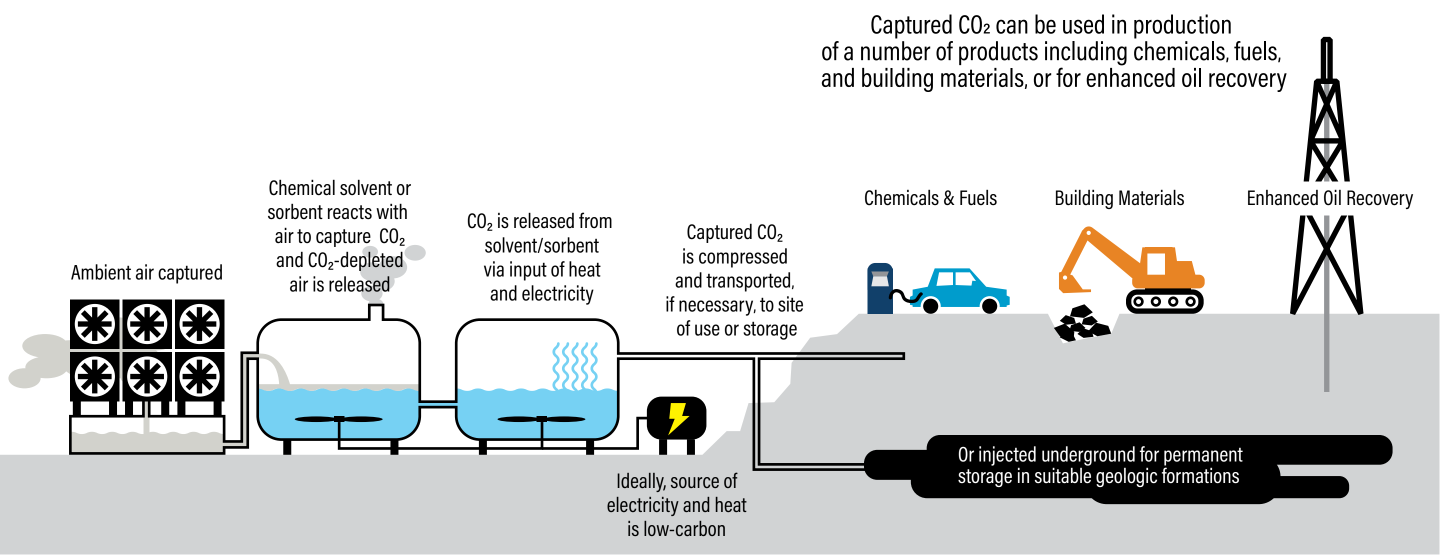
- Current technology could approach **\$100 per tCO_2** removed as it is optimized through deployment experience. Direct air capture systems must be tested under real environmental conditions for extended times before costs and opportunities for further cost reduction can be fully understood (NAS 2018a).
- Readiness for scaled deployment will be contingent on the pace and extent of cost reduction. The National Academies have called for a concerted public research, development, and demonstration program to reduce costs by optimizing system materials and designs (NAS 2018a). Additionally, expanded incentives for private sector deployment will be crucial to enable "learning by doing" to drive down cost.
- This program will require **\$150 million per year** on average over the next 10 years for basic and applied research, pilot testing, and a larger-scale demonstration of promising systems. The funding need in the first years is closer to \$60 million per year but will increase over time. An additional **\$360 million** in tax expenditures would be needed **per year by 2025** to support the scale of deployment envisioned, increasing to \$**1.3 billion** by 2030, with further increases as the technology scales.

Direct Air Capture 101

In a direct air capture (DAC) system, CO_2 is captured from the air by a liquid solvent or solid sorbent (NAS 2018a)[11] that binds the CO_2, separating it from other gases in the air. Once the solvent or sorbent is saturated, heat or other energy is applied to it to release the collected CO_2, which is then released and either used on-site or transported for storage or use.[12] The capture agent (solvent or sorbent) is then reused to capture more CO_2.

DAC has outsized technical potential compared with other carbon removal pathways. With enough low-carbon energy, the technology can be scaled in a way that natural carbon capture or mineralization could not, given constraints on available land area and access to reactive source material, respectively. Additionally, direct air capture can be sustained over time given the large long-term geological storage potential in the United States, whereas removal from natural carbon capture approaches declines over time given carbon dioxide saturation (ICEF 2018). Several companies have already developed direct air capture systems (see Box 2), providing proof of concept.

Figure 7 | **Basic Illustration of Direct Air Capture Technology**



Note: While solid sorbent and liquid solvent direct air capture facilities are somewhat different, this illustration offers a general representation of both technologies. In liquid solvent systems there are two simultaneous cycles—one for absorption and one for regeneration, while in solid sorbent systems, these happen together, one after the other. Additionally, liquid solvent systems require a higher level of heat input for regeneration.

Sources: Adapted from NAS 2018a; Gunther 2011.

Direct air capture requires more energy than CO_2 capture from power plant flue gas because the CO_2 is much more dilute in air (0.04 percent in the atmosphere compared with 5 percent from natural gas–fired flue gas and 12 percent from coal-fired flue gas) (ICEF 2018). The power requirements for direct air capture are also higher than for capturing carbon dioxide from flue gas streams because of the need to overcome the pressure drop in the air contractor arrays (NAS 2018a). The regeneration of liquid solvent systems in particular requires high-temperature heat—up to 900 °C—requiring significant energy inputs (NAS 2018a). The largest operating cost is energy, while the largest capital cost varies among different versions of the technology (NAS 2018a). The National Academies estimate that direct air capture requires 5 gigajoules (GJ) per ton of CO_2 captured (for a sorbent-based system) to 10 GJ per ton of CO_2 captured (for a solvent-based system). For reference, combustion of 100 gallons of gasoline would produce 13 GJ of energy and produce about one ton of CO_2 emissions (NAS 2018a). Scaling direct air capture to 1 $GtCO_2$ per year would require the equivalent of nearly 10 percent of today's total energy consumption in the United States, assuming 10 GJ per ton of CO_2.

Heat energy, which is used to regenerate sorbents and solvents, is a greater requirement than electrical energy (ICEF 2018). There is the potential to use waste heat, which could lower costs (NAS 2018a). The energy provided for electricity and heat must be low-carbon—e.g., solar energy or natural gas with carbon capture—in order for direct air capture to be carbon-negative (ICEF 2018; NAS 2018a). The National Academies note that if coal is used for the thermal source, about the same amount of CO_2 emissions is produced as is captured by a direct air capture system (NAS 2018a).

The technology does not require arable land and its footprint is relatively small—a facility with a 0.3–2.0 square-mile footprint would provide the same carbon removal capacity (1 $MtCO_2$ per year) as 20 million trees spanning 156 square miles (Larsen et al. 2019; NAS 2018a). Facilities can also be sited flexibly near energy sources, sequestration sites, and/or utilization sites (NAS 2018a; Larsen et al. 2019; ICEF 2018). The effective footprint of direct air capture will be larger, however, if it requires dedicated use of renewable energy facilities—especially land-intensive sources like solar. If all electrical and thermal requirements were met with solar energy, land requirements would be 14,500 acres (58.6 km^2) (NAS 2018a). If 100 $MtCO_2$ were removed in a year (equivalent to 100 plants of 1 $MtCO_2$ each), an area the size of Delaware would be required (NAS 2018a).

Box 2 | Stage of Direct Air Capture Development

Currently several companies have developed direct air capture (DAC) systems. Climeworks was the first to commercialize its system with a demonstration plant in Switzerland operating at 900 t/yr in which the captured CO_2 generated is sold to a greenhouse (NAS 2018a). Climeworks is capturing CO_2 at \$600/tCO_2. Other companies working to commercialize DAC include Carbon Engineering, Global Thermostat, Infinitree, Skytree, Silicon Kingdom Holdings, and others (NAS 2018a; ICEF 2018). Companies are operating at various stages, from the laboratory (in the case of Infinitree) to a pilot phase (in the case of Carbon Engineering and Global Thermostat) (NAS 2018a). These efforts have helped to inform the design of the technology, with companies developing their own proprietary processes. Investments in direct air capture to date have been primarily privately funded. Some companies interested in combining enhanced oil recovery with direct air capture are increasing investments. For example, Occidental Petroleum is partnering with Carbon Engineering to build potentially several direct air capture plants.

The federal government has a critical role to play in scaling direct air capture, given the current lack of incentives and market prospects; the need for publicly accessible data, lessons sharing, and standard setting; and its experience from other technology development efforts that can be applied to direct air capture.

Key Barriers to Direct Air Capture

The primary barrier to deployment of direct air capture is high cost, lack of a market for the product, and, related, a lack of adequate public subsidy for deployment (NAS 2018a). According to the National Academies, net carbon removal costs of current technology range from \$88–\$264 per tCO_2[13] (see Box 3 and Appendix B) depending on system design (NAS 2018a). Current policy incentives and market opportunities do not yet provide enough support for direct air capture to break even (Larsen et al. 2019), except in some niche applications where waste heat can be used as energy inputs and captured CO_2 can be used in economically valuable applications. While these niche

Box 3 | Costing Direct Air Capture

The estimated costs of direct air capture span a large range in the literature. There are many explanations for the upper and lower bounds of the costs. The National Academies state that the costs of direct air capture could conceivably fall below \$100/tCO$_2$ and suggest that sorbent-based systems could be reduced to about \$90/tCO$_2$ (NAS 2018a). The Climeworks demonstration plant reports its costs as \$600/tCO$_2$ currently (NAS 2018a). At \$100/tCO$_2$, sustaining direct air capture at the 1 GtCO$_2$ per year scale would require \$100 billion in annual public subsidy—about 15 percent of the current budget for the U.S. Department of Defense (NAS 2018a).

A wide divergence in the estimated costs in the literature prior to the National Academies' study is largely a reflection of differences in the materials and design of evaluated systems and in assumptions related to the contingency costs associated with a first-of-a-kind facility versus an nth-of-a-kind facility, among other factors. See Appendix B for more information.

deployment opportunities will not provide significant net carbon removal, if fully leveraged they could support at least the first several years of deployment (Wilcox et al. forthcoming). This could prove critical for driving down costs of the technology. Other potential barriers include availability of low-carbon energy to support deployment at large scale and public acceptance challenges related to geological storage sites.

Federal Policy Design for Direct Air Capture

Driving down cost will require the development and testing of new materials, components, and systems as well as private sector experience building and operating the technology. Toward these ends, federal policy will need to provide (1) public investment in technology development to drive cost down and (2) incentives for private sector deployment to enable "learning by doing." These key policy features are common to several existing federal technology development programs. The federal government did not meaningfully invest in direct air capture until FY2020, when it appropriated \$60 million for carbon removal technologies, including at least \$25 million for direct air capture.

PUBLIC INVESTMENT IN TECHNOLOGY DEVELOPMENT

The federal government has a long history of successful public investment in technology development. In the case of direct air capture, the federal government is particularly critical because there are currently few market prospects for the private sector (Larsen et al. 2019). Despite this need, while national governments have spent \$15 billion on clean energy technology R&D, direct air capture has received little attention (ICEF 2018). To date, total cumulative federal spending on direct air capture RD&D is estimated to be \$11 million (Larsen et al. 2019).

The National Academies recently put forward a roadmap for direct air capture technology development (see Table 2). Altogether the 15-year NAS roadmap calls for a 10-year \$23–35 million annual investment in basic science and applied research;[14] an overlapping \$13–25 million annual investment over 10 years in development; and \$145–180 million annually for 10 years for demonstration. These investments are staggered and sequenced to iteratively move results from basic and applied research into development. Stage gates are used to move only the most promising systems into demonstration-scale deployment over time, while basic and applied research continues to reveal new opportunities for cost reduction. While each stage occurs over a decade, some of these phases would run in parallel, at least partially, and the effort is designed to deliver commercial-scale technology at a substantially lower cost—\$100 per tCO$_2$—within 10–20 years. The Energy Futures Initiative has also developed a cross-cutting federal RD&D initiative, including DACs, and proposes a detailed roadmap for an RD&D portfolio, including for improving materials, engineering development, scale-up and testing, analysis, and military operational applications (Hezir et al. 2019).

Notably, the scale of investment called for by the National Academies pales in comparison to Department of Energy (DOE) spending on applied energy RD&D programs (Hezir et al. 2019; Larsen et al. 2019).

DOE's Office of Fossil Energy and National Energy Technology Laboratory (NETL) have existing infrastructure suitable to manage such an agenda, given their processes to fund universities, companies, and research organizations, as well as to manage contractors, testing, and analysis. Other institutions that could play key roles include the Department of Defense, given that direct air capture can be used to meet the defense need for distributed fuel

Table 2 | **National Academies Technology Development Agenda for Direct Air Capture**

	RESEARCH AND DEVELOPMENT NEED	COST ($/Y) (ESTIMATED IN 2018 US$, MILLIONS)	DURATION (YEARS)
BASIC SCIENCE AND APPLIED RESEARCH	Basic research and early phase technology development (e.g., on new materials [solvent/sorbents], new equipment concepts, and new system concepts such as renewable integration).	20–30	10
	Independent analysis, third-party materials testing and evaluation, and public materials database.	3–5	10
DEVELOPMENT	Scaling-up and testing air capture materials and components.	10–15	10
	Third-party professional engineering design firm assistance for the above effort, including independent testing, and a public database.	3–10	10
DEMONSTRATION	Design, build, and test pilot air capture system (>1,000 tCO$_2$ per year). In this scenario, project costs would be around $20 million and operate for three years, with one to two projects every year.	20–40	10
	National air capture test center support of pilots (including developing third-party front-end engineering design and economic analysis and maintaining public record of pilot plant performance).	10–20	10
DEPLOYMENT	Design, build, and test air capture demonstration system (>10,000 tCO$_2$ per year). In this scenario, project costs would be around $100 million and operate for three to five years, with one project every two years.	100	10
	National air capture test center support of demonstrations (support full-scale plant demonstration projects, maintain public record of full-scale plant performance and economics).	15–20	10

Note: The ten years of basic research, development, and demonstration funding begins in year one; the ten years of deployment funding begins in year four.

Source: Adapted from NAS (2019).

production, as well as the National Institute of Standards and Technology (e.g., for life-cycle assessment methodologies) (Larsen et al. 2019; ICEF 2018).

DEVELOPING NEW SYSTEMS

The research program would focus first on developing new materials, new equipment concepts, and new system concepts (e.g., equipment configurations and renewable energy integration). Of particular importance is the advancement of solvent and sorbent materials,[15] which bind the CO$_2$ and separate it from other gases in the air.

These capture agents vary in the efficiency with which they bind CO$_2$ and the extent and form of energy (commonly heat) required to be "regenerated"—to release CO$_2$ for collection and removal and return to their original state for reuse. Developing new solvents and sorbents that bind CO$_2$ with greater efficiency, and that can be regenerated with less energy, is a key focal point for cost reduction. Optimizing air contactors—the systems that expose solvents or sorbents to CO$_2$ in ambient air—is also needed (ICEF et al. 2018).

Also important in system design is the integration of energy sources. While there is significant global research into renewable heat, the latter's integration into direct air capture systems is less studied (NAS 2018a). Using waste heat has the potential to lower costs, [16] but this source is ultimately limited. Variable sources of renewable energy can also be used, and further analysis is needed to explore how to maximize such a resource in direct air capture (ICEF 2018).

New components, equipment designs, and system designs would be tested at increasing scales in laboratory settings. Promising systems would progress to field-testing and demonstration.

DEMONSTRATING AND COMMERCIALIZING NEW SYSTEMS

Field testing will be needed to validate designs and material choices (NAS 2018a). Accordingly, the National Academies recommend one to two pilot-scale projects annually at $20 million each capturing more than 1,000 tons of CO_2 per year. The National Academies envision a National Direct Air Capture Test Center—akin to the National Center for Photovoltaics for solar cell research (NAS 2018a)—to operate pilot projects.

Progressing to commercial-scale operation at 10,000 tCO_2 per year will play an important role in validating innovations tested at smaller scales as well as informing optimal siting. Siting considerations include CO_2 storage and/or utilization locations (or pipelines for CO_2 in the event that it is to be transported), availability of low-carbon energy sources, and favorable air conditions, including temperature and winds (ICEF 2018). Although the availability of storage capacity is not a near-term challenge, individual sites need to be validated, and mapping of low-carbon energy sites together with geological formations will be important for direct air capture siting (Mulligan et al. 2018c).

Public funding will be needed to subsidize the cost of operation at demonstration scale for promising direct air capture systems. Because commercial-scale (>10,000 tCO_2 per year) deployment costs are high—the National Academies estimate around $100 million per project—public investments would be made only after paths to commercialization have been shown to be viable (NAS 2018a).

PROVIDING INDEPENDENT EVALUATION AND ENSURING PUBLICLY AVAILABLE DATA

Central to the role of publicly funded technology development is the generation, standardization, and public availability of data on performance and reliability. These data are essential to enable learning and advancement by a broad set of actors in the innovation ecosystem—national laboratories, universities, and prospective private sector entrants. But companies have little incentive to disclose proprietary data from privately funded technology development efforts.

Standardized testing and evaluation by independent third parties is critical to ensure the integrity and comparability of results. Maintaining a public database with performance results can help private investors assess risks and accelerate development efforts outside of the federal government.

Public sector incentives for private-sector learning by doing

In parallel to a public technology development enterprise for direct air capture, "learning by doing" within the private sector can yield cost improvements through increased manufacturing experience, the aggregation of many minor innovations, and the standardization of supply chains (Kavlak et al. 2017). The federal government has a key role to play in providing adequate incentives for private-sector construction and operation of direct air capture facilities.

Major options for federal incentives include

- bolstered tax incentives for direct air capture; and
- federally assured markets for fuel derived from air-captured CO_2.[17]

The pursuit of a variety of avenues for adoption of supportive policies may increase chances of success. Leveling the playing field and creating incentives related to the management of captured CO_2—for example, regarding permitting processes for underground CO_2 injection, characterization of individual CO_2 storage sites, and product standards and certifications (Larsen et al. 2019)—will also be important. However, these challenges will need to be addressed in the course of building out carbon capture from point sources of emissions, which is likely to occur at scale sooner than direct air capture. Finally, should new comprehensive climate policies be developed at the federal level—a carbon tax, cap-and-trade, or a clean energy standard—providing eligibility for direct air capture will play a crucial role in supporting private-sector deployment experience. State governments also can play an important role in providing deployment incentives.

BOLSTERED TAX INCENTIVES

Tax incentives have played a critical role historically in advancing various clean energy technologies by encouraging private investment (ICEF 2018; Larsen et al. 2019). Tax incentives can take the form of investment or production credits, or accelerated depreciation (Mulligan et al. 2018c). Strengthening tax incentives for direct air capture represents a direct and cost-effective means for achieving the objective of private-sector deployment experience (Larsen et al. 2019). Although direct air capture was recently incorporated into the expanded Section 45Q tax credit (Box 4), which provides a credit per tCO_2 captured and used or stored, several amendments to the structure and value of the 45Q tax credit will be needed to support deployment of direct air capture at a meaningful scale.

Extending the commence-construction deadline for direct air capture from 2024 to 2030 would enable sufficient time to plan novel systems. Lowering the minimum capture and use threshold for direct air capture to 10,000 tCO_2 per year would leverage the tax credit for smaller, demonstration-scale projects (Larsen et al. 2019). Both of these changes may be critical to encouraging new entrants and fostering innovation.

Long-term planning certainty will also be important for driving private investment. Extending the credit payout period for direct air capture from 12 years to match the potential useful life of a direct air capture facility (e.g., 30 years) would provide greater revenue certainty to justify private investment (Larsen et al. 2019). Instead, or in addition, the tax credit could be revised to allow project owners to claim the capture and storage credit after the latter's expiration. This would give project developers an added incentive to site direct air capture facilities where captured CO_2 can be both used in the near term and permanently stored in the mid- to long term.

Lastly, the value of the credit for direct air capture will have a bearing on its effectiveness in driving deployment at scale. The current value of the credit for capture and storage ($50 per ton) is clearly inadequate to support direct air capture. Larsen et al. (2019) recommend increasing the value of the credit for direct air capture specifically to $180 per ton. This proposed revision is important not only to begin removing and storing CO_2 but also to send a clear demand signal to project

Box 4 | **The 45Q Tax Credit**

Section 45Q of the United States tax code provides a tax credit to qualifying power plants and industrial facilities that capture and store CO_2 through injection for permanent storage or use for beneficial purposes. Originally enacted in 2008, it was revised in early 2018. These revisions include the following:

- From 2018 to 2026, the tax credit value will increase linearly from $25.70 to $50 per metric ton of carbon dioxide for secure geological storage and from $15.30 to $35 per ton used in carbon dioxide–enhanced oil recovery (CO_2-EOR) that results in secure geological storage or other uses that permanently store carbon dioxide. It will increase at the rate of inflation after 2026.
- Capture projects must begin construction by January 1, 2024, to receive the credit and once in service will receive the credit for 12 years.
- There is no cap on the number of credits that can be issued (previously it was capped at 75 $MtCO_2$ in total).
- Direct air capture facilities are qualified sources.
- Credits go to the owner of carbon capture equipment but are transferrable to any other entity involved in the storing or beneficial use of CO_2.
- Minimum capture thresholds have been revised to
  - 500,000 $MtCO_2$ for power plants (previously the threshold for all facilities);
  - 100,000 $MtCO_2$ for all other industrial facilities, including direct air capture; and
  - 25,000 $MtCO_2$ for other facilities that capture CO_2 and put it to beneficial use aside from enhanced oil recovery.
- Projects that use the credit for making products must demonstrate a favorable life-cycle analysis under the Clean Air Act.

45Q is designed like a production tax credit and is meant to encourage private investment in a range of technologies and industries for carbon capture. Earlier modeling found that 45Q could help capture and store 50–100 $MtCO_2$, depending on factors such as public acceptance and readiness of enabling infrastructure like pipelines (Waltzer 2017; EFI 2018).

developers and prospective new entrants. It would require up to \$360 million in annual federal tax expenditures by 2025 to support 2 $MtCO_2$, potentially increasing to \$1.4 billion per year by 2030 assuming a 30 percent annual growth rate. This would represent less than half the annual federal expenditures on solar photovoltaic tax credits.

In the near term, CO_2 utilization could plausibly provide a lower-cost option for direct air capture deployment experience. The largest, most immediate utilization opportunity is enhanced oil recovery (Box 5), where CO_2 is injected in oil fields to release trapped oil, increasing production by 2–3 barrels per ton of CO_2 (IEA 2015). EOR is performed today predominantly with CO_2 extracted from natural reservoirs. EOR with air-captured CO_2 is unlikely to provide meaningful net carbon removal but could significantly reduce the net emissions of produced oil and could make direct air capture technology financially viable today—especially where oil field operators lack access to cheaper sources of CO_2.[18]

In any event, EOR will not deliver the needed scale on its own, and the necessary transition away from fossil fuels will eventually narrow its usefulness. The opportunity for CO_2-EOR in the United States is substantial; however, it is not clear how big a role direct air capture will play in the EOR market relative to other, cheaper sources of captured CO_2 like refineries and power plants. Policy measures to incentivize or require a shift from using CO_2 mined from natural reservoirs (the predominant practice today) to using anthropogenic CO_2 (like CO_2 captured from the atmosphere) may increase the opportunity space for direct air capture in CO_2-EOR while sharpening the reduction in net emissions.

Other markets for the utilization of CO_2 may develop and grow over time as CO_2 becomes more readily available as a potential feedstock. Direct air capture could be a cost-competitive source of CO_2 for the U.S. beverage industry today, but the scale of potential is limited to about 3 $MtCO_2$ per year (Wilcox et al. forthcoming).

Other tax-related incentives could also reduce investment costs but operate less directly than the 45Q tax credit and are likely insufficient on their own to support direct air capture at the needed scale (Larsen et al. 2019). These include an investment tax credit, tax-exempt debt financing, master limited partnerships, private activity bonds, and a bonus depreciation of capital assets (ICEF 2018; Larsen et al. 2019).

FEDERALLY ASSURED MARKETS FOR FUEL DERIVED FROM AIR-CAPTURED CO_2

Another avenue for driving private-sector investment in direct air capture would be to provide an assured market for fuel or other CO_2 utilization products. The potential market for CO_2 utilization products is \$1 trillion in the United States and almost \$6 trillion globally (Larsen et al. 2019). Developing these markets could provide an important stepping-stone for scaling direct air capture by supporting early-stage private-sector deployment, even though the conversion of captured CO_2 to short-lived products like fuel diminishes the net climate benefits of direct air capture (ICEF 2018). The federal government can provide assured markets by directly procuring fuel from air-captured CO_2 and/or by using a private sector fuels mandate—either an expanded Renewable Fuel Standard or a new low-carbon fuel standard.

The fuels pathway has garnered significant attention given the scale of the potential market, the value of fuel relative to other CO_2 utilization commodities like aggregate, the emission reduction benefits of displacing fossil fuels with fuel comprised of recycled CO_2, and the stated business strategy of one of the three direct air capture companies. However, the fuels pathway presents policymakers with advantages and disadvantages.

On the one hand, Larsen et al. (2019) found that either federal procurement—primarily by the Department of Defense as well as the General Services Administration—or a fuels mandate sized to 0.4 percent of 2017 on-road fuel consumption would be sufficient to support the needed direct air capture scale-up through 2030 (9 $MtCO_2$ capacity). These mechanisms offer additional avenues for adopting policy incentives. They may also serve other policy objectives—for example, enabling the military to generate its own fuel where fuel supply lines are vulnerable, or opening a pathway for decarbonizing aviation.

On the other hand, the fuels pathway represents a costlier avenue for incentivizing private-sector deployment of direct air capture—potentially by a wide margin. By generating product revenue, direct air capture companies can recoup a portion of operating costs. However, the conversion of CO_2 to fuel itself, which requires hydrogen, catalytic, and added energy inputs, adds considerable cost. If the cost of conversion is less than the product revenue generated on a per ton basis, then the fuels pathway would reduce the total need for public subsidy relative to an operation that simply stored captured CO_2. If the cost of conversion exceeds product revenue, the process would

Box 5 | Enhanced Oil Recovery with CO_2

Enhanced oil recovery (EOR) involves injection[a] of CO_2 into oil wells to increase production of oil that would not otherwise have been available. In the United States, around 63 $MtCO_2$ per year is injected for CO_2-EOR, accounting for around 4 percent of annual U.S. oil production. Today, the vast majority (78 percent, or 46 $MtCO_2$) of CO_2 used for EOR in the United States is sourced from natural underground reservoirs of the gas, with the remaining 22 percent, or 13 $MtCO_2$, coming from captured CO_2 (EPA 2015). Data on storage proportions of injected CO_2 is scarce since it involves proprietary information on CO_2 purchase amounts; however, the data available show that more than 99 percent of injected CO_2 is stored,[b] while the remainder is lost to fugitive and operating emissions (Hill et al. 2013). The advantage of CO_2-EOR over storage in saline aquifers is the generation of product revenue (from the sale of recovered oil) to help offset the cost of carbon capture from point sources of emissions or the ambient air.

CO_2-EOR has been posited as an important climate change mitigation strategy, despite the enhanced recovery of oil. Shifting CO_2-EOR from primarily mined sources of natural CO_2 to captured sources of anthropogenic CO_2 clearly provides a relative emissions benefit (Azzolina et al. 2016; IEA 2015). The degree to which CO_2-EOR provides an emissions benefit relative to its absence depends primarily on the rate at which oil produced via CO_2-EOR displaces oil that would have been produced elsewhere—a reflection of how readily consumers respond to changes in the price of oil. The IEA estimated that 8 of every 10 barrels of CO_2-EOR oil will displace oil that would have been produced anyway, reflecting inelastic demand for oil given a lack of alternatives for consumers. But the other 2 barrels would not have been produced otherwise, offsetting some of the net emissions reduction. If this displacement rate holds true, the IEA (2015) estimates that CO_2-EOR reduces net emissions by 0.19 tCO_2 per barrel produced (or by 0.63 tCO_2 per ton of CO_2 used). This represents a roughly 40 percent net reduction in the emissions from oil.

The displacement rate is uncertain, however, and may change over time as alternatives to oil become more available. If the displacement rate lowers to 5 out of 10 barrels, the net emissions reduction from CO_2-EOR disappears. This underscores the need for policies that reduce oil demand—like pricing carbon and investing in electric vehicles—to ensure that consumers switch to clean technologies despite the marginal effects of CO_2-EOR on oil supply. For reference, 10 $MtCO_2$ of direct air capture, if used for CO_2-EOR, could produce 30 million barrels of oil each year. According to the IEA, this would lead to a net increase in oil supply of 6 million barrels per year (0.08 percent of U.S. oil consumption) and lead to a net emissions reduction of 5.7 $MtCO_2$ per year. Assuming a lower displacement rate of 0.5, the net increase in oil supply would be 15 million barrels per year (0.2 percent of U.S. oil consumption) and there would be no overall change in net emissions (IEA 2015).

Other factors also play into the net emissions dynamics, including the ratio of CO_2 injected to oil produced,[c] the emissions intensity of the oil produced, the emissions intensity of the oil it displaces, and the product that is made from the crude oil produced, among other factors (Wong et al. 2013; Jaramillo et al. 2009). If the carbon intensity of the produced oil is higher, the net effect will decrease. In the case of CO_2-EOR with direct air capture, the energy source also matters. Renewable energy enables an increased net emissions reduction over natural gas even where its emissions are captured.[d]

The objective of CO_2-EOR to date has been to produce as much oil as possible from a given well with the least amount of CO_2 injected, and there has been little incentive to design with storage in mind and monitor it over the long term (IEA 2015). Further research is needed to develop reservoir engineering methods that co-optimize oil production and CO_2 storage (NAS 2018a). The National Academies recommend conducting two field-scale experiments in partnership with industry as well as supporting research on new approaches, at a total cost of $50 million per year for 10 years.

[a] CO_2 injection is not the only type of EOR; there is also thermal EOR, chemical EOR, and EOR where nitrogen or another gas is injected to produce tertiary oil.

[b] Not all injected CO_2 is stored after the first injection—the gas rises to the surface with produced oil and is captured, recycled, and injected again, so that with each injection progressively more is stored permanently underground through capillary action. In the end, some CO_2 will remain free and can either be recovered and recycled elsewhere or left underground (IEA 2015).

[c] To maximize profit, the amount of CO_2 injected per barrel of oil produced is minimized; to shift focus to increasing storage capacity of CO_2-EOR, however, the amount of CO_2 injected per barrel of oil produced must increase. The IEA (2015) estimates that the ratio is currently around 0.3 tCO_2 injected per barrel of oil produced.

[d] Every ton of CO_2 injected typically yields 2–3 barrels of oil. Some portion of this produced oil displaces oil that would have been produced elsewhere, but the remainder would not have been produced otherwise. Thus, CO_2-EOR represents a trade-off between CO_2 sequestered from the atmosphere and additional direct emissions from oil. Where direct air capture is powered by renewable energy, all of the CO_2 injected is CO_2 that was removed from the atmosphere. In contrast, where direct air capture is powered by natural gas, as much as a third of the CO_2 injected is CO_2 that was captured from the combustion of that natural gas. This affects the balance between total CO_2 removed from the atmosphere and additional direct emissions of CO_2 from the production and ultimately consumption of oil, diminishing the net emissions reduction gained from the process.

add to the total need for public subsidy. Expected product revenue is likely in the \$2–\$4 per gallon range, or \$355 per ton of captured CO_2. However, the estimated cost of converting CO_2 to diesel fuel today is \$8.91 per gallon, or \$784 per ton of captured CO_2.[19] Other fuel derivatives such as methanol may offer a more cost-effective but smaller alternative market. The cost of conversion may come down in the coming years—and federal incentives for fuel derived from CO_2 may accelerate those cost reductions. In the meantime, subsidizing direct air capture through fuels would require 2–3 times more public expenditure than direct subsidies for direct air capture and storage.[20]

AGRICULTURAL SOIL CARBON MANAGEMENT

In Brief

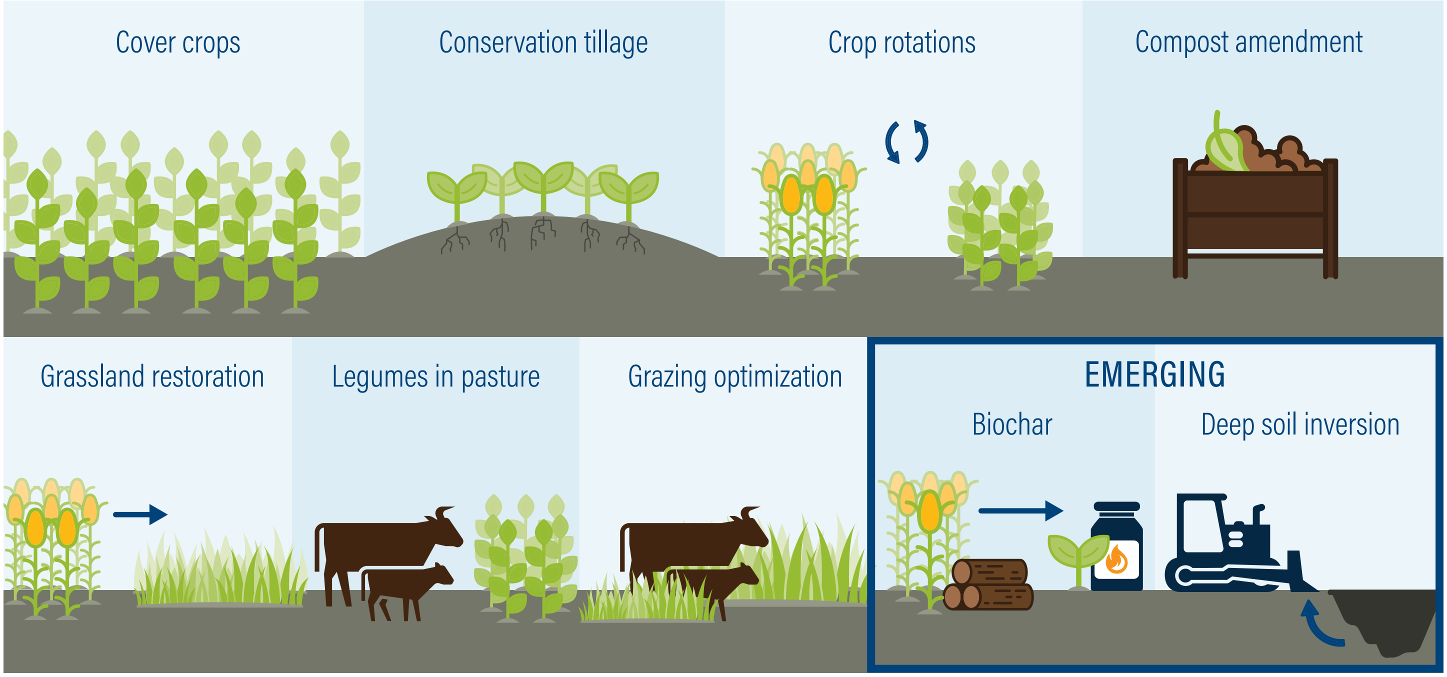
- Several management practices in both cropland and grazing land are thought to increase carbon stocks in agricultural soils (see Figure 8).
- Estimates of the carbon removal potential in agricultural soils generally do not account for spatial heterogeneity in practice efficacy across soil types and depths, crop types, farming systems, and climate. They also overlook practical constraints on soil management and fail to verify the permanence of carbon sequestration in soils. These uncertainties could limit the total potential for carbon removal from this pathway.
- Despite these challenges and uncertainties, it is clear that some agricultural practices tend to result in more soil carbon than others and that increased soil organic carbon has important agronomic benefits, including improved soil fertility, reduced soil erosion, and reduced nutrient leaching, in addition to mitigating climate change.
- We estimate that further research and innovation in agricultural soil carbon management could enable the removal of **100–200 $MtCO_2$ per year** by 2050 in the United States, recognizing not only scientific uncertainty and significant practical hurdles but also the possibility of uncovering additional potential not reflected in the literature (upper bound with safeguards: 300 $MtCO_2$ per year; see Figure 9).
- In addition to those described above, major uncertainties relate to the carbon sequestration and yield effects of any given practice on any given acre, the time lag between practice implementation and agronomic benefits, and the extent to which farmers and ranchers would continue to implement practices after any government assistance expires. Realizing the full carbon removal potential of soil management is therefore contingent on addressing these uncertainties through on-farm implementation and monitoring.
- Financial, technical, and cultural barriers also challenge implementation of better agricultural soil management. Pairing implementation and monitoring efforts with financial and technical assistance for farmers and ranchers is critical to addressing the range of barriers in this pathway.
- A 10-million acre on-farm research and innovation program would require **\$500 million** annually over 10 years for necessary financial and technical assistance as well as monitoring and research costs (see Figures 10 and 11).

Soil Carbon Management 101

Globally, nearly 500 $GtCO_2$ has been lost from soil carbon stocks over the last 12,000 years, with the rate of loss accelerating drastically over the past 200 years (Sanderman et al. 2017). While soil management practices cannot recover the full volume of carbon that soils have lost over that time, there is substantial evidence that a range of management practices in croplands and grazing lands (see Box 6) can restore some portion of that soil carbon debt (NAS 2018a). Estimates in the literature of the national potential for carbon removal from agricultural soil management vary widely, and are generally the product of scaling per acre carbon removal rates—based on meta-analysis of data field studies, which remain sparse for some practices—to the total available land area. As a result, they do not account for significant spatial heterogeneity in practice efficacy across soil types, crop types, farming systems, and climate (Minasny et al. 2017) or practical constraints that could preclude full adoption of the practices considered (Searchinger et al. 2019; Wilson et al. 2013).

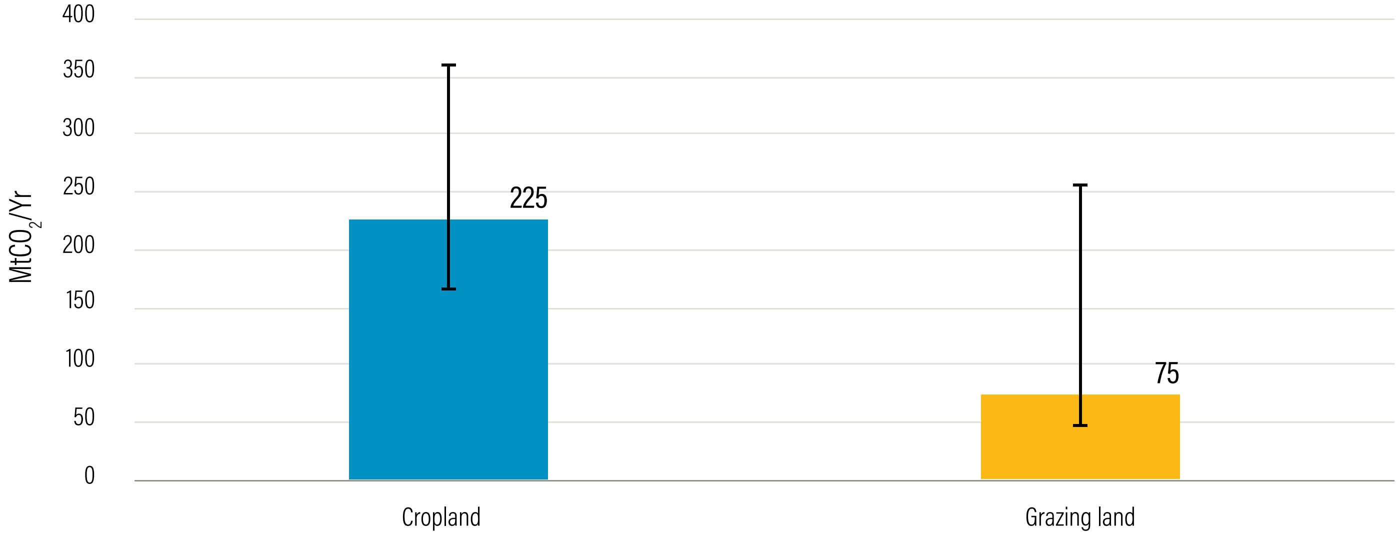
Recognizing these shortcomings, we conservatively estimate the upper-bound potential based only on the lower end of ranges cited in the literature, with an average of 300 $MtCO_2$ per year (range: 200–400 $MtCO_2$ per year).[21] The distribution of this potential across U.S. croplands and grazing lands, along with the range of estimates from the literature, is shown in Figure 9 (Lal et al. 1998, 2003; Sperow et al. 2003; Sperow 2016; Follett et al. 2001; Schuman et al. 2002).

Figure 8 | **Key Agricultural Soil Carbon Management Practices**



Source: Authors.

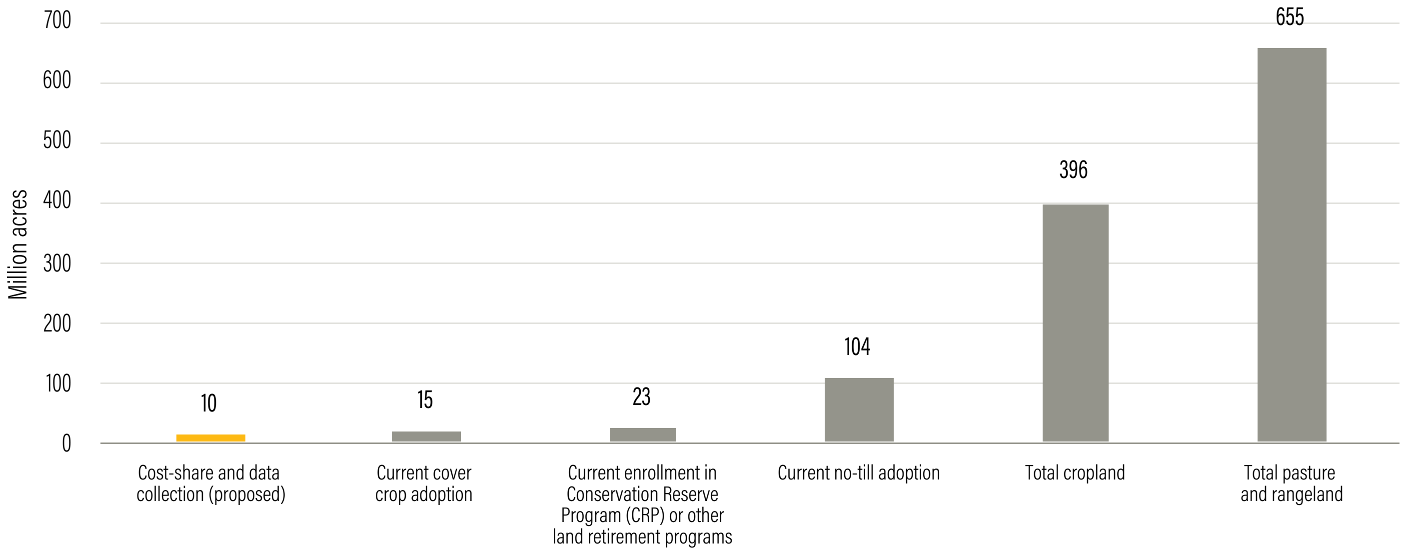
Figure 9 | **Composition of the Carbon Removal Opportunity in Agricultural Soil Management**



Note: Error bars represent the average range of low and high estimates for carbon removal from croplands and grazing lands, respectively. Outlier estimates of the high-end potential excluded in croplands from Lal et al. (1998) and in grazing lands from Follett et al. (2001).

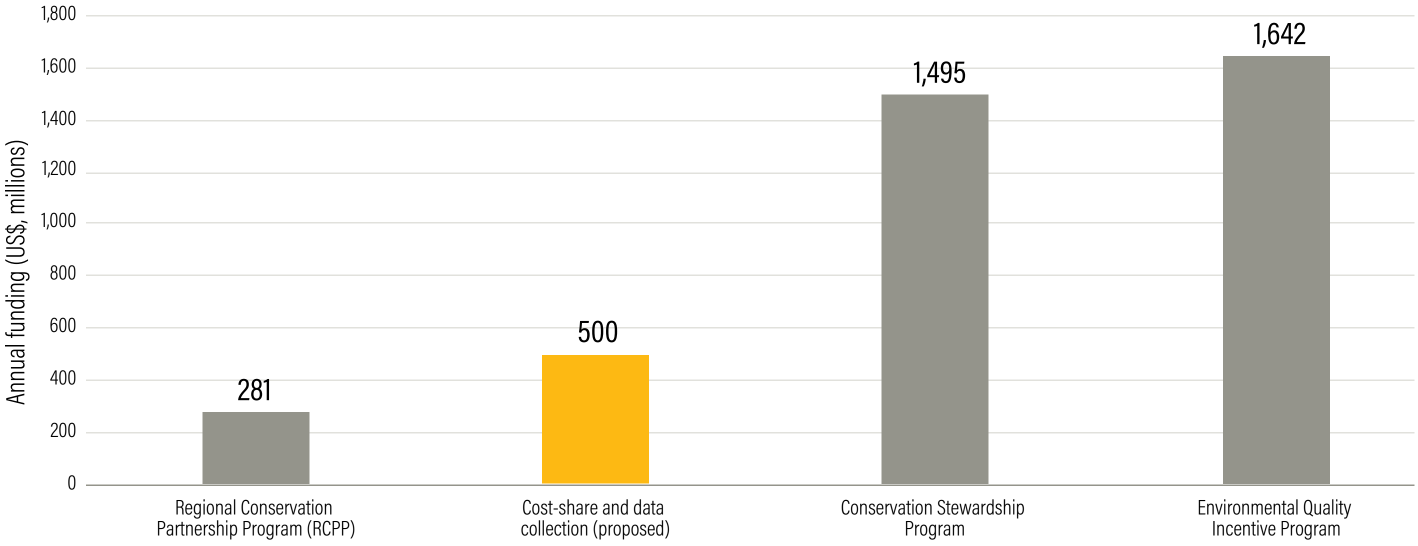
Sources: Cropland data from Lal et al. (1998, 2003); Sperow et al. (2003); and Sperow (2016). Grazing land data from Follett et al. (2001); Schuman et al. (2002); and Lal et al. (2003).

Figure 10 | **Relative Scale of Proposed Acreage in Agricultural Soil Carbon Program in Comparison with Other Key Metrics for U.S. Agricultural Soil Carbon Sequestration**



Sources: NASS (2017); USDA Economic Research Service (2012).

Figure 11 | **Relative Scale of Proposed Funding for Agricultural Soil Carbon Program in Comparison with Funding Levels in Other USDA Cropland Cost-Share Programs**



Sources: USDA (2019a).

Taken individually, agricultural soil management practices have varying levels of carbon removal potential, supporting scientific evidence, and constraints to deployment across the United States. Taken together as complementary tools in a soil carbon toolbox, however, soil management practices may be able to provide carbon removal at scale while enhancing the quality of agricultural lands with a host of co-benefits, including for water resources. In parts of the United States, soil management practices are already incentivized based on their capacity to improve water quality or reduce soil erosion, but their carbon removal potential remains largely unrecognized in public policy.

Restoring carbon to agricultural soils at scale will require learning within several key stakeholder groups. These include farmers and ranchers, for whom carbon-beneficial practices represent changes in management; the federal government, as it strives to identify the optimal design elements for a program to promote changes in prevailing soil management regimes; and a scientific community that currently lacks the data to inform efficient policy incentives at scale. The federal government has the unique capacity to institute nationwide data collection and monitoring systems across farms and ranches as they implement different soil management practices. These new data and monitoring systems will be key to building confidence among policymakers and underpinning more targeted and ambitious policy investments in these practices. The federal government is also well positioned to galvanize widespread adoption of soil management practices by farmers across the country, given extensive farm support and conservation programs.

These investments would come at a critical juncture for U.S. agriculture, as small farms are struggling to survive and U.S. trade policies have squeezed margins for agricultural production across the board. Directing resources to help agricultural lands realize their full potential for carbon removal constitutes both an investment in the agricultural economy and a contribution to climate mitigation.

Key Barriers to Soil Carbon Management

Economic, technical, and cultural barriers all challenge wide-scale adoption of agricultural soil management practices. Despite long-term net benefits, upfront costs can present a hurdle to commodity-crop producers who already operate on razor-thin margins and hold record levels of debt (Carlisle 2016; CTIC 2017; Long et al. 2014; Farm Bureau 2019). Farmers who rent rather than own their land—a group that now manages over half of U.S. cropland—may also have less incentive to make short-term investments in soil management practices for long-term gains (Bigelow et al. 2016; Carlisle 2016). Transaction costs, including the cost of obtaining information on new management practices and the opportunity cost of interfering with traditional crop production processes, are more difficult to quantify than other sources of upfront cost but may add substantially to the economic cost of adopting new practices (Biardeau et al. 2016).

Lack of technical expertise and access to markets represent additional challenges for adoption. Timing the planting and termination of a cover crop within the confines of a corn or soy production schedule is a key barrier to would-be adopters of that practice, for example, as is the disappearance of regional markets for alternative crops that could make up a diversified crop rotation (Arbuckle and Ferrell 2012; Roesch-McNally et al. 2018). Carlisle (2016) found that farmers who were more knowledgeable about a new management practice, and were more confident in their ability to properly implement it, were more likely to adopt the practice.

Prevailing social norms around the "correct" way to grow crops or raise livestock make the challenge of shifting production practices even more intractable. Producers who show stronger associations with environmental goals and land stewardship values have been shown to adopt soil management practices at higher rates (Prokopy et al. 2019), which implies that economic and technical considerations are not the only factors affecting adoption. Risk aversion and resistance to behavior change are important drivers of soil management regimes for many producers (Sykes et al. 2019). While federal policy may not be able to address cultural barriers head-on, it can set the stage for culture change by removing economic and technical hurdles and supporting a critical mass of early adopters who can generate lessons for others and begin to shift social norms.

Federal Policy Design for Soil Carbon Management

Federal policy targeting the restoration of carbon to agricultural soils at scale must equally prioritize investments in financial assistance for producers, accompanying technical assistance, and monitoring and research efforts. This hybrid policy approach is necessary because of the twin needs for accelerated adoption and scientific learning in this field—and the two are mutually reinforcing:

Box 6 | Key Agricultural Soil Management Practices

A variety of soil management practices can promote incremental carbon removal in agricultural soils. Some practices may be implemented in tandem on the same agricultural acres, though in most cases little research has been done on the synergistic or dampening effects of implementing multiple soil management practices simultaneously. Other practices are mutually exclusive—for example, cropland cannot be subject to both conservation tillage and deep soil inversion; nor can cropland be planted with cover crops while being restored to grassland. Independently, however, all these practices have been shown to contribute to carbon removal under at least some circumstances, and all should be considered in a program to accelerate carbon removal through agricultural soil management.

The list of practices described below is not exhaustive but includes many of the practices being implemented or researched on U.S. croplands and pasture lands. "Conventional practices" are those that are already practiced on a significant number of agricultural acres or are at least backed by a robust body of research demonstrating their carbon benefits. "Emerging practices" are those that are still in early stages of research and adoption but show considerable promise for catalyzing carbon removal at scale if barriers to implementation at scale can be addressed.

CONVENTIONAL PRACTICES

Cover crops: Cover crops provide continued carbon sequestration in soil between the harvest and planting of market crops, when fields would otherwise be fallow. Other benefits of cover crops include reduced soil erosion and compaction, nitrogen accumulation in the case of legumes, enhanced water storage, and, in some cases, increased market crop yields (Figures 10–11). Globally, cover crops are estimated to sequester 0.47–0.80 tCO_2 per acre per year (Poeplau and Don 2015; Abdalla et al. 2019). At this rate, if cover crops were adopted on all available croplands in the United States now planted with any of the five major market crops (corn, soy, wheat, cotton, and rice), they would sequester 100–175 $MtCO_2$ annually. This estimate does not account for additional possible climate mitigation impacts from N_2O emission reductions, reduced use of nitrogen fertilizers, and changes to cropland albedo (Kaye and Quemada 2017)—but neither does it account for potentially significant limitations to the viability of cover crops in some areas, for example where winter conditions are too dry or too cold for the crops to grow (Unger and Vigil 1998; Wilson et al. 2013; Nielsen et al. 2015). Uncertainty therefore remains as to the feasible national potential of cover crops as a carbon removal strategy, and—relatedly—to the economic viability of cover crops in regions that may have marginal conditions for cover crop growth. In these areas, forage production has been posited as an economic rationale for adopting cover crops where other benefits fall short (Gabriel et al. 2013; Nielsen et al. 2015), but the effect on carbon sequestration of harvesting cover crops for forage is not well understood. If forage derived from cover crops replaces forage that would otherwise be grown on dedicated land, then cover crops may also serve as a "land sparing measure" that opens further opportunities for carbon removal on spared land.

Conservation tillage: No-till and reduced-till—practices collectively known as conservation tillage—build carbon in cropland soil organic matter by reducing soil disturbance and erosion. Some form of conservation tillage has been practiced on nearly 50 percent of acres growing the five major market crops in the United States over the last four years, though only 20 percent of these acres practiced conservation tillage consistently for the whole period (Claassen et al. 2018a). Published carbon sequestration rates for the United States range from 0.1 to 0.8 tCO_2 per acre per year, with significant regional variation (Ogle et al. 2019; NAS 2018a). Eagle et al. (2012) found an annual carbon sequestration potential of 115 $MtCO_2$ from transitioning all croplands to continuous no-till, thought to be the most carbon-beneficial form of conservation tillage. However, more recent meta-analyses have questioned the efficacy of conservation tillage at building soil carbon stocks, arguing that much of the increase in topsoil carbon content that results from conservation tillage is offset by carbon losses at greater soil depths, fully eliminating any carbon benefit under some conditions (Ogle et al. 2019; Powlson et al. 2014). Carbon removal gains can also be reversed if no-till fields are later subjected to more intense tillage, even if only occasionally (Pape et al. 2016). The actual contributions of conservation tillage to the nation's carbon removal portfolio may therefore be lower than its technical potential suggests—especially as the practice is currently practiced only intermittently on a plurality of U.S. cropland acres (Claassen et al. 2018a).

Crop rotations: Crop rotations build soil carbon by increasing the use of crops with greater carbon-sequestering properties, such as legumes or perennial forages. Such rotations were common on U.S. croplands in the mid-20th century but have since given way to monocropping or corn-soy rotations as a result of rising prices for key commodity crops. Estimated carbon sequestration rates for improved crop rotations range from 0.15 to 0.50 tCO_2 per acre per year (NAS 2018a). Carbon removal potential in the United States has been considered negligible for diversified annual rotations but up to 29 $MtCO_2$ per year for rotations including perennials; additional climate benefits in both scenarios come from reduced N_2O emissions (Eagle et al. 2012). Other benefits may come from weed suppression, disease resistance, and enhanced soil fertility. Adoption of some crop rotations, particularly those that include perennials, is limited by water availability, with the suitable land area in the United States corresponding to humid regions (Eagle et al. 2012). Crop rotations can also be limited by the lack of regional markets for crops other than corn and soy (Roesch-McNally et al. 2018). Some evidence has shown that crop rotations can produce similar yields as monocrop systems (Davis et al. 2012), but the impact of diversified crop rotations on agricultural productivity and overall food security across the United States remains uncertain.

Compost amendment: Applying composted organic wastes to croplands or pastures improves soil carbon soil health, provides nutrients, reduces the need for fertilizer, and avoids landfill emissions by diverting organics from the waste stream. One study on California rangelands found a sequestration rate of 8.5 tCO_2 per acre over the first three years following compost application, though this is tempered by emissions associated with transportation and application of the compost, as well as emissions released during decomposition of the organic material (DeLonge et al. 2013). Large-scale deployment of compost on croplands and rangelands requires a large organic waste stream to serve as the input source. Food, yard,

Box 6 | Key Agricultural Soil Management Practices (Cont.)

and agricultural wastes offer the largest input opportunities for compost, with an upper-bound estimate of 162 Mt of input material for compost projected to be available by 2040 (NAS 2018a). However, most agricultural wastes are already used as feedstocks or fertilizers, bringing into question the availability and additionality of carbon sequestration from composting these wastes. Composting all food and yard wastes, meanwhile, offers a net carbon removal potential of less than 25 $MtCO_2$ under optimistic assumptions.[a] To increase the total carbon removal potential available from compost, additional feedstocks such as animal manure, wood wastes, or marine biomass would be necessary.[b] Net emissions vary significantly based on input stream, and comprehensive life-cycle analysis is needed to understand the benefits of land application of compost (NAS 2018a).

Grassland restoration: Converting idle cropland to native perennial grass is a locally effective method of accumulating soil carbon (NAS 2018a). However, shifting land out of crops may cause leakage of crop production onto grassland and other natural ecosystems elsewhere, offsetting net carbon gains. Perennial grasses amass large amounts of soil carbon because of their proportionally large root systems and long-lived grass species. Excluding net leakage effects, restoring grassland cover is estimated to sequester carbon in soils at a rate of 0.8–1.8 tCO_2 per acre per year (Fargione et al. 2018; Eagle et al. 2012). Limiting grassland restoration to an estimated 5.1 million acres of marginal or idle cropland that is suitable for conversion, predominantly in the Intermountain West and Plains states (Pape et al. 2016), would yield 4–9 $MtCO_2$ per year in carbon removal.

Legumes in pasture: Legumes have been shown to store up to 30 percent more soil organic carbon than other species due to their nitrogen-fixing microbial symbionts (Kumar et al. 2018). Legumes can also increase forage productivity in pasture lands, further catalyzing additional carbon sequestration in these systems (Henderson et al. 2015). Globally, sowing legumes in pasture is estimated to sequester 0.81—0.98 tCO_2 per acre per year (Henderson et al. 2015; Conant et al. 2017); U.S.-specific rates, however, are likely closer to 0.53 tCO_2 per acre per year (Henderson et al. 2015). Carbon removal potential in the United States has been estimated at 7–13 $MtCO_2$ annually, but with a recognition that spatial variation in climate benefits of the practice is uncertain (Fargione et al. 2018; Pape et al. 2016). Another key uncertainty for the practice is how carbon sequestration changes with soil depth; one study found a carbon sequestration rate four to five times higher than the global average by sampling deeper in the soil (Guan et al. 2016).

Grazing optimization: Grazing optimization can entail either lower stocking rates of grazing animals on pasture or rangelands, which promotes carbon removal by reducing stress on overgrazed forage, or implementing rotational grazing, which promotes carbon removal by allowing for periods of forage regrowth between intensive grazing operations. Relatively little research has been done on these practices in the U.S. context. Most of the estimates that do exist show negligible rates of carbon sequestration (0.06–0.08 tCO_2 per acre per year) or rates not significantly different from zero, with clearer benefits on moist pasture land than on arid rangeland (Henderson et al. 2015; Eagle et al. 2012). Sequestration rates may be significantly higher in some circumstances (e.g., Stanley et al. 2018), but at a national scale, this pathway likely has a small potential (Rotz et al. 2019). Fargione et al. (2018) posit that grazing optimization can remove 11 $MtCO_2$ per year, though their estimate is not significantly different from zero. Key uncertainties for this practice include the spatial heterogeneity and feasibility of this practice across U.S. pasture and rangelands.

EMERGING PRACTICES

Biochar: Biochar is produced through biomass conversion in various high-temperature processes and can be used as a soil amendment that increases soil carbon and nutrient cycling, as well as water retention. Biochar characteristics vary significantly depending on the biomass input composition and the conversion process (Serapiglia et al. 2015). Notably, biochar can be highly stable in soils, with 79 percent of carbon stored for more than 100 years—this equates to a potential of 95 $MtCO_2$ per year (Fargione et al. 2018). Sequestration stability and soil health benefits may be inconsistent, making quantification difficult. Furthermore, the process requires a significant amount of input energy and/or fuel, adding to life-cycle carbon impact (Gaunt and Lehmann 2008). Additionally, competition for biomass may limit the deployment scale, as other sectors compete for the same input biomass feedstocks. Other more lucrative offtake streams, such as wastewater treatment, may further limit scaling potential as competing offtake pathways (Weber and Quicker 2018).

Deep soil inversion: Deep soil inversion could build soil carbon by burying carbon-rich topsoil at depths of at least 50 cm and exposing deeper soil to the surface, where it could accumulate additional organic matter from crop residues and roots. To date, however, deep inversion tillage has not been tested in the United States (NAS 2018a). Initial test sites in Germany show that the rate of carbon sequestration could be relatively high—about 1.5 tCO_2 per acre per year over 40 years (Alcántara et al. 2016)—but considerable uncertainty exists around whether such an indicative sequestration rate would apply in the United States. The proportion of U.S. agricultural lands that could be suitable for deep inversion tillage is also unknown.

[a] Assumes that 28 tons of compost are applied per acre, with a net benefit of 9 tCO_2 per acre. While local benefits are quite significant, total potential nationwide is limited by the total availability of feedstocks for composting. Total available food and yard waste input streams for compost are estimated to be 78 Mt by 2040 (assuming a 19 percent increase from current levels), limiting total carbon benefit to 25 $MtCO_2$ per year. Increasing input streams to include all agricultural wastes increases the benefit to 51 $MtCO_2$ per year. Biomass to stored CO_2 captured via composting is estimated to have a conversion efficiency of 0.32 (DeLonge et al. 2013; NAS 2018a).

[b] Animal manure from confined feeding operations, for example, offers 335 Mt of input material (Graham and Nachman 2010), but the vast majority of these wastes are already applied to agricultural land as fertilizer (Wu et al. 2013; Graham and Nachman 2010).

increased adoption rates across different soil types and regions offers the opportunity for data collection and scientific study, which in turn will inform further investment by producers and policymakers alike in scaling adoption in ways that are most beneficial. Focusing policy solely on deployment incentives and technical assistance would not ensure that public investments translate effectively and efficiently to carbon removal outcomes because of lingering uncertainty around the impacts and regional variability of some practices. In contrast, a singular focus on research and monitoring would miss critical near-term opportunities to remove carbon through deployment. This hybrid approach would also generate "proofs of concept" for soil management practices and spur farmer-to-farmer learning that could underpin long-term cultural change.

The initial implementation period of such a program would be designed to generate data across a diverse range of soil management practices, crop or forage types, and environmental conditions. Analysis of these data, along with data shared through existing subnational programs (see Box 7), could provide lessons essential for designing follow-on policy to cost-effectively scale adoption of soil carbon management practices. These lessons could include the following:

- Improved understanding of the biophysical efficacy of soil management practices for carbon removal, including the permanence of carbon sequestered in soils, as well as any positive or negative feedback loops associated with interactions between multiple soil management practices.
- Improved understanding of success factors in promoting adoption and persistence of soil management practices in the absence of continued financial assistance—including cost-share contract lengths and rates, technical assistance, and social factors.
- Identification of any additional barriers that arise as adoption rates increase—for example, seed production for cover crops or legumes in pasture, access to markets for crops and forage from crop rotations or cover cropping, or institutional resistance from trade groups, private companies, or other influential organizations in agricultural communities.
- An assessment of how technical assistance can effectively maximize on-farm benefits from practice adoption.
- Improved calibration of carbon models like DAYCENT to facilitate more precise planning and policymaking efforts going forward.

The sections that follow discuss considerations in structuring the financial, technical, and scientific components of this program to effectively and efficiently harness the carbon removal potential of agricultural soil carbon management.

Subsidy to address financial barriers to adoption

We approximate an annual federal funding need of $400 million, assuming an average per acre per year subsidy of $40 (though rates may vary over time or by practice) for 10 million enrolled acres. This average subsidy rate is consistent with paying 100 percent of direct costs for the first year of cover crop implementation (see Figures 11–12) and is within the range of subsidy rates that have led to significant increases in cover crop adoption at the state level (Maryland Department of Agriculture 2018; Virginia Department of Conservation and Recreation 2019)—though a wider variety of soil management practices could be eligible for the subsidy. Higher or lower rates may be more appropriate for other soil management practices, but data to quantify differential rates by practice are scarce.

Technical assistance, education, and research and monitoring programs to complement the financial subsidy, described in more detail in the sections that follow, would require additional funding. The National Academies propose an agricultural research agenda totaling up to $30 million per year that includes some, but not all, of the research and monitoring objectives considered here (NAS 2018a). For a modest expansion of the National Academies' proposed research agenda alongside needed additional investments in technical assistance and education, we approximate a funding need of $100 million, pushing the total federal funding need for the proposed soil carbon management program to $500 million.

Financial subsidies for agricultural soil management practices are primarily aimed at covering the upfront costs of practice implementation, which may include some combination of seed or other inputs, specialized equipment, and temporary forgone production. These costs can be seen as an investment, as research suggests that producers may break even or even generate net financial gains over the long term where yield gains and avoided costs are realized (Fargione et al. 2018; Roberts et al. 1998; O'Reilly et al. 2012; Keene and Curran 2016; Lichtenberg 2004; Myers et al. 2019). Although net economic gains can be positive, however, risk-averse producers lacking on-farm experience with the economic returns of soil management practices may be reluctant to invest the upfront costs on their own.

As an example, Figure 12 and Figure 13 show the costs and economic benefits farmers could expect by planting either leguminous or nonleguminous cover crops. The cost of seed and equipment exceed the short-term yield benefits of cover cropping plus the avoided costs that would accrue in subsequent growing seasons for weed and pest control and labor-intensive measures to repair soil erosion damage. The farmer can break even in the short term by planting leguminous cover crops to reduce the need for synthetic fertilizer, but even then net private benefits would not be sufficient to warrant the additional complexity and transaction costs associated with adopting the practice.

In the longer term (5–10 years of continuous cover cropping), additional on-farm benefits like resilience to drought and increased soil fertility make the practice more economically attractive. Until these knock-on benefits make their way to the farmer's bottom line, however, the farmer remains financially exposed as a result of planting cover crops. The amount of financial exposure has a direct dampening effect on adoption of the practice—in Maryland, for example, farmers were 14 percent less likely to plant cover crops for every 1 percent increase in the cost of the practice (Lichtenberg 2004).

Consequently, cost-share is likely necessary to entice first-time adoption of new soil management practices, especially those with high costs and few immediate benefits to producers' bottom lines. The need for cost-share has been shown to be highest for practices that require taking land out of agricultural production, and lowest for practices like conservation tillage that have little impact on operations and may actually save producers money in the near term (Claassen et al. 2018b). Cost-share has empirically proved successful in stimulating adoption of cover crops. In Maryland, for example, a state cost-share program that pays farmers a minimum of $45 per acre for planting cover crops has yielded adoption rates of 40–50 percent—an order of magnitude higher than the national average (Hellerstein et al. 2019).

Box 7 | Subnational Programs for Soil Carbon Management

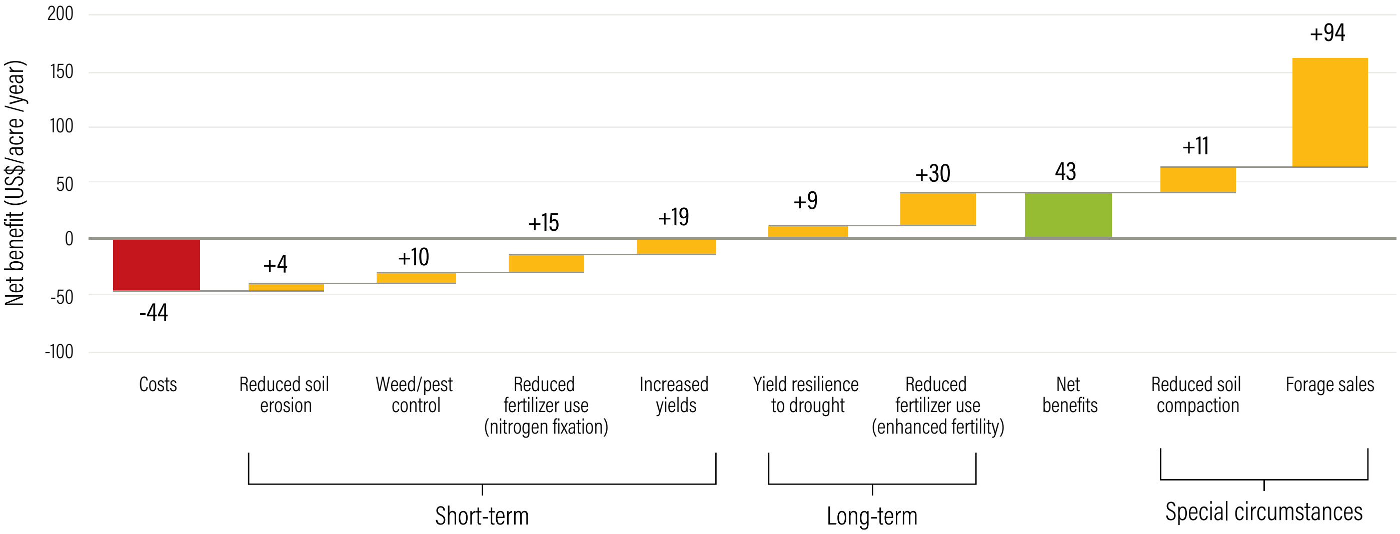
Several states have adopted "healthy soils" programs in recent years, providing financial and technical assistance to farmers who adopt practices that build soil health by sequestering carbon. These programs also include investments in research, monitoring, and demonstration projects that can help answer key questions for scaling adoption of soil carbon management practices within those states. Over a dozen states have either passed legislation relating to the formation of healthy soils programs or have legislation currently pending (Soil4Climate 2019). In addition to serving as "laboratories" to test policy approaches that could later be codified in federal policy, these state programs could also serve as implementation vehicles for a federal program on soil carbon management. For example, the federal government could provide funding directly to states that achieve federal targets for carbon removal in agricultural soils. This federalism framework would encourage innovation and ambition at the state level.

Efforts also continue outside of government to advance the science and implementation of soil carbon management. Multiple for-profit and nonprofit start-up organizations are developing their own market-based platforms to incentivize adoption of soil carbon management practices while collecting on-farm data to improve the quantification of carbon sequestration benefits from specific practices under a variety of conditions (Burwood-Taylor 2019; Davies 2019; Jospe 2018).

Beyond existing cost-share mechanisms, however, effectively harnessing the potential of agricultural soil management as a carbon removal pathway will require additional measures:

- Pairing cost-share with significant field data-collection activities focused on carbon sequestration and producer needs and constraints.
- Developing a mechanism at USDA for quantifying carbon benefits derived from public investments and applying new data and science to target and scale promising practices.
- Providing cost-share resources commensurate with demand.

Figure 12 | Net Costs and Benefits of Cover Cropping (Legumes)

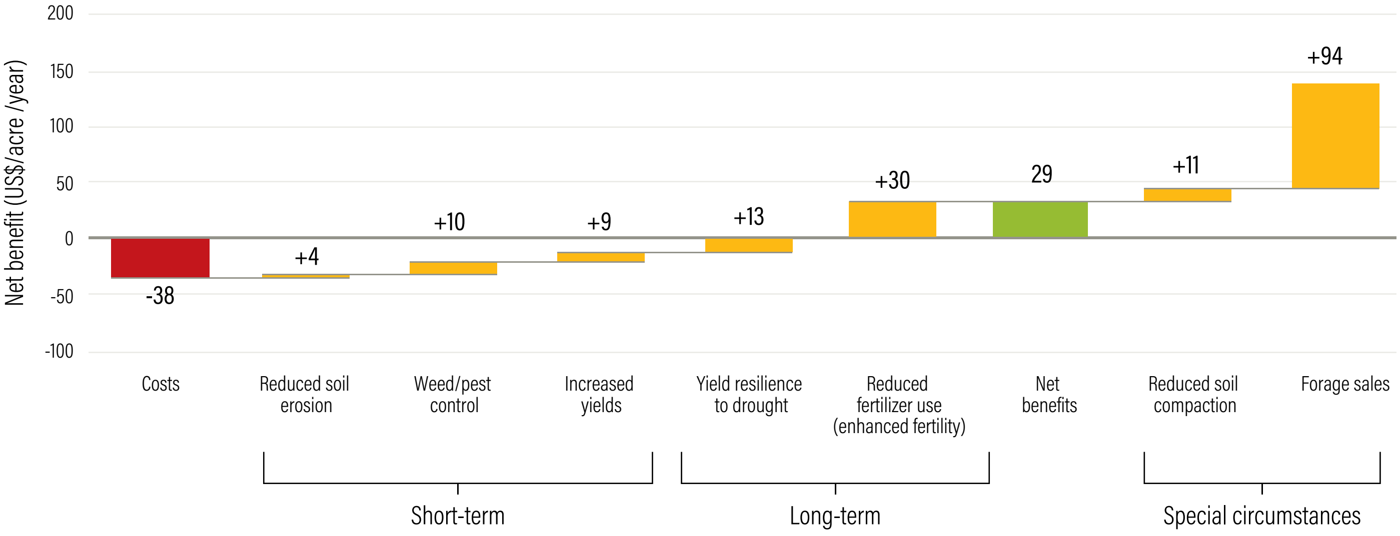


Note: "Special circumstances" refers to instances where farmers may gain additional economic value by reducing the need to till compacted soil or by harvesting and selling cover crops for animal feed, but these benefits are contingent on external factors (historical soil compaction problems, or infrastructure and markets to sell forage crops) that may apply in a minority of cases (Myers et al. 2019).

Removing the cover crop biomass from the field, rather than leaving residues to decompose, may compromise some of the on-farm environmental and carbon benefits that cover crops would otherwise impart. The net carbon sequestration impact of this practice has not been quantified.

Sources: NRCS (2014); Bergtold et al. (2017); Gabriel et al. (2013); Pratt et al. (2014); Myers et al. (2019); Cartwright (2015a); Robertson et al. (2000).

Figure 13 | Net Costs and Benefits of Cover Cropping (Nonlegumes)



Sources: NRCS (2014); Schnitkey et al. (2016); Bergtold et al. (2017); Gabriel et al. (2013); Schipanski et al. (2014); Pratt et al. (2014); Cartwright (2015b, 2018); Myers et al. (2019).

A cost-share program including these key features could feasibly be implemented through (1) a direct payment program such as EQIP or (2) a premium subsidy within the federal crop insurance program.

NRCS already provides cost-share for conservation practices through programs like EQIP, CRP, and CSP (see Box 8). New cost-share funding for agricultural soil management could sit in a special set-aside within EQIP or a parallel program. In either case, walling off the program envisioned here from existing programs would help preserve its specific mandate to advance understanding and deployment of practices for carbon removal, though it may add some incremental administrative expense.

Enrolling a sufficient number of acres to make possible statistically significant analysis across different practices will be important to begin generating robust data on a national scale in the first few years of the program. The minimum acreage target to achieve this goal would be 10 million acres over five years, an area less than half the size of the annual 2018 enrollment in CRP.[22] Soil carbon monitoring tools are able to confidently detect average changes in soil carbon over a minimum of five years (Conant and Paustian 2002), so monitoring efforts would need to begin within five years to produce preliminary results by the end of a 10-year "pilot phase" for the payment program. Following successful enrollment of the first 10 million acres, the program could either cap new enrollments at that same acreage level, in essence only backfilling contracts as they expire, until preliminary findings from the 10-year "pilot phase" are available to inform expansion of the subsidy program; or the program could continue to expand to build greater statistical power in the monitoring results while sequestering more carbon in soils. Both scenarios are represented in Figure 14. The latter scenario is more consistent with the progress needed to capture the full potential for carbon removal in agricultural soils, which extends across hundreds of millions of acres, by midcentury: even in the low-deployment scenario for this pathway, cost-share enrollment would need to expand by 10 million acres annually starting in 2030.

Two important policy design questions in establishing a subsidy program for soil management are how to set rates to ensure uptake and how to maximize persistence of adoption after cost-share contracts expire. The choice of rate has implications for both the cost-effectiveness of the policy and its ability to attract new landowners to adopt soil management practices. Using basic economic logic, the minimum sufficient cost-share rate would be equal

Box 8 | Existing Policy Landscape

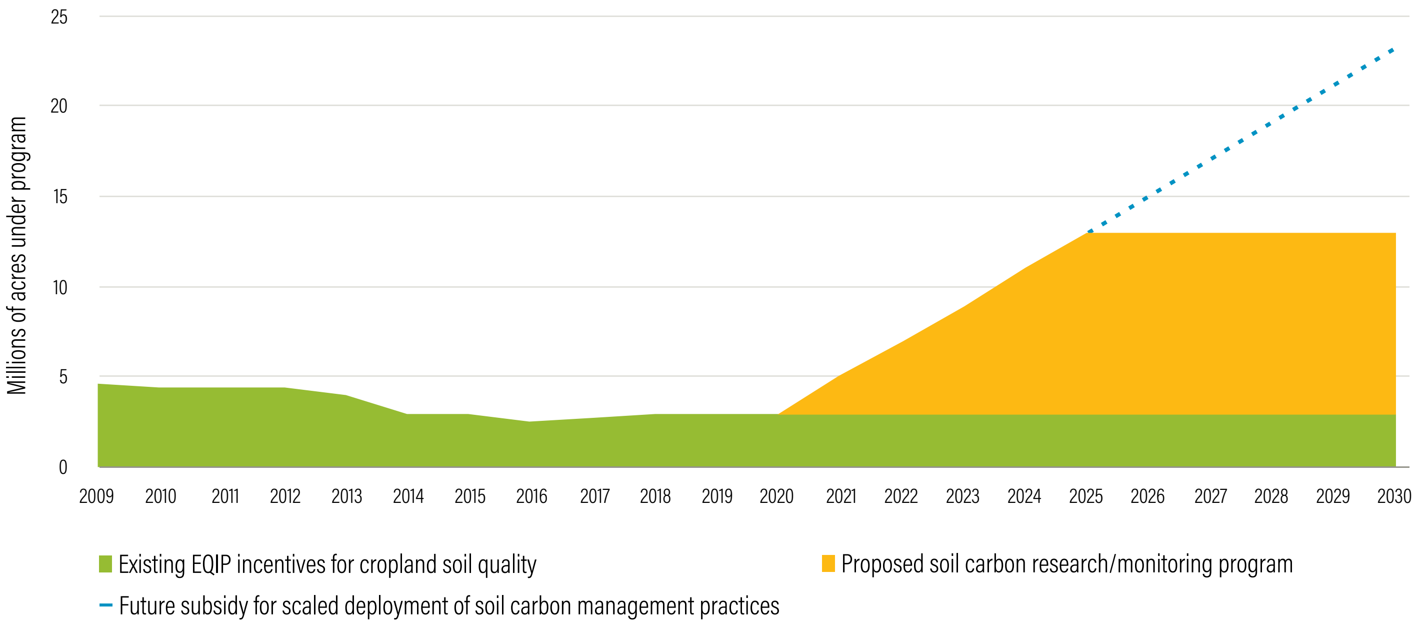
Federal policy support for the adoption of agricultural soil management practices has primarily come through USDA Farm Bill programs:

The **Environmental Quality Incentives Program (EQIP)** provides one-time cost-share payments to farmers to implement specific soil management practices on partial or individual fields. **EQIP** provided financial assistance to producers implementing conservation practices on 13.7 million acres in 2018 (NRCS 2018). **EQIP** contracts are typically short-term—less than five years—with no option for reenrollment. Rates are set regionally, up to 75 percent of the average cost of the practice (or 90 percent for disadvantaged and other special classes of farmers). Currently, 50 percent of national **EQIP** funds are reserved for livestock operations, including grazing management practices, and another 10 percent are reserved for practices that benefit wildlife habitat (National Sustainable Agriculture Coalition 2019). Of the remaining funds that can be directed to cropland soil management practices, the share supporting cover crop implementation has increased sharply over the last decade as funding for nutrient management and no-till has declined. **EQIP** funding for cover crops now represents half of the program's payments to the top five soil management practices (Marshall et al. 2019).

The **Conservation Stewardship Program (CSP)** provides recurring incentive payments to farmers to implement a suite of environmental "enhancements" for improved soil health, which may include cover crops, across their whole farm. The **CSP** payment structure includes a base payment for maintaining existing conservation practices alongside a payment schedule for incorporating additional practices into the land management regime. **CSP** is specifically targeted toward "good actors" who can demonstrate a preexisting baseline level of environmental stewardship on their land. Unlike **EQIP**, **CSP** participants can continually reenroll in five-year **CSP** contracts by adding new "enhancement" practices on their land.

The **Conservation Reserve Program (CRP)** pays farmers an annual rental rate to remove cropland from production and plant native species to improve the environmental health and quality of land and water resources. **CRP** enrolls up to 25 million acres per year (increasing to 27 million acres by 2023) in 10–15-year conservation contracts, with an average payment of $76 per acre per year that tracks agricultural land values (USDA Farm Service Agency 2018). Grazing lands are considered ineligible for **CRP.** Unlike **EQIP** and **CSP**, **CRP** finances soil management practices specifically by taking land out of production, and therefore provides payment primarily based on the opportunity cost of that lost production rather than the added cost of soil management. These attributes make **CRP** neither a cost-effective nor an easily scalable model to provide targeted incentives for carbon removal in agricultural lands.

Figure 14 | **Expanding Cropland Area Receiving Cost-Share for Soil Carbon Management**



Source: Data on existing EQIP enrollment from NRCS (2018).

to the cost of practice adoption (including risk, cost of capital, time preference for money, and other "soft costs") minus the present value of expected economic benefits. However, producers may not be financially able to pay upfront costs now for the promise of uncertain future benefits—and may not even realize the avoided-cost benefits of implementing practices if their operations are not sufficiently adaptable (Pratt et al. 2014). Therefore, practices with higher upfront costs for implementation and/or lower direct on-site economic benefits (e.g., through yield enhancements) may warrant higher cost-share rates or a high lump-sum payment to cover upfront costs followed by lower annual incentives in subsequent years, so long as expected public benefits are commensurate with the public investment. New data generated by the program on location-specific costs and producer constraints can inform rate-setting over time.

Key to the cost-effectiveness of the envisioned public investment is the extent to which producers will continue to implement carbon-beneficial practices beyond the expiration of a cost-share contract. Research on persistence in implementation of practices has found that 59–86 percent of producers continue cover cropping in particular areas following the expiration of an economic incentive like cost-share (Long et al. 2014; Schaefer Center for Public Policy 2005), while 44–61 percent of producers continue conservation tillage year-to-year (Tran and Kurkalova 2019). These high levels of persistence could be explained by the fact that most of the direct and indirect costs of implementing a new soil management practice are weighted toward the first year of implementation; once a farmer has invested in the proper equipment and taken the time to learn proper implementation technique for a new practice, the barriers to continuing that practice in future years diminish considerably.

While there is not currently sufficient empirical data to design cost-share programs to maximize persistence, several financial, technical, and social factors may matter—for example, whether producers gain adequate technical knowledge and realize economic benefits in the cost-share period and whether other producers nearby are also adopting the practice. These factors should inform USDA research within the scope of the program, with findings applied to hone program design elements—like adjusting cost-share contract length or targeting cost-share contracts in community clusters—on an ongoing basis.

As a complement or alternative to a traditional cost-share structure, subsidies could also be disbursed through discounts to crop insurance. Nearly 89 percent of acres producing major field crops in the United States are currently enrolled in the federal crop insurance program (USDA Risk Management Agency 2017), although it is important to note that grazing lands are not eligible for crop insurance and therefore could not take advantage of this form of financial assistance for soil management. For croplands, incorporating incentives for soil management practices into the crop insurance program would have three principal benefits:

- U.S. farmers could access financial assistance for soil management practices without applying to a separate program administered by a different USDA agency, thereby reducing program complexity and transaction costs for farmers.
- Awareness and interest among farmers may increase if the opportunity for financial assistance is offered in the course of normal business operations (retaining crop insurance).
- Better soil management promotes soil health and mitigates the risk of crop failure due to drought or flooding, thereby making farmers less reliant on crop insurance payouts and enhancing the cost-effectiveness of the entire crop insurance program.

Current crop insurance premiums total over $9 billion over 238 million enrolled acres of farmland (USDA Risk Management Agency 2017). The federal government already subsidizes roughly 60 percent of insurance premiums on average (CBO 2018), in part a reflection of the interest in Congress in ensuring adequate enrollment to deal with crop failure with an insurance mechanism as opposed to disaster response funding. Still, producers pay roughly $3.5 billion annually, or $15 per acre, in premiums—in effect, this is the maximum level of subsidy that could be provided for soil management practices through the crop insurance program.

For an example of such an approach, federal policymakers could look to a pilot program in Iowa—the result of a partnership between the Iowa Department of Agriculture and Land Stewardship and USDA's Risk Management Agency—which offers a $5 per acre crop insurance premium discount to farmers who plant cover crops (Plastina and Sawadgo 2018). However, it is still too early to determine the effectiveness of this new pilot program in increasing cover crop adoption.

Technical assistance and education

Scaling adoption of soil management practices that enhance carbon removal will require significantly higher levels of customized technical assistance to farmers and ranchers than these shrinking services can presently provide. In a national survey, free technical assistance and more information on appropriate species to plant ranked among the top interventions that would convince farmers to adopt cover crops (CTIC 2017). Technical assistance may also be necessary to adjust farm operations in ways that allow producers to realize potential avoided-cost benefits of practice adoption, such as reduced need for fertilizer applications due to nitrogen fixation by legumes or avoided repairs for erosion damage due to increased vegetative cover.

Historically, NRCS field offices and cooperative extension offices from land-grant universities have been the primary purveyors of technical assistance and educational resources to producers. Ninety percent of NRCS's workforce of over 10,000 is located in field offices across the United States, but NRCS's shift in focus from multiyear land retirement contracts to shorter-term contracts on working lands has more recently strained the administrative capacity across these field offices, leaving insufficient staff capacity to provide individualized technical assistance. Meanwhile, driven by a decades-long decline in inflation-adjusted federal funding for the cooperative extension system alongside more recent cuts in state and local appropriations, the full-time workforce in extension offices declined 22 percent between 1980 and 2010, with even greater losses in key agricultural regions (Mercer 2014; Wang 2014).

Pairing administration of cost-share funding with a federal effort to retain and grow staff focused on technical assistance at NRCS field offices, along with greater federal support for cooperative extension offices, may be critical for achieving and sustaining the adoption of soil management practices. Greater capacity in NRCS field offices and extension offices can also be leveraged by state departments of agriculture, soil and water conservation districts, and private industry—agribusiness networks, for example, maintain existing relationships with farmers and producer organizations and could provide both inputs and technical assistance for cover cropping (Carlisle 2016). Expanding innovative programs like the Regional Conservation Partnership Program (RCPP) can enhance the value of federal funding by further leveraging nonfederal providers of technical assistance and landowner outreach.

Research and monitoring

Alongside incentives for practice adoption and technical assistance programs, rigorous biophysical and socioeconomic monitoring and evaluation is critical to realizing the potential of agricultural soil management. A nationally coordinated agricultural soil carbon monitoring program that combines plot-based direct measurement with landscape-scale modeling could build the data and evidence base around the efficacy, cost, constraints, and challenges of various soil management practices in different regions, soil types, and farming systems (Smith et al. 2019). The effort would provide a basis for program evaluation and adaptive management and underpin the provision of public resources for scaling adoption. It would also allow the provision of better data on soil health benefits to farmers, enabling them to make more-informed decisions about inputs such as fertilizer and post-cost-share management practices.

A core element of a robust monitoring and evaluation effort is a consistent national plot network that can collect long-term data. The Forest Inventory and Analysis (FIA) program services this function for forest carbon. USDA operates the National Resource Inventory (NRI), a national network of tens of thousands of farm plots that have extensive land management data records dating back several decades. However, NRI does not collect soil carbon data. Adding this function to NRI's mandate—at an estimated cost of $5 million per year—is a National Academies recommendation. The land management history in NRI plots can greatly enhance researchers' ability to make scientific inferences relating to the factors affecting soil carbon stocks and provide locally applicable baseline data to compare to soil measurements associated with new adoption of management practices.

The National Academies also recommend a field network for long-term (>12 years) experiments at 10–15 sites operated by USDA and land grant universities at a total cost of $6–$9 million per year to advance field research and improve modeling capabilities for soil carbon (NAS 2018a). This type of closely controlled and coordinated experimental network is advantageous for scientific study in that it enables consistency in measurement protocols and methods. These experimental sites are costly, however. Some level of scientific experimentation for soil carbon is also already occurring through the USDA Agricultural Research Service's Greenhouse Gas Reduction through Agricultural Carbon Enhancement Network (GRACEnet) and Long-Term Agroecosystem Research (LTAR) network, as well as some sites within the National Science Foundation's Long-Term Ecological Research (LTER) and National Ecological Observatory Network (NEON) programs. These networks focus on creating standardized research practices, experimental coordination at multiple sites, and open-source databases highlighting long-term research. Coordinating multilateral soil carbon research goals across networks could promote more efficient understanding of the regional limitations and opportunities for carbon removal in agricultural soils.

Taking a different approach, Congress recently expanded the Conservation Innovation Grant program to include monitoring projects—and added a $25 million per year on-farm conservation innovation trial program that will allow USDA to gather new data on the benefits of agricultural soil management practices (Stubbs 2019). This approach will enable producers to experiment, and researchers to collect on-farm data from real-world implementation. However, a $25 million grant program will ultimately be limited in its contribution to the data and science behind soil carbon practices. A clear next step would be to fund monitoring and data collection activities, standardized according to a common sampling protocol like GRACEnet, as part and parcel of a larger-scale cost-share program (see "Subsidy to address financial barriers to adoption" above).

New technologies for sampling soil carbon in the field may prove critical to keeping costs down for a large-scale soil carbon monitoring program. Laboratory-based testing of soil core samples is prohibitively expensive for such a program, and while new technologies like reflectometers that can more cheaply and quickly measure soil carbon in the field are in development, they are not yet precise enough to be deployed at scale (Chatterjee et al. 2009; Nayak et al. 2019). Federal investments in testing and refining spectral methods for soil carbon measurement, if successful, would pay outsize dividends by reducing costs for a national-scale monitoring effort.

Remote sensing technologies also show promise as a powerful tool to monitor soil carbon flux at the landscape and national scale (see "Natural Carbon Capture Monitoring" section). When calibrated to a robust network of repeated field measurements, aerial or satellite imagery can show soil carbon fluxes across the heterogeneous agricultural land base (Smith et al. 2019). Integrating remote sensing tools into federal soil carbon monitoring will therefore enable USDA to better assess and value the contributions of different management practices to building soil carbon stocks across the nation.

CARBON MINERALIZATION

In Brief

- Carbon mineralization includes a number of approaches (Figure 15) that aim to speed up natural reactions between carbon dioxide in the air and reactive sources, like silicates and rocks rich in calcium or magnesium, to form solid carbonate minerals (NAS 2018a). Proposed mineralization approaches vary widely in technology readiness, theoretical potential, cost, risks, and barriers.
- One promising approach that yields a product of economic value is the mineralization of mined reactive rock for use in synthetic building and construction materials. The upper-bound potential of this approach is quite large—around 1.2 $GtCO_2$ per year in the United States alone—given the sheer volume of aggregate used in construction. However, plausibly achievable potential over the coming decades is not well understood given challenges related to accessing and transporting reactive rock at scale and competition with conventional products. We assume it would be feasible for mineralized construction material to gain up to a one-third market share by 2050, yielding removal of **410 $MtCO_2$ per year**.[23]
- Additional research and field-testing is needed to better understand the feasible potential for other mineralization approaches—including spreading finely ground reactive rock dust on agricultural land (which may improve soil quality and crop yields in acidic soils) and in situ (below-ground) mineralization to provide an enhanced storage mechanism for direct air capture or point-source CCS.
- Initial estimates indicate considerably lower costs than direct air capture for use with reactive mining and industrial waste but increasing costs at larger scales due to the need to mine reactive minerals and overcome associated logistical constraints.
- Key unknowns for surficial mineralization relate to the potential scale of economically accessible source material, possible negative environmental effects, and full life-cycle carbon gains of scalable processes.
- Roughly **$25 million per year** in federal research and development funding would likely be adequate for a well-targeted program until approaches warranting public incentive are demonstrated (Figure 16).

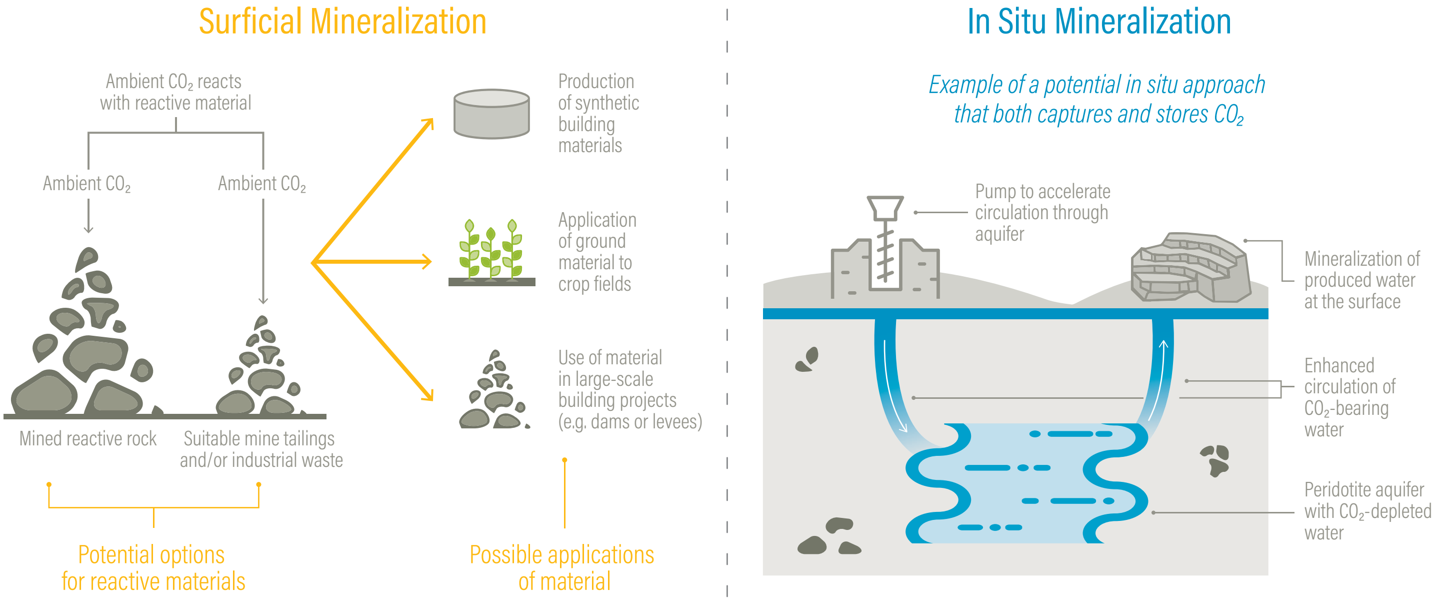
Carbon Mineralization 101

Conceptualized applications of carbon mineralization for carbon removal remain relatively underexplored given their conceivable potential. These concepts are the product of theoretical exploration and still-limited laboratory- or field-scale testing. There are significant known challenges and much that is still unknown about practical potential, cost, and environmental effects.

The reservoir of rock suitable for carbon mineralization is massive—estimated at as much as 10 quadrillion tons at or near the surface in the United States (NAS 2018a). For every three to four tons of this reactive rock, around one ton of CO_2 can be captured, depending on the specific type of rock (Strefler et al. 2018; NAS 2018a). Mineralization offers permanent carbon storage with no risk of leakage, a benefit over storage via injection into saline aquifers, for example, which must be monitored for years after injection (NAS 2018a). Mineralization also allows capture and storage to occur in a single step, avoiding the cost and logistics of pipelines or other transport options to move CO_2 from the point of capture to the storage location. Some conceptualizations of mineralization also produce useful commodities—especially synthetic limestone, which can be used in building materials.

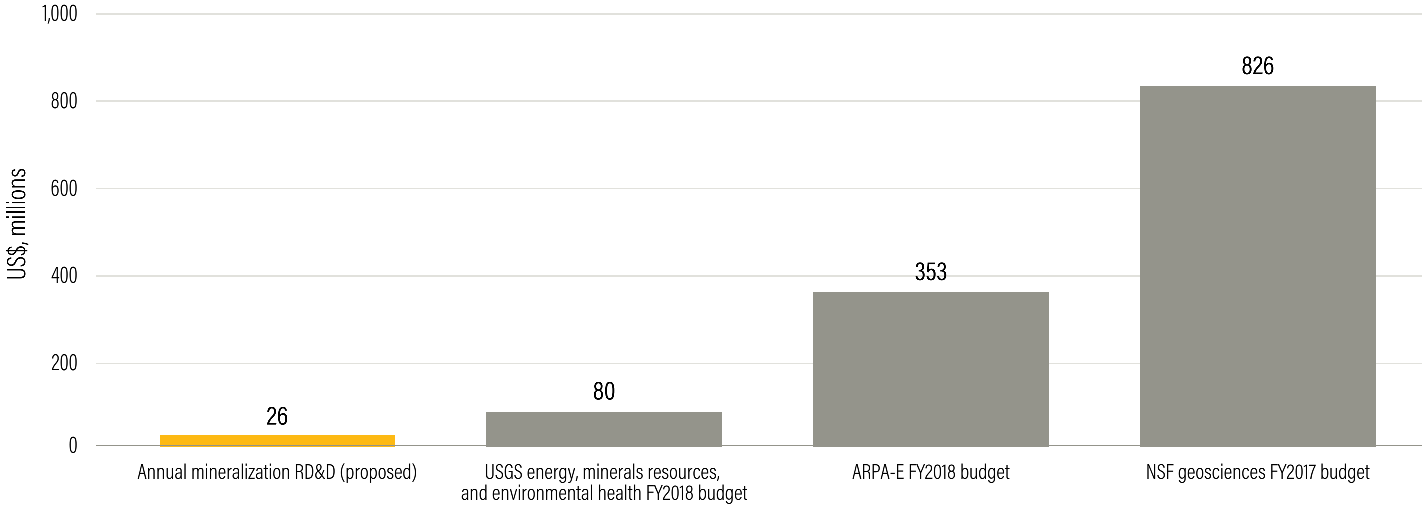
The primary challenge facing scientists and developers is how to bring reactive material in contact with CO_2 from the atmosphere at scale, at reasonable cost, without incurring offsetting emissions in the process, and while

Figure 15 | Potential Approaches for Surficial and In Situ Carbon Mineralization



Source: Adapted from NAS 2018a.

Figure 16 | Proposed Carbon Mineralization RD&D Investment in Comparison with Other RD&D Budgets



Sources: NAS (2018b); ACS (2018); AIP (2019).

minimizing negative environmental effects. A related, secondary challenge is the disposal of the resulting material. General approaches in the terrestrial setting include reaction of ground-up suitable rock at the surface ("surficial mineralization") with CO_2 and injection of CO_2-bearing water into suitable rock ("in situ mineralization").

We focus here on the use of mineralization to form synthetic construction materials like limestone and other aggregate. In this approach, suitable rock[24] would be mined, crushed, and then exposed to CO_2 to form synthetic limestone and other materials that can be used in building materials and for other applications, displacing mined material from other sources. While more reactive and/or readily available source material is available from industrial wastes, these sources are ultimately limited such that scaled deployment will require the use of mined rock as source material (Kirchofer et al. [2013] find that there is opportunity to remove just 7.6 $MtCO_2$ per year in the United States through mineralization of industrial waste, including fly ash, cement kiln dust, and iron and steel slag). One key feature that sets this approach apart is the production of a commodity with market value. Other surficial approaches would amass piles of reactive rock or manipulate existing mine tailings for the sole purpose of carbon removal via mineralization. These approaches may be valuable for field-testing but may be less likely to scale relative to approaches that produce a commodity.

Aggregate—fragments of rock ranging in size from sand to gravel—is a globally ubiquitous building material and can be produced in ways that capture and store CO_2. It is used in combination with cement to make concrete as well as directly in building projects like roads, railways, and dams. Conventional versions of these products together constitute the largest global material flows aside from water (NAS 2018b). In the United States, 2.36 billion tons of aggregate were produced in 2018, along with 85 million tons of cement (McCarthy 2019; USGS 2019).

Mining and grinding rock for carbon capture and storage has about the same cost as direct air capture plus permanent storage in deep sedimentary formations, ranging from roughly $55 to $500 per ton depending on the percentage of reactive minerals and excluding economic benefits that could come directly through selling aggregate or indirectly through improved soil productivity (NAS 2018a; Renforth 2012). If mined rock is ultimately used in building materials, costs could increase due to transportation needs between mines and the location of use. Mining new rocks for carbon mineralization will also result in CO_2 penalties associated with the energy inputs needed for mining, grinding, and transporting rock. Depending mainly on the final grain size, but also on the type of source rock and the mineralization approach, net carbon removal could be reduced by 10–30 percent due to energy inputs (Moosdorf et al. 2014; Beerling et al. 2018).

In this way, CO_2 can be captured from the atmosphere for mineralization with a simplified and less expensive version of direct air capture (essentially a fan) or from point sources of emissions with carbon capture.

Another surficial approach includes application of reactive rock dust (for example, basalt) to cropland, which, via soil runoff, ultimately leads to addition of dissolved bicarbonate in the ocean for permanent storage. In addition to providing carbon removal, the use of basalt can improve soil nutrient content, reduce acidity (a challenge across most cropland), and potentially increase crop yields (Beerling et al. 2018). It can also add phosphorus, potentially reducing the need for fertilizer application. However, application to soils would require the addition of massive quantities of basalt relative to typical application of lime and fertilizer. Like other mineralization approaches, mineralization in soils requires further research and testing across a range of crop and soil types (Beerling et al. 2018).

Finally, in situ (below-ground) mineralization would largely serve as an enhanced storage mechanism for CO_2 captured from direct air capture or point-source CCS, rather than a direct carbon removal mechanism. However, one promising in situ concept—circulating CO_2-enriched water through reactive rock—could also reduce the cost and energy-intensity of direct air capture by allowing lower levels of CO_2 enrichment from the ambient air (Kelemen et al. forthcoming).

Key Barriers to Surficial Mineralization

The main barriers to large-scale deployment of surficial mineralization relate to process development for less reactive but more abundant source material, including optimizing logistics and minimizing energy inputs associated with mining, grinding, and transport for any process operating at scale, as well as potential environmental or social impacts.

As any mineralization approach is scaled up, use of less reactive but more abundant source material like basalt will be necessary. Techniques to accelerate the mineralization process with these materials will need to be developed.

Federal Policy Design for Carbon Mineralization

Mineralization concepts require further basic and applied research and field trials to bring clarity to viable configurations and subsequent technology development needs. The National Academies propose a package of federal research and development investments covering the full scope of mineralization concepts and totaling $50 million per year (NAS 2018a). Given significant uncertainties affecting conceptualized approaches for mineralization, a more targeted set of federal policy investments is needed to address key unknowns and chart a course to scale the most promising mineralization concepts that warrant prioritization. For example, Hezir et al. (2019) propose a portfolio of basic research, field experiments, and environmental studies that increase investment levels over time.

Key focal areas for federal research and development activities include:

- preparing for mineralization with abundant source material via basic research and pilot testing; and
- improving understanding of environmental and social impacts of expanded mining and various value-added mineralization products.

In addition, incentivizing use of mineralized synthetic building materials—for example, through government procurement and/or the establishment of standards for CO_2 utilization products—would leverage private sector investment and learning-by-doing. This type of federal intervention may become a priority once further research elucidates viable paths to scale.

Preparing for mineralization with abundant source material

Carbon mineralization is already being incorporated into the production of aggregate and cement by a number of companies (see Box 16). These companies tend to rely on highly reactive and readily available but relatively scarce industrially produced source material. As the mineralization pathway scales, it will necessarily shift to underground and less reactive but more abundant natural source material—such as basalt. Anticipating this shift, federal research and development activities can focus on techniques to optimize mineralization processes with these more abundant source materials.

Given the lower reactivity of rock like basalt, pretreatment and other optimization techniques may be needed. Pretreatment methods might include grinding to increase surface area or heating to remove chemically bound water. Both of these processes are energy-intensive (NAS 2018b). Other approaches, such as microbial decomposition to increase surface area, have also been proposed and require additional research (NAS 2018a; Kantola et al. 2017). Further research may also identify novel concepts for mineralization—new configurations for bringing atmospheric CO_2 together with abundant source material in a cost-effective way. To this end, basic and applied research can expose new ideas and field-testing can quickly dispense with those that are not scalable.

The National Academies propose $5.5 million per year over 10 years for basic research on mineralization kinetics. This foundational research could inform any mineralization concept and could lead to breakthroughs in accelerating mineralization processes. An additional $3.5 million per year is proposed for pilot studies to explore efficient and safe ways to mineralize various source materials already at the surface (NAS 2018a). Focusing these resources instead, or in addition, on more abundant underground source materials will help clarify viable paths to scale. Developing a resource database for carbon mineralization research and field studies ($2 million per year) will help accelerate learning and progress among researchers.

Improving understanding of environmental and social impacts

Depending on the type of rock being mined and the location, there is potential for contamination of surface or groundwater resources and bioaccumulation of trace metals that should be examined. Safe handling procedures, especially for value-added inputs to building materials, will likely be an important feature of scaled deployment. The National Academies also propose $10 million per year to study environmental impacts of mineral additions to terrestrial, coastal, and marine environments, and $5 million per year to examine the social and environmental impacts of an expanded extraction industry for mineralization (NAS 2018a). These kinds of investments should be focused on specific conceptualizations of mineralization with the greatest potential to scale. In total, proposed RD&D investment for mineralization comes to $26 million per year for the first 5 years and $21 million for years 5–10 (see Table 3).

Table 3 | **Summary of Proposed RD&D Activities to Advance Carbon Mineralization**

ACTIVITY	PROPOSED ANNUAL FUNDING (US$, MILLIONS)	DURATION (YEARS)
Basic research on mineralization kinetics	5.5	10
Surficial mineralization pilot studies	3.5	10
Development of resource database for carbon mineralization	2	5
Studying environmental impacts of mineral additions to terrestrial, coastal, and marine environments	10	10
Studying social and environmental impacts of an expanded extraction industry	5	10

Source: Adapted from NAS (2018).

ENHANCED ROOT CROPS

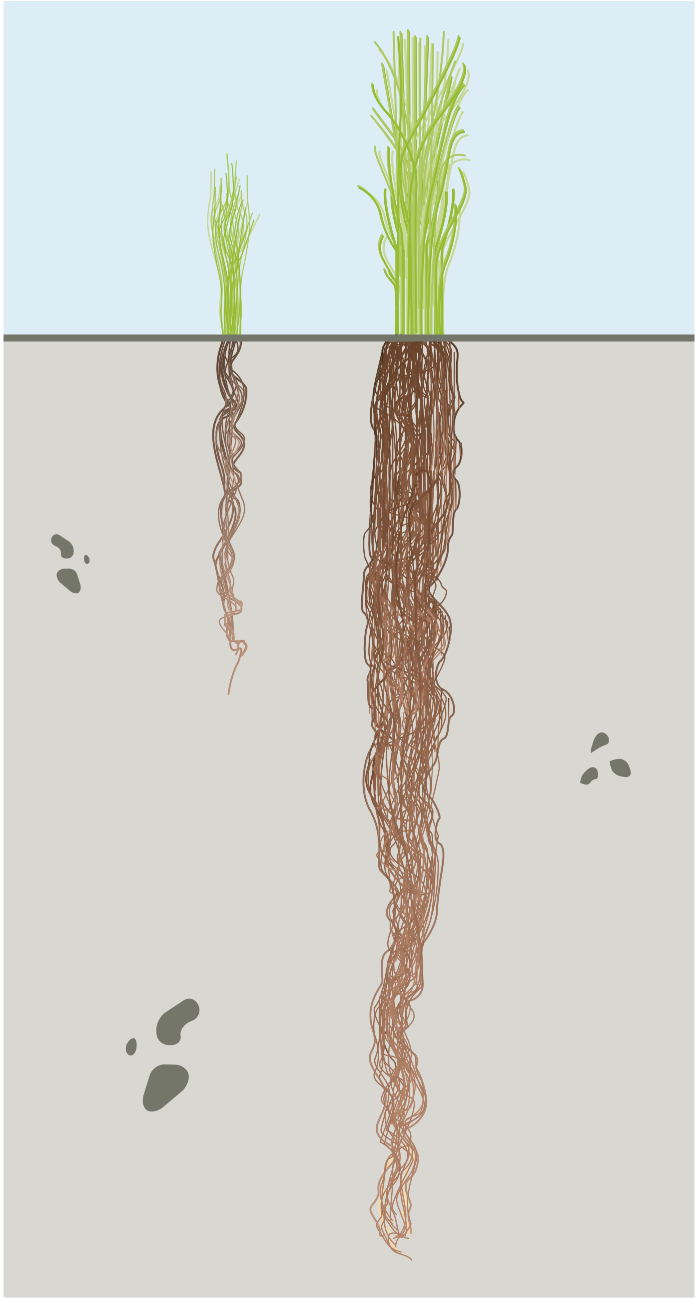
In Brief

- Breeding crops with more, deeper, and larger roots could increase carbon sequestration in soils (see Box 9 and Figure 17). Such enhanced root systems can deliver a number of benefits—like erosion control, improved soil quality, and ability to plant on marginal lands—that could benefit farmers and consumers, as well as the climate, especially as population and food demand continues to grow.
- Enhanced root crops are for the most part in the early stages of development and require additional research to understand feasibility and carbon removal potential.
- Plausible potential, which is highly theoretical, is estimated to be up to **185 $MtCO_2$ per year** across the planted area of major U.S. crops (249 million acres) and depends on the extent of change in carbon input and root depth (Paustian et al. 2016). These estimates are conditional on increases in root size and depth similar to perennial grasses but that have not yet been achieved in commercial crop breeds.
- The main barriers associated with enhanced root crops include maintaining consistent yields comparable to conventional crops and advancing the breeding process at a speed that would allow wide-scale deployment before 2050 across all major crop varieties.
- The most significant unknown is to what extent roots can be meaningfully enhanced without sacrificing yield (or taste or other function). Other unknowns relate to public perception and uptake as well as cost of enhanced crop variety seeds.
- An RD&D budget of **$40–50 million per year**, sustained over a decade or longer, is recommended to accelerate development of new or enhanced varieties for major crop types and understand the feasibility and potential of this approach (NAS 2018a). An initial time-bound investment to achieve proof of concept may be appropriate before continuing such a program.

Enhanced Root Crops 101

Soils (to 2 m depth) hold two to three times the amount of carbon in the atmosphere, but conventional agriculture has diminished carbon stocks in many places by disturbing the soil and planting crops with shallow root systems that do not regenerate the lost carbon (Crews et al. 2018). Developing crop varieties that increase the input of carbon into the soil, through larger root systems, and/or slow the decomposition of organic matter in the soil, through deeper or more recalcitrant roots, can begin to reverse this trend (see Box 9) (Kell 2011). Research is underway to develop both perennial analogs of annual crops—which have deeper roots and preclude the need for tilling and replanting every year that can release lots of carbon—and plants (crops and noncrops) that hold more carbon in their roots and are more resistant to decomposition.

Figure 17 | **Root Growth in Annual Wheat (Left) and a Perennial Analog of Wheat under Development (Right)**



Source: Image adapted from Van Tassel and DeHaan (2013).

There is considerable uncertainty as to the potential scale of carbon removal achievable from these concepts. Most crop-breeding efforts for enhanced carbon sequestration remain in early phases of development and lack consistent data on carbon balances before and after intervention. Some estimates in the literature are based on theoretical increases in soil carbon input based on root size and depth or observed soil carbon levels after cropland is converted to grassland (Paustian et al. 2016; Chambers et al. 2016; Deng et al. 2016)—enhanced root versions of major U.S. crop species are not yet commercially available.

Scenarios for carbon sequestration potential in the literature range from less than 100 $MtCO_2$ per year to 500 $MtCO_2$ per year across the planted area of major U.S. crops (249 million acres), depending on the extent of change in carbon input and root depth (Paustian et al. 2016). On an acre by acre basis, this means increases of less than 0.4 tCO_2 per acre per year up to 2 tCO_2 per acre per year. Achieving the upper-bound estimate would require doubling carbon input by crop roots and shifting their distribution downward to a level on par with perennial grasses (Paustian et al. 2016).

While these estimates are based only on theoretical potential, they can nonetheless be useful for bounding expectations and informing RD&D spending and priorities. In the United States, 249 million acres are used for growing eight major field crops: corn, soy, wheat, cotton, sorghum, barley, sunflower oilseed, and rice (USDA 2019b). While it is likely not feasible for every acre of this cropland to be planted with enhanced root crops, this provides a plausible upper bound for area that could be planted. Acres in pasture and hay are excluded from scale potential considerations here because in many places they are already planted with deep-rooted perennials.

Rates of carbon sequestration will likely be higher in the years immediately after crops with enhanced roots are planted—as some sequestration is associated with incorporation of carbon in plant tissues—and will begin to level off once the soil saturates with carbon. The literature suggests that around one-third of equilibrium sequestration will accrue after 30 years (Paustian et al. 2016). More significant increases in root carbon production and root depth will likely require additional nitrogen to be added in order to maintain a carbon-to-nitrogen input ratio of 10:1 for soil organic matter. For the most optimistic breeding scenarios, this could reduce net carbon gains by as much as 28 percent (Paustian et al. 2016).

Preliminary research on carbon balance in soils planted with perennial grains similar to wheat shows that perennial varieties can meaningfully increase carbon sequestration[25] relative to annual varieties.[26] However, the yields of these early varieties are only one-tenth to one-third that of conventional wheat (Gewin 2018). Varieties that sacrifice yield, or other functions like taste, are unlikely to be tenable. While it has been argued that perennial varieties of plants will inherently allocate more energy to root development as opposed to seed development, experience with modern plant breeding has shown that artificial selection can overcome these negatively correlated traits (Crews et al. 2018). However, determining whether even a portion of the estimated sequestration potential can be achieved without sacrificing yield will require continued experimentation.

Key Barriers to Enhanced Root Crops

The most prominent barrier facing enhanced root crops is a lack of technological readiness. Crop-breeding research for carbon sequestration is, in almost all cases, still in the laboratory phase and faces challenges that can only be overcome through additional research. To achieve commercial success, enhanced root crop varieties need to be able to produce yields on par with conventional crops. Currently, both the total yield and consistency of yield require additional research.

If conventional plant breeding methods are employed,[27] researchers must wait for growth of new generations (two years for perennial varieties) before selecting the next generation. Increasing the number of organizations and researchers working on each crop variety, as well as increasing the number of crop varieties being investigated, would accelerate progress (Crews et al. 2018). Wait times are minimized if molecular breeding approaches like gene editing and genomic selection are used, but regulatory and public perception challenges may arise, along with potential unintended plant characteristics.

In addition to scientific ones, cultural barriers may arise with the introduction of new and different varieties of crops—for both farmers and consumers. Farmers may be reluctant or unwilling to use new seed varieties, particularly if the yield, flavor, or seed price is not comparable to conventional varieties. Consumers may similarly be reluctant to buy products made with such crops if the flavor or price is different from conventional products.

Box 9 | Crop Breeding for Carbon Removal

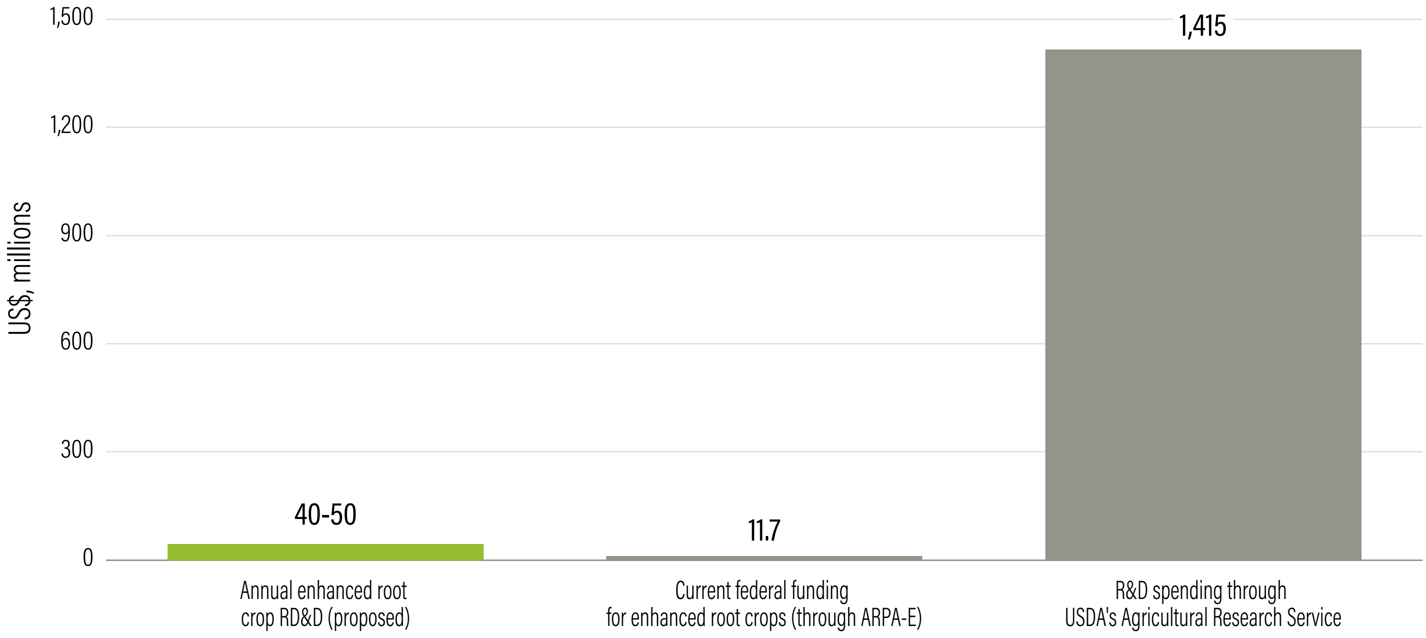
Modern agriculture relies mostly on annuals, including cereals, oilseeds, and legumes, which have caused soil carbon loss from the original conversion of natural land to cropland and, since then, have not regenerated that lost soil carbon. Annuals need to be planted each year, which disturbs the soil and can contribute to soil carbon losses. They also focus most energy on aboveground seed production, meaning that root growth is smaller compared to perennials, which were dominant before modern agriculture interventions (Crews et al. 2018). Developing annuals with larger root systems, or perennial versions of annuals, can help reverse some of these trends: they stabilize soil against erosion and potentially require less water and fertilizer input, which in turn means lower fossil energy and cost inputs. Deeper-rooted crops are also able to grow on marginal or arid lands where, for example, the soil quality is poor, or land is sloped (Ryan et al. 2018).

One approach in the crop-breeding portfolio, perennialization of annual crops, not only provides the above benefits but also saves farmers the time, energy, and cost of replanting crops every year. Perennial grain crops retain soil carbon by avoiding annual tillage that comes with replanting, can sustain high yields for 3–10 years or more without replanting (de Oliveira et al. 2018), require less pesticide input, are more efficient at utilizing water, and may be more productive given their longer growing season (Glover et al. 2010).

Another approach to increasing carbon sequestration by crops aims to increase the amount of suberin, or cork, in roots. Suberin is made up of carbon and resistant to decomposition. This characteristic could theoretically be applied to any plant. Instead of increasing carbon sequestration via larger roots that increase soil carbon inputs, it instead directly focuses on developing larger roots that have higher carbon content and are resistant to decomposition (Salk Institute 2017). In this way roots could act as underground sequestered biomass even after the aboveground plant dies.

Research on perennialization and other approaches to crop breeding is, in most cases, still in the laboratory or early pilot stage. However, in China's Yunnan province a strain of perennial rice was made available to farmers in late 2018 following decades of research and numerous on-site trials (Huang et al. 2018). Farmers have welcomed the reduced labor input it requires and the comparable yield. Development of an upland variety of the perennial version and research on life-cycle emissions is ongoing (Land Institute 2019). In the United States, a perennial analog to wheat is in the process of being developed, though its yield remains significantly below that of annual wheat varieties.

Figure 18 | **Cost of Proposed Annual Federal RD&D Spending on Crop Breeding for Enhanced Carbon Storage Compared to Other Annual Spending on Other Federal Agricultural Research Programs**



Sources: NAS (2018a); ARPA-E (2019); AAAS (2019)

Lastly, crop breeding for perennialization may not be aligned with the interests of the private seed industry, and most plant breeding research effort has shifted into the private sector from the public sector since the 1980s (Crews et al. 2018). Increasing public support for these efforts will be important to accelerate progress and realize their potential.

Federal Policy Design for Enhanced Root Crops

The National Academies recommend investing $40–50 million per year over 20 years to advance basic and applied RD&D and begin field-testing of high-carbon input crop phenotypes (NAS 2018). This represents a four- to fivefold increase over current federal funding for crop breeding for enhanced carbon sequestration—which totals $35 million for 10 multiyear projects through ARPA-E's ROOTS projects (ARPA-E 2019; NAS 2018)—but just a fraction of the $1.4 billion allocated to improvement of conventional crops each year (NAS 2018) (see Figure 18). This research could be carried out by the Department of Energy, the Department of Agriculture, and the National Science Foundation together with relevant universities and private companies.

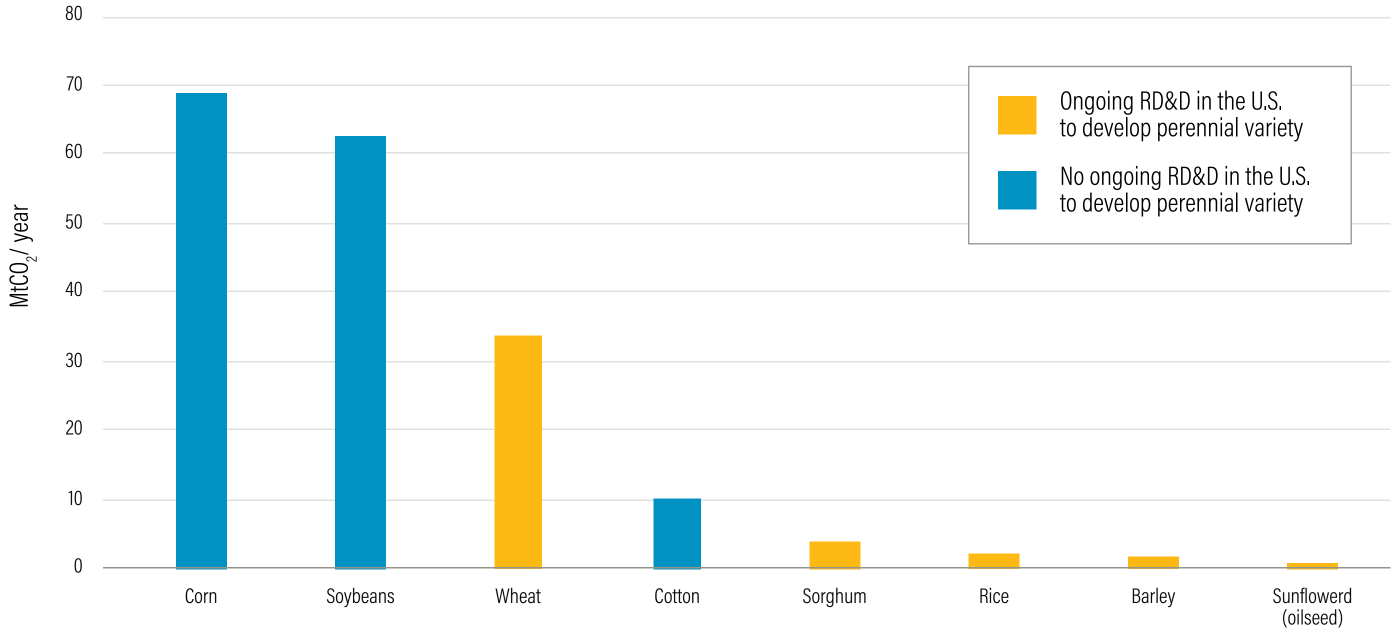
Perennialization represents a major focus of existing enhanced root carbon crop-breeding research efforts and should be accelerated. Recent advances in understanding of plant genomics can help breeding efforts by providing an understanding of the DNA associated with various phenotypic traits. Emerging approaches such as gene editing may also yield returns.

Federal funding should focus on a wide diversity of crops and climatic conditions. Successful scale-up requires developing enhanced varieties for a broad set of major field crops, since potential is limited by both per acre sequestration rates and total available acreage. Figure 19 shows the theoretical potential of enhanced root crop varieties for each crop type based on current U.S. land area in use for cultivation of eight major crop varieties and sequestration rates observed when land is converted from cropland to perennial grasses, which aligns with changes observed in preliminary data collected after planting perennial analogs of wheat (Paustian et al. 2016; Chambers et al. 2016; Deng et al. 2016). Because results are preliminary, we also rely on estimated theoretical potential. The figure also indicates whether perennialization breeding efforts are underway in the United States for each crop.

Additional investment is also needed to support technologies like those to monitor root growth and depth and soil carbon content and measure life-cycle emissions. Finally, as with other public research and development investments, creating a central database to compile data from ongoing research efforts can allow a broader set of actors to learn and accelerate progress.

If enhanced root crops are successfully developed, additional policy support may be needed to bring them to commercial deployment. If yields are commensurate with conventional varieties, significant economic benefits could be realized in reduced cost of annual planting and increased resilience to drought. Such crops would make economic sense for farmers and rapid uptake would be expected.

Figure 19 | **Theoretical Potential of Carbon Sequestration through Perennialization of Major Crop Species**



Sources: USDA (2019b); Chambers et al. (2016); Deng et al. (2016).

SUPPLEMENTAL PATHWAYS

In Brief

- Several additional carbon removal pathways—bioenergy with carbon capture and storage (BECCS), wood waste preservation, and extended timber rotations—could together add up to a meaningful contribution in a carbon removal portfolio. These pathways have relatively clear upper bounds that limit potential carbon removal to modest levels. They also face several technical or economic challenges that would further constrain practical potential.
- Constraining feedstocks to agricultural and forestry by-products in the United States limits the upper-bound net carbon removal potential of BECCS to **180 $MtCO_2$ per year**, accounting for losses in conversion to energy (NAS 2018a). Competing uses for these same feedstocks will likely further constrain potential for net carbon removal, but additional carbon gains could be achieved by displacing fossil energy.
- Wood waste preservation is limited to **less than 100 $MtCO_2$ per year** through 2050 (NAS 2018a), even assuming full preservation of wood in municipal solid waste and construction and demolition waste in the United States. Achieving additional potential would require systems to preserve forestry by-products as well. Some of these feedstocks are likely to be used in other carbon removal or emissions reduction pathways instead.
- Extended timber rotations could provide **up to 25 $MtCO_2$ per year** by 2050 by deploying the practice on 1 million acres each year. This estimate reflects our expectation, based on empirical evidence, that reducing harvests locally is likely to prompt significant leakage of timber production in other areas.

BECCS

Bioenergy with carbon capture and storage is the process of using biomass for energy and capturing and storing the embodied carbon before it is released back into the atmosphere. BECCS can be used in several applications, including the generation of power and production of fuels. The process enhances the carbon removal benefit of biomass growth by preventing the natural return of biomass carbon to the atmosphere. Using biomass to produce power and capturing and storing the CO_2 released in the process is an attractive proposition conceptually, given the potential both to displace emitting sources of power generation and to sequester carbon embodied in biomass that would otherwise return to the atmosphere. However, BECCS faces substantial challenges and constraints.

The National Academies constrain their estimate of potential carbon removal from BECCS to waste feedstocks like forestry and agricultural residues that do not require dedicated use of land. Growing dedicated energy crops or using whole-tree biomass as feedstocks is likely to displace food production and/or natural ecosystems, in both instances triggering indirect effects that could offset carbon benefits of BECCS (Searchinger et al. 2019). Some additional sources of sustainable feedstock may be obtainable in temporary energy crop rotations in areas slated for reforestation, plants like agave in areas not suitable for crop or livestock production, and potentially other narrow arrangements. However, the potential in these areas has not been quantified. Finally, increased demand for biomass for BECCS could conceivably drive some of the tree restoration efforts highlighted previously, especially improved management to restore stocking rates in existing timberlands. Leveraging this effect intentionally while avoiding potential offsetting carbon losses and other unintended consequences would require considerable policy safeguards and strong monitoring and accounting frameworks that have thus far proved elusive.

The National Academies report carbon removal potential for BECCS of 522 $MtCO_2$ per year by 2040, excluding dedicated energy crops. However, this estimate represents the full embodied CO_2 in waste-derived feedstocks rather than net removal potential, which is inevitably smaller. Although the National Academies note that full accounting of carbon losses in biomass transport, conversion, and imperfect capture can cut net removal in half, the total estimate of potential does not account for these losses (NAS 2018a). In addition, the single largest component of the feedstock underlying the National Academies' estimate is municipal solid waste. This includes food waste that could be avoided or composted, paper that could be recycled, and waste wood that could be reused or preserved.

Excluding municipal solid waste and accounting for losses in conversion limits potential to 180 $MtCO_2$ per year. Even then, competing future uses for the same forestry and agricultural feedstocks—for example biochar or fuel—would likely further constrain net potential. BECCS can be applied in the production of fuels, where some CO_2 can be easily captured in fermentation, but ultimately a sizeable portion is released back to the atmosphere via combustion. BECCS-to-power offers more complete capture but is at a competitive disadvantage relative to solar, wind, and both natural gas and coal with carbon capture. Fuel and transportation costs for biomass alone are double that of coal (NAS 2018a). The carbon removal benefit of BECCS in the power sector comes at a cost of $105 per ton.

However, BECCS can also reduce emissions by displacing fossil energy (or bioenergy without capture). For example, using available forestry and agricultural by-products for BECCS in the power sector could yield an additional 125 $MtCO_2$ per year in emissions reductions if BECCS displaces coal, dropping the total cost per ton avoided to roughly $70 (NAS 2018a; Sanchez and Callaway 2016). Since emissions-intensive sources of generation would phase out in a deep decarbonization pathway, the total carbon benefits of BECCS will decline over time and its effective costs per ton will rise, all else equal. Moreover, lower abatement costs can be achieved by using limited waste biomass feedstocks for fuels, suggesting limited economic potential for BECCS-to-power.

BECCS-to-fuels pathways capture CO_2 in the fuels production process but generally capture a smaller portion of the total embodied carbon in the biomass, as carbon-based fuels are then combusted without capture. The exception is the gasification of biomass to hydrogen—a fuel that does not produce CO_2 when combusted.

The National Academies outline a suite of research and development priorities for BECCS-to-power ranging from life-cycle assessment and integrated assessment modeling to biomass supply and logistics research to technological development for high-efficiency biomass power. Although each of these components would be useful, the binding constraint on BECCS-to-power is high-cost relative to other options for generating power. Consequently, federal policy investments in BECCS-to-power should focus on increasing biomass-to-power conversion efficiency. The National Academies also suggest that current federal technology development efforts for BECCS-to-fuels pathways are adequate.

Wood Waste Preservation

Wood waste preservation refers to the collection and disposal of wood waste in ways that preserve its embodied carbon in solid form—for example in alternative landfills designed to slow decomposition (NAS 2018a). This effectively extends the carbon removal achieved by past forestry activities and harvested wood products. In general, we expect woody biomass that can be collected at meaningful scale to be used or reused in ways that generate economic value—for example in the production of products, energy, or biochar. However, wood waste that is “contaminated” with paint and other material may be more easily stored than safely combusted or otherwise used. As an upper bound, full preservation of all wood in municipal solid waste and construction and demolition waste in the United States would yield 93 $MtCO_2$ per year by 2040 (NAS 2018a). It is not clear how much of this wood waste would be directed to other uses or whether the full volume could be collected and diverted for preservation. The National Academies propose $5 million per year for a set of federal research and development activities related to the collection and disposal of wood waste and alternative landfill design to maximize preservation of wood waste.

Extended Timber Rotations

Improved forest management is commonly referenced in the literature as a natural climate solution. However, most estimates of national potential in this category center on extending rotation lengths in managed timber stands (Fargione et al. 2018; Murray et al. 2005; McKinley et al. 2011; Sohngen and Brown 2008). This practice necessarily entails a temporary reduction in the supply of fiber from forests. Global fiber markets are likely to compensate for this reduction by increasing harvest in other forests, offsetting a large portion of estimated carbon gains (Murray et al. 2004). Fargione et al. (2018) attempted to counteract this “leakage” effect by substituting lost fiber with new fiber from fire management treatments and reforestation. However, practical constraints related to sawmill configuration and the location of new fiber relative to lost fiber and mills would likely preclude such a substitution. We therefore constrain the extended timber rotations pathway on all timberlands to 1 million acres per year—roughly 10 percent of the forest area harvested each year—to keep the reduction in timber supply within the bounds of historical fluctuations (Forest Inventory and Analysis n.d.). This constraint is similar to that imposed by Fargione et al. (2018) on extending rotations for timber plantations.

For the 30 million cumulative acres converted to extended rotation lengths by 2050, a 25-year hiatus in harvesting timber would result in an avoided loss of forest carbon of 26 $MtCO_2$ per year, with a range of 23–30 $MtCO_2$ (Fargione et al. 2018). An additional carbon removal benefit would accrue from incremental sequestration in forests as the average stand age increases and the postharvest decomposition of dead wood and litter occurs less often. The magnitude of this benefit may vary significantly with stand age at harvest, forest type, and region, but on average it ranges from 10 $MtCO_2$ per year for stands extended from 40- to 65-year rotations, to 39 $MtCO_2$ per year for stands extended from 20- to 45-year rotations (Smith et al. 2006). Adding together the central estimates of carbon benefits from incremental sequestration and the harvest hiatus, the upper-bound potential with safeguards for this pathway is 47 $MtCO_2$ per year by 2050, with a range of 33–69 $MtCO_2$ per year. As rotations are extended on more acres, the potential could continue to grow well beyond 2050, at an average rate of 1.6 $MtCO_2$ per year.[28]

The estimate of potential for this pathway is subject to significant uncertainty, especially related to leakage impacts of a 10 percent reduction in annual harvested acres. If leakage rates approach those observed on previous occasions where harvests were reduced substantially, the carbon effects from the harvest hiatus would be almost completely offset by increases in harvests in other domestic or global forests (Murray et al. 2004). The benefit from incremental sequestration, however, would continue to accrue as timberlands produce more biomass. Another major source of uncertainty pertains to the willingness of timber companies and other private timberland owners to reduce harvests, even given federal incentives to do so, considering that their business model—or for many family forest owners, their retirement security—depends on unlocking the financial value stored in timber on specific timetables. If most timberland owners prove unwilling to extend harvest rotations, the achievable carbon removal from this pathway would be negligible.

The carbon effect of the harvest hiatus, if it does indeed materialize, would saturate once timberlands transition to the longer rotation length. Assuming that all timberlands under age 40 would benefit from such an extension and 1 million acres are "enrolled" each year, it would take nearly 300 years for the harvest hiatus benefit to fully saturate (Oswalt et al. 2014). The benefit from incremental sequestration would continue to accrue indefinitely.

Several other forest management practices have been credited with increasing carbon in biomass and soils in existing forests. This includes restocking understocked forests, which we include in the Tree Restoration pathway. Others include active replanting after harvest, forest fertilization, reduced impact logging, and thinning less carbon-dense and invasive species to enable better growth by more carbon-dense tree species. Some of these practices are important for overall forest health and the resilience of the existing forest carbon sink into the future. However, the carbon removal potential of these practices has not been estimated in the literature, in part due to complications related to baseline estimation—many of these practices are implemented today under state forest practice regulations or voluntarily under forest certification standards, but practice data are not publicly available (Van Winkle et al. 2017). An uncertain baseline also poses challenges for ensuring additionality in policy. Given the possibility that these practices could play a role in enhancing the carbon removal function of existing forests, the lack of clear quantification of potential at the national level is a critical knowledge gap.

CREATING NEW OPTIONS THROUGH SUSTAINED FEDERAL RD&D

Given the challenges and limitations facing each of the pathways examined in this paper, continual efforts will be needed to explore innovative variations of these pathways and nascent and as-of-yet untested concepts. For example, a forthcoming article posits the possibility of combining partial direct air capture with in situ mineralization through dissolution of CO_2 in water in a way that could substantially reduce cost and energy intensity compared to "conventional" direct air capture (Kelemen et al. forthcoming). Additionally, recently published research presents a laboratory-scale demonstration of direct air capture using a specialized battery that absorbs CO_2 as it charges and releases the gas when discharging, eliminating the need for thermal energy input and pressure variations and potentially dramatically reducing overall energy requirements (Voskian and Hatton 2019). Another emerging concept would also reduce the cost of direct air capture by employing metal organic frameworks—a relatively new class of versatile and porous materials with high surface areas and nano-sized pores in their crystal structure that allow for gas separation and could potentially be used for capture of CO_2 (Babu et al. 2019). Related emerging concepts for direct air capture include the use of industrial refrigeration equipment to directly sublimate CO_2 out of chilled air ("cryogenic DAC") and the use of amino-acidbased liquid solvents with dramatically reduced temperature requirements for regeneration. Several ocean-based carbon removal pathways have also been posited in the literature (but are beyond the scope of this assessment). Only a small number of these have been tested to understand their practical feasibility and ecological effects.

Sustained federal resources for laboratory and field experiments and associated modeling for emerging carbon removal concepts would support dedicated attention in the nation's laboratories and universities to uncovering new pathways to scale carbon removal in the United States and globally.

DEPLOYMENT SCENARIOS

Pathway-by-Pathway Deployment Scenarios

For each pathway, we impose assumptions related to the rate and extent of deployment given relevant considerations. These include uncertainty in the estimated upper-bound potential (with safeguards), as well as technology development time frames, economic and logistical constraints on the rate of scale-up, and cultural barriers. These scenarios are intended to be illustrative. They highlight the potential implications of uncertainty and various practical constraints, as well as the level of effort that would be needed in order to achieve a given level of deployment. Table 4 summarizes the prioritized federal policy options that feed into these scenarios.

TREE RESTORATION

The plausible carbon removal potential for tree restoration is likely lower than that estimated in the literature and spatial datasets due to the presence of conflicting high-value land uses, like golf courses and playing fields, that are difficult to discern in national datasets. Landowner preferences may further limit the plausible extent of tree restoration relative to the estimated upper bound with safeguards. Even with a subsidy adequate to make tree restoration profitable for landowners, the subsidy may fail to overcome competing nonfinancial interests of some landowners, like cultural ties to an open landscape aesthetic. For silvopasture and cropland agroforestry, landowner capacity and willingness to shift to a more intensive management regime may also inhibit tree restoration. The rate of scale-up may also be constrained by the available workforce for tree planting and maintenance and the need to dramatically expand tree nursery capacity. Some unavoidable rate of tree mortality will further constrain the achievable long-term carbon removal potential.

Table 4 | **Summary of Prioritized Federal Policy Options**

POLICY OPTION	CATEGORY	PROPOSED AVERAGE ANNUAL FEDERAL INVESTMENT (2020-30)	PLAUSIBLE CARBON REMOVAL BY 2050 ($MTCO_2$ PER YEAR)
Tree restoration campaign	Staples	\$4–4.5 billion	180–360
Federal direct air capture technology development program, including an expanded 45Q tax credit	Staples	\$633 million	190–1,400
10-million-acre farm innovation program	No Regrets	\$500 million	100–200
Foundational research program for carbon mineralization	Speculative Bets	\$25 million	Negligible–410
Accelerated development of enhanced root crops	Speculative Bets	\$40–50 million	0–185
BECCS	Supplemental Pathways	Not prioritized	Negligible–180 (plus possibility of displaced fossil emissions)
Wood waste preservation	Supplemental Pathways	Not prioritized	Negligible–<90
Extended timber rotations	Supplemental Pathways	Not prioritized	Negligible–25

Source: Author calculations based on estimates in the literature and assumed rates of deployment; see "Tree Restoration" chapter through "Supplemental Pathways" chapter for more information.

None of these constraints is quantified or explored in the literature for a tree restoration campaign of this magnitude. We assume that this combination of obstacles reduces net plausible adoption of tree restoration across the identified total suitable acreage for this pathway by a certain percentage, with the high and low scenarios reflecting varying levels of conservatism in this assumption. Both scenarios include a range around the central estimate to account for uncertainty in the average sequestration rate achieved through tree restoration.

HIGH SCENARIO

Tree restoration practices are adopted on two-thirds of suitable acres over 20 years, beginning in 2021. In this scenario, the average carbon removal over the first 20 years of tree growth is **360 MtCO$_2$ per year by 2040** (range: 210–730 MtCO$_2$), assumed to continue through 2050.

This scenario requires an estimated **$2.8 billion** in annual federal funding, not including any hidden costs incurred by landowners. This amount is equal to federal expenditures in 2018 on the investment tax credit for solar power (Sherlock 2019).

LOW SCENARIO

Tree restoration practices are adopted on one-third of suitable acres over 20 years, beginning in 2021. In this scenario, the average carbon removal over the first 20 years of tree growth is **180 MtCO$_2$ per year by 2040** (range: 110–360 MtCO$_2$), assumed to continue through 2050.

This scenario requires an estimated **$1.4 billion** in annual federal funding, not including any hidden costs incurred by landowners. This amount is comparable with federal expenditures in 2018 on the tax rebate for plug-in electric vehicles (Sherlock 2019).

DIRECT AIR CAPTURE

A scale-up rate of 15–30 percent for direct air capture would be consistent with historical diffusion rates for other technologies, like solar, wind, and nuclear power (Realmonte et al. 2019; Larsen et al. 2019). Accordingly, for the purposes of this paper we assume a high scenario with a scale-up rate of 30 percent, which leads to 1,411 MtCO$_2$ per year by 2050, starting from 2 MtCO$_2$ in 2025. This is broadly consistent with the deployment by Larsen et al. (2019) of 1–2 MtCO$_2$ of direct air capture capacity by 2025 and growth to nearly 600 MtCO$_2$ per year by 2050 in a low scenario and roughly 1,850 MtCO$_2$ per year in a high scenario. Larsen's high scenario reflects a compound annual growth rate of slightly over 31 percent (the scale-up rate of 30 percent would reach this level just a year later in 2051). We assume the high scenario in Larsen et al. (2019) is plausible given the modularity of direct air capture, a characteristic that Realmonte et al. (2019) note enables high growth rates relative to more complex facilities. However, we observe that achieving this ambitious scenario is dependent on providing long-term policy certainty to the industry.

Due to its relatively high cost, we assume direct air capture is the "last in" pathway and its deployment will be moderated relative to the high scenario if other, lower-cost pathways are successfully scaled (Figure 20). In the low scenario, direct air capture follows a more modest 20 percent annual growth rate until the 2 GtCO$_2$ per year target is met by the broader portfolio.

HIGH SCENARIO

Steady scale-up at a 30 percent compound annual growth rate from 2 MtCO$_2$ in 2025 to deliver **1.4 GtCO$_2$ per year by 2050**. Federal subsidies for deployment are roughly commensurate with current clean energy tax expenditures through 2040. However, scaling in this high scenario would likely require $140 billion in annual public subsidy by 2050, assuming $100 per ton of net removal.

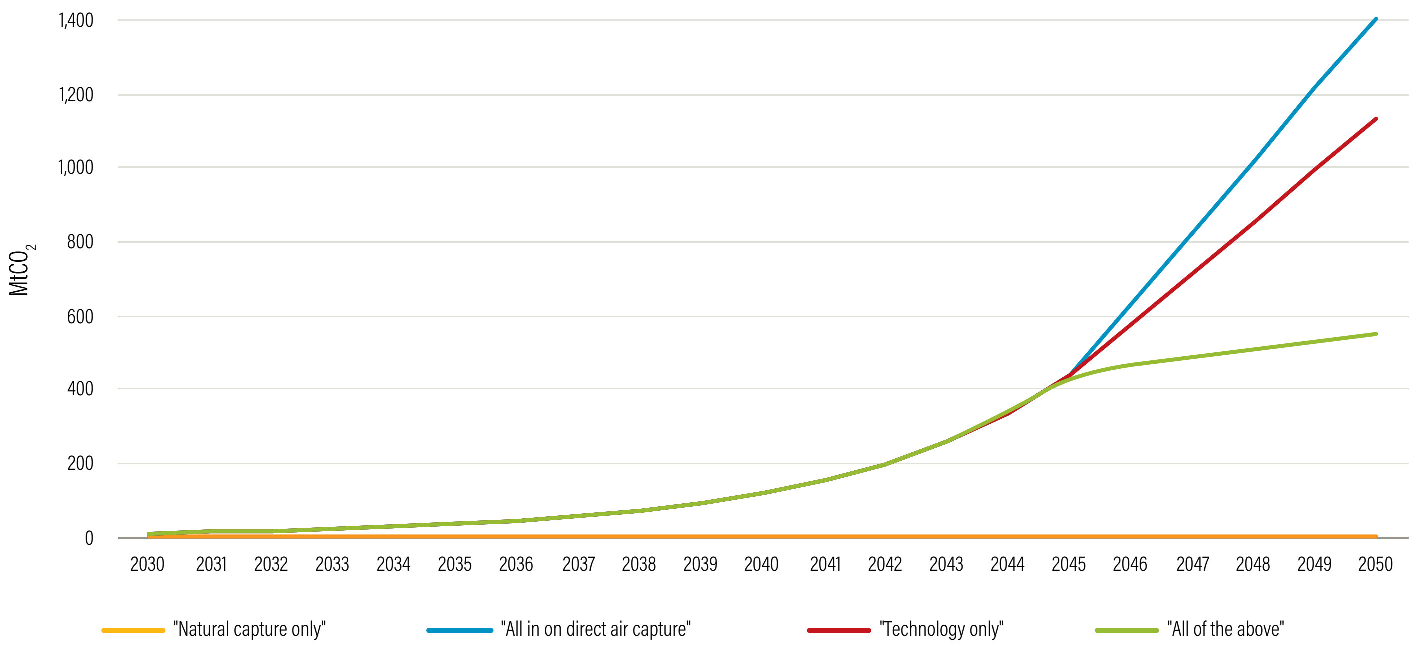
Total capital investment at this scale would be **$1.3 trillion.**[29] The direct air capture fleet, occupying 1,878 square miles, would require the equivalent of 2,825 terawatt-hours each year,[30] about 76 percent of 2018 U.S. electricity generation.

LOW SCENARIO

Steady scale-up at 20 percent compound annual growth rate from 2 MtCO$_2$ in 2025 to **190 MtCO$_2$ per year by 2050**. Federal subsidies for deployment are roughly commensurate with current clean energy tax expenditures through 2040 and reach $19 billion per year by 2050, assuming $100 per ton of net removal.

Total capital investment at this scale would be **$178 billion**. The direct air capture fleet, occupying 255 square miles, would require the equivalent of 383 terawatt hours each year, 10 percent of 2018 U.S. electricity generation.

Figure 20 | **Direct Air Capture Growth by Scenario**



Note: Rapid scale-up of DAC deployment in earlier years will ensure that we are on track for continued rapid deployment in later years, in the case that other carbon removal approaches do not come through.

Sources: Larsen et al. (2019); author calculations.

AGRICULTURAL SOIL CARBON

In all deployment scenarios, the 10-year period starting in 2021 focuses on expansion of current on-farm trial programs for agricultural soil management with a focus on supporting scientific research and monitoring. Adoption by the end of this period in directly enrolled farms reaches 10 million acres and removes 5 $MtCO_2$ per year at a cost to the federal government of $400 million per year. Scale-up beyond 2030 relies on a new set of policy interventions based on lessons learned from the first decade.

HIGH SCENARIO	**LOW SCENARIO**
Federal policy contributes to the scale-up of viable and effective practices to two-thirds of available agricultural acres between 2030 by 2050, resulting in carbon removal at the level of **200 $MtCO_2$ per year by 2050** and 2.2 $GtCO_2$ cumulative removals through 2050. Failure to reach full adoption of management practices over all agricultural acres is likely due to the difficulty of reaching all farmers through cost-share and technical assistance programs; the gradual nature of the cultural changes required to prompt widespread management changes; and the possibility that some "legacy acres" revert back to conventional practices after the expiration of cost-share assistance. Even so, this level of adoption will require implementing soil carbon practices on nearly 20 million additional acres each year over those two decades. Total federal costs will depend on the efficiency of policy mechanisms still to be developed.	Federal policy contributes to the scale-up of viable and effective practices to one-third of available agricultural acres between 2030 by 2050, producing **100 $MtCO_2$ per year of carbon removal by 2050** and 1.1 $GtCO_2$ cumulative removals through 2050. This scenario requires implementing soil carbon practices on nearly 10 million additional acres each year starting in 2030. It is consistent with more conservative assumptions about the challenges presented by reaching farmers, catalyzing culture change, and retaining legacy acres.

CARBON MINERALIZATION

HIGH SCENARIO

Synthetic mineralized aggregate replaces one-third of the total U.S. market for aggregate by 2050, assuming the market continues to grow at recent rates—around 2.5 percent per year (BusinessWire 2018) and basalt is used as source material. Scale-up follows a linear path from 2030, resulting in **410 MtCO$_2$ per year in removals by 2050** and 2.3 GtCO$_2$ cumulatively through 2050. By 2050, sustaining this level of removal will require mining and processing 1.6 billion tons of basalt each year—equivalent to about a third of the total material mined in the United States today (industrial minerals, metals, and coal combined).

LOW SCENARIO

Mineralization provides negligible carbon removal through 2050. This reflects significant uncertainty related to the feasible scale of access to source material, and the possibility that a large portion of the mineralization substitution in the aggregate market draws on CO$_2$ captured from point-source CCS, rather than the atmosphere.

ENHANCED ROOT CROPS

HIGH SCENARIO

Distribution of enhanced crop varieties begins in 2040 and scales to cropland of eight major crop varieties (249 million acres)[31] within 10 years. This provides for 20 years of continued research and development before enhanced crop varieties are ready for distribution but requires that improved varieties be developed for all major crop types.

A per acre sequestration rate of 0.74 tCO$_2$ per year, roughly equivalent to the level of carbon sequestration on a per acre basis that is observed when agricultural land is converted to grassland, and representing roughly a 50 percent increase in root carbon input to the soil between a 5 and 20 percent downward shift in root distribution (Paustian et al. 2016; Chambers et al. 2016; Deng et al. 2016), provides **185 MtCO$_2$ per year sequestration by 2050** and 1 GtCO$_2$ cumulatively through 2050.

LOW SCENARIO

Enhanced root crop development efforts fail to meaningfully increase carbon removal, likely due to lower yields in enhanced varieties.

SUPPLEMENTAL PATHWAYS

HIGH SCENARIO

BECCS configurations that provide net carbon removal come online in 2030 and follow a linear path to full utilization of available feedstocks by 2040, capturing 180 MtCO$_2$ per year. Feedstocks are limited to the portion of agricultural and forestry by-product feedstocks that are not currently utilized and that can be obtained for $66 per dry ton of biomass—a common bounding for economic feasibility (NAS 2018a). Half of the carbon embodied in these biomass feedstocks is assumed to be lost or offset in collection, transport, pretreatment, imperfect capture, and CO$_2$ transport and injection (NAS 2018a). This likely requires that BECCS deploys in the power sector.

Timber rotations are extended on 1 million acres in 2021 and scale up linearly through 2050, reaching 25 MtCO$_2$ per year of sequestration. Leakage of timber harvests offsets close to 85 percent of the carbon benefit from reducing harvests (Murray et al. 2004), but carbon benefits continue to accrue from the incremental sequestration provided by older trees.

In addition, facilities for wood waste preservation begin to come online in 2030. The pathway follows a linear path to 2040, when half of all wood waste from municipal sources and construction and demolition waste is preserved, reaching up to 90 MtCO$_2$ per year of sequestration.

This collection of pathways provides **295 MtCO$_2$ per year in sequestration by 2050**. At full deployment, BECCS in the power sector will likely require roughly **$14 billion per year** in public subsidy unless power conversion efficiencies are improved.[32] Extending timber rotations has been cited at less than $50 per tCO$_2$ for the majority of potential (Fargione et al. 2018), though it is unclear whether this marginal cost reflects the true value of incentives that would be required by timber companies and private landowners to forgo harvesting. Costs for wood waste preservation are uncertain.

LOW SCENARIO

Net-negative BECCS achieves negligible deployment, reflecting competitive disadvantages relative to other sources of energy and alternative uses of available feedstocks. Unwillingness from timber companies and private landowners to reduce harvests results in negligible carbon removal from extended rotations. Similarly, increases in the use of waste wood feedstocks in ways that prevent the release of embodied carbon to the atmosphere also prove to be negligible

Portfolio Scenarios

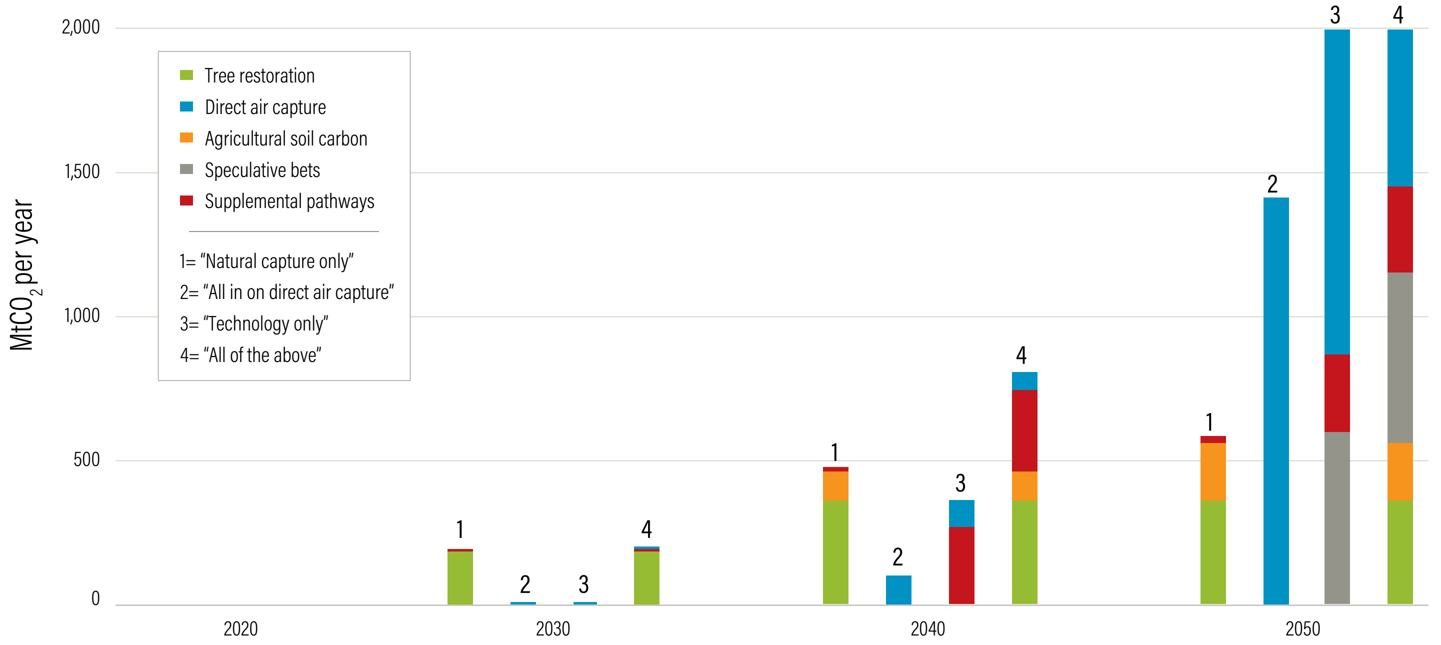
To illustrate possible construction of prioritized portfolios, we compile several deployment scenarios designed to provide removals at a 2 $GtCO_2$ per year scale by 2050 (see Figure 21a and Figure 21b). A little more than 30 percent of total 2017 GHG emissions in the United States, removals at this scale would be a substantial contribution to the broader mitigation portfolio. Based on estimates of total potential and plausible deployment time frames, this also represents an ambitious objective for the carbon removal portfolio. It is also likely that the United States will need carbon removal at roughly this scale by 2050 to reach and maintain carbon neutrality in line with limiting global temperature rise to 1.5°C. The U.S. Mid-century Strategy for Deep Decarbonization, for example, left roughly 2 $GtCO_2$ of net annual emissions unaddressed, if carbon removal technology and growth in the land sink are excluded (White House 2016). Similarly, Larsen et al. (2019) found a residual need for roughly 2 $GtCO_2$ per year in carbon removals to reach carbon neutrality by 2045.

SCENARIO 1. NATURAL CAPTURE ONLY

Ambitious investments (over $5 billion per year) are made in natural capture pathways—including tree restoration, agricultural soil management, and extending timber rotations. Despite having lower annual removal potential than direct air capture, the natural pathways can log significant removals through 2050 because they can be deployed at scale much sooner. In this scenario, no investments are made in carbon removal technologies.

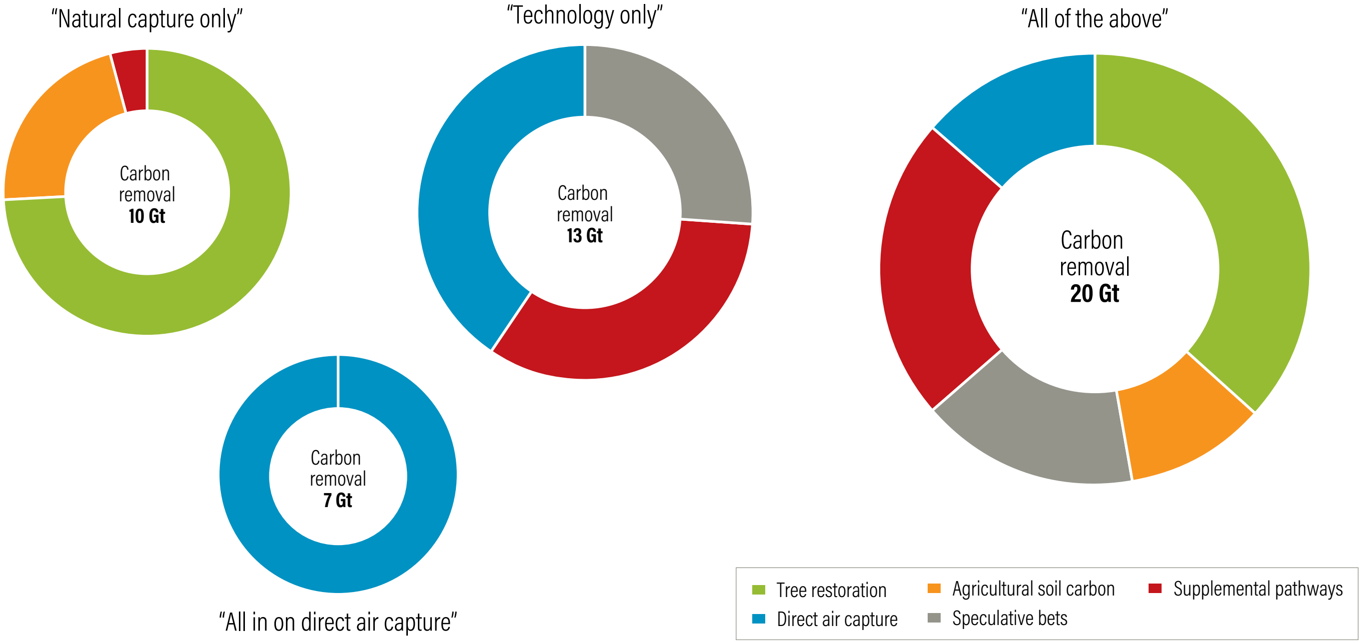
Annual removals from the natural capture pathways can provide less than half of the 2 $GtCO_2$ target. Saturation rates will also eventually diminish the contribution from natural pathways, underscoring the need for technological pathways. Total costs are low in this scenario, in part because natural pathways are among the least-cost options available for carbon removal, but also because total removals are well below the 2 $GtCO_2$ target in 2050. Average cost to the federal government through 2050 is $18/$tCO_2$.[33]

Figure 21a | **Carbon Removal Deployment Scenarios**



Source: Author calculations based on estimates in the literature and assumed rates of deployment; see "Pathway-by-Pathway Deployment Scenarios" section for more information.

Figure 21b | **Cumulative Carbon Removal in 2050 of Each of the Above Scenarios ($GtCO_2$)**



Source: Author calculations based on estimates in the literature and assumed rates of deployment; see "Pathway-by-Pathway Deployment Scenarios" section for more information.

SCENARIO 2. ALL IN ON DIRECT AIR CAPTURE

In this scenario, direct air capture is aggressively pursued through a roughly $200 million per year public technology development program and the establishment of a substantial direct air capture industry. Between 2040 and 2050, a $1.2 trillion public works–style investment is made to expand direct air capture capacity to provide roughly 1.4 $GtCO_2$ removals per year by 2050. Note that at this scale-up rate, 2 $GtCO_2$ would be exceeded in less than two years following 2050. No investments are made in technologies other than direct air capture.

Direct air capture alone could hit the 2 $GtCO_2$ per year target shortly after 2050 if its scale-up rate can match that achieved recently by solar energy and be sustained for 25 years. Direct air capture could also continue to deploy beyond 2050. Total costs in 2050 are over $140 billion, though the portfolio does not quite reach the 2 $GtCO_2$ target by that year. Average cost through 2050 is $102/$tCO_2$.

SCENARIO 3. TECHNOLOGY ONLY

In this scenario, a broad-based technology development and deployment campaign successfully scales the full range of carbon removal technologies. Direct air capture—assumed to be the costliest option—is pared back to fill the gap to the 2 $GtCO_2$ target. No investment is made in natural capture.

Total costs in 2050 are nearly $180 billion. Average cost through 2050 is $74/$tCO_2$.[34]

SCENARIO 4. ALL OF THE ABOVE

This scenario features full-throated pursuit of all pathways. Direct air capture is pared to fill the gap to the 2 $GtCO_2$ target. Pursuing this scenario is the most risk-averse strategy in that it creates the most options for achieving the 2 Gt target by 2050. It also provides the most cumulative carbon removal through 2050 of any scenario, despite scaling to the same annual rate by 2050, since deployment occurs at greater scale on average throughout the intervening period. Scaling up all pathways substantially reduces but does not eliminate the need for considerable deployment of direct air capture. Because this scenario still requires aggressive development of direct air capture technology, this scenario positions direct air capture to scale beyond 2050, or earlier if one of the other pathways fails to materialize. Total costs in 2050 are just over $130 billion. Average cost through 2050 is $46/tCO$_2$.

CREATING A STRONG ENABLING ENVIRONMENT

In Brief

- Several investments in infrastructure, technology, markets, and data systems can directly or indirectly facilitate the scaled deployment of one or more carbon removal pathways (Box 10).
- Expansion of low-cost carbon-neutral energy is critical to minimize offsetting carbon emissions for carbon removal approaches that require energy input.
- Credible life-cycle assessment—full accounting of greenhouse gas removals and emissions on relevant timescales—is critical for informing actions by technology developers, investors, businesses, legislators, and regulators across the full portfolio of carbon removal pathways.
- Improved capabilities for transporting, using, and storing captured CO$_2$ are critical for direct air capture and BECCS as well as fossil CCS.
- The accuracy, timeliness, and granularity of monitoring systems for greenhouse gas fluxes from the land sector is increasingly important for enabling smart investments by the public and private sectors alike to retain and grow the natural carbon sink.
- Improved efficiency in the use of land—for example, through smart growth policy and productivity gains in agricultural and forestry—is a critical strategy for relieving conflicts between growing food demand and development and efforts to retain and expand tree cover globally.

Box 10 | **Concepts for Federal Action to Support a Strong Enabling Environment for Carbon Removal**

1. Establish a federal authority charged with ensuring the development of a wide range of on-grid and off-grid low-carbon energy sources to power a carbon removal and utilization economy.
2. Establish an independent governmental or quasi-governmental scientific commission to conduct credible life-cycle assessment and provide accounting frameworks for government regulations.
3. Extend and enhance the CarbonSafe program to continue to build the scientific and engineering knowledge to facilitate safe and effective geological storage operations—including saline aquifer storage and in situ mineralization (NAS 2018).
4. Review permitting requirements for CO$_2$ injection and storage in saline aquifers (Class VI well permits) to ensure both adequate safeguards and workability for industry.
5. Strengthen the 45Q tax credit for CCS to incentivize storage in saline aquifers.
6. Assess requirements for CO$_2$ pipelines to enable scale-up of direct air capture and BECCS and consider public-private partnerships to develop and size CO$_2$ pipelines to service a deep decarbonization future with significant carbon removal.
7. Invest in technology development for CO$_2$ utilization technologies.
8. Establish federal procurement programs for products and commodities that utilize captured CO$_2$.
9. Boost technical and financial resources provided to states to develop and implement state programs for natural carbon capture.
10. Integrate remote sensing tools, including light detection and ranging (LiDAR), into the Forest Inventory and Analysis (FIA) program to sharpen the nation's forest carbon monitoring system.
11. Reinstitute soil carbon sampling in the National Resources Inventory (NRI) field plots.
12. Improve the accessibility of USDA data to academic researchers to facilitate scientific advances in soil carbon sequestration while protecting privacy and confidential business information.
13. Provide grants or incentives to states and communities that implement smart growth plans to prevent conversion of natural forests and grasslands.
14. Invest in RD&D for agricultural productivity and rural broadband to support adoption of existing technologies like precision agriculture.

Abundant Low-Carbon Energy

Rapid expansion of renewable and other low-carbon energy is critical not only for decarbonizing major emitting sectors but also to power the carbon removal engine. Today's direct air capture technology requires about two terawatt-hours of low-carbon power (or equivalent thermal energy) per 1 $MtCO_2$ removed each year (Larsen et al. 2019). Deployment at the 1 $GtCO_2$ per year scale would require the equivalent of nearly half of today's total electricity generation in the United States—or roughly 40 percent of projected 2050 electricity generation (EIA 2019a). This energy would need to come from low-carbon sources like wind, solar, natural gas with carbon capture and storage, or advanced nuclear.

Additionally, various CO_2 utilization options (see below) require hydrogen to convert CO_2 to fuel and other chemicals. Optimizing the methods to produce hydrogen with renewable energy is critical as established methods rely on natural gas steam reforming. Cleaner methods, like electrolysis, require significant amounts of ideally low-carbon electricity input. For example, CO_2 conversion to methanol requires three hydrogen atoms for each carbon atom. Electrolysis requires considerable energy to split hydrogen from water. Converting 100 $MtCO_2$ per year to methanol would require roughly 10 percent of the total electricity generation in the United States just to produce the needed hydrogen (not counting energy input needed to convert CO_2 and H_2 to methanol).

Energy requirements to sustain a carbon mineralization operation at scale are more modest but still considerable. Mining and grinding reactive rock requires roughly 14 kWh per ton of material. Assuming 0.25 tons of CO_2 removed from the atmosphere per ton of reactive rock, scaling this pathway to 400 $MtCO_2$ per year would require 22,400 GWh per year, or roughly a third of total 2018 solar photovoltaic electricity generation in the United States. Additional energy would be required for transporting material.

The magnitude of these energy requirements underscores the need to develop a wide range of low-cost, low-carbon sources of energy. Given the cost and the lead time required to develop new power facilities, energy supply could quickly become a bottleneck for direct air capture and CO_2 utilization, in particular.

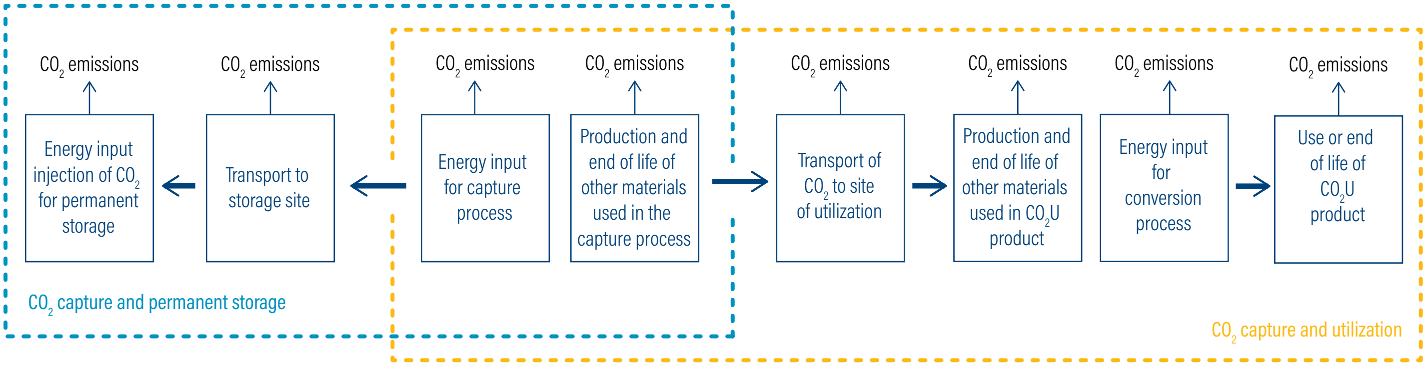
Life-Cycle Assessment

Life-cycle assessments provide full accounting of greenhouse gas removals and emissions, as well as other inputs like water and energy (see Figure 22), to understand the net balance of inputs, outputs, and emissions over the life cycle of a process or product. These assessments are critical for understanding whether carbon removal and CO_2 utilization pathways actually result in negative emissions, and to what extent (NAS 2018b). Technology developers, investors, and policymakers alike need standardized ways to measure and validate claims about the full life-cycle impacts of carbon removal and utilization pathways.

Due to its complexity and the possibility of arriving at very different results given different input assumptions, life-cycle assessment has become a common battleground for proponents and opponents of various pathways and practices. Bioenergy and enhanced oil recovery are two highly contentious practices whose life-cycle benefits are commonly debated. Forest health treatments, where net carbon benefits rely on an unknown counterfactual—whether the forest would burn without the treatment, and when—are also debated. Even a relatively straightforward technology like direct air capture has sparked debate over the net climate effects of its energy requirements.

The need for rigorous and timely life-cycle assessment will only grow as new configurations of carbon removal technologies and new CO_2 utilization pathways are developed and seek public and private investment. To ensure rigor and credibility, life-cycle assessment should be conducted by independent entities insulated from the political pressures of vested interests. Under some conditions, federal agencies may be able to play this role.

Figure 22 | **General Representation of Life-Cycle Assessment Components for CO_2 Capture and Storage or Use Showing Where Offsetting CO_2 Emissions Might Be Produced That Would Reduce the Net Amount of Captured CO_2**



Source: Adapted from Zimmerman et al. (2018).

Geological Storage of CO_2

Geological storage refers to the injection of captured CO_2 deep into suitable rock formations—those with sufficient porosity to allow for commercial-scale sequestration, as well as an impermeable "cap rock" to prevent leakage of trapped CO_2 on geological timescales. Technologies that yield CO_2 in gaseous form—direct air capture and BECCS—require that captured CO_2 be permanently stored in order to provide net carbon removal. While some CO_2 utilization options provide for long-lived storage, geological storage will be required to support deployment at scale. Investments in geological storage may pay off even if these carbon removal technologies do not achieve large-scale deployment, because geological storage capabilities are also required for carbon capture from various sources of emissions in the industrial and power sectors.

Geological storage can be conducted in saline aquifers, oil and gas reservoirs, and underground reservoirs of ultramafic rock (Box 11). Total U.S. geological storage capacity is estimated to be at least 3,000 Gt (NAS 2018a) technically available below onshore areas and state waters, although each site must be individually validated and annual sequestration rates in some types of sites must be controlled to avoid excessive pressure buildup (Blondes et al. 2019). This type of injection of CO_2 is also subject to Class VI permitting (Box 12). Geological storage is occurring successfully today, and significant experience, built up over decades of oil and gas operations, would allow for expansion of storage in oil and gas reservoirs and saline aquifers (NAS 2018a). However, investing in improved methods for identifying and validating the best sites and managing for leakage and seismicity risks will allow scaling of CO_2 sequestration to the Gt per year scale to happen faster, safer, and more cost-effectively.

The National Academies recommend a $250 million per year federal investment in research and development activities to continue to build the scientific and engineering knowledge to facilitate significantly scaled-up storage operations (NAS 2018). Some of these activities are already conducted under DOE's $68 million CarbonSafe program—and would be an extension and expansion of that program. Costs are relatively high for this area of research and development, which has progressed to the costlier demonstration-scale field-testing stage.

Box 11 | Major Types of Geological Storage

SALINE AQUIFERS

Injection in underground saline aquifers results in storage through three main processes, the importance of which depends on the site: capture in structural or stratigraphic rock "traps," dissolution in saline water, and/or geochemical reaction to form minerals in pore spaces of rock. Unlike CO_2-EOR, where injected CO_2 replaces oil previously occupying pore space, injection in saline aquifers increases pore pressure if no fluids are produced, increasing the risk of physical leakage. At the same time, saline aquifers generally occur at depths where there is already significant pressure—generally deeper than drinking water aquifers.

Deep saline aquifers in the United States are estimated to have significant storage capacity—estimates range from 1,600 to 20,000 $GtCO_2$, or 1 $GtCO_2$ per year for 50 years in the United States without requiring pressure management techniques (Jahediesfanjani et al. 2018; Celia et al. 2015)—and potentially orders of magnitude more if pressure management is included. Avoiding the need for pressure management is important, since it can add \$20–\$80 per tCO_2 (Blondes et al. 2019). Storing 1 $GtCo_2$ per year would require just under 9,000 wells—roughly the number of oil wells in Colorado (Jahediesfanjani et al. 2018; EIA 2019b). Saline aquifer injection has been practiced for decades in about a dozen projects in the United States, Australia, Algeria, Norway, and a few other countries, with five commercial-scale projects in total (NAS 2018a).

OIL AND GAS RESERVOIRS

Geological storage in oil and gas reservoirs can occur in tandem with CO_2-EOR operations (see Box 5) or in reservoirs without active production, but potential scale is smaller than in deep saline aquifers. Storage potential in depleted oil and gas wells in the United States is estimated to be around 100 $GtCO_2$, much lower than saline aquifers.

While industry is good at using CO_2 injection to maximize oil recovery, more effort is needed to build the knowledge base to enable industry to maximize CO_2 storage to improve the net climate benefits of enhanced oil recovery over the mid-term. The National Academies propose developing reservoir engineering approaches for co-optimizing oil recovery and sequestration.

MINERALIZATION STORAGE

Injection of CO_2 or CO_2-rich fluids in underground reservoirs of reactive rock like basalt or peridotite results in a chemical reaction that incorporates CO_2 into a solid, inert mineral, reducing risks of leakage. This approach is promising but remains in the early stages of testing (NAS 2018a). Two medium-scale field studies have tested this approach in basalt—the Wallula project in Washington State and the CarbFix project in Reykjavik, Iceland (NAS 2018a), as well as some smaller-scale field experiments (Blondes et al. 2019). No field-testing has been done in peridotite. Data from these projects show that reaction rates are faster than anticipated (Blondes et al. 2019), but they also point to areas that require further research and field-testing before this approach can be scaled up. In particular, research is needed to understand when mineralization causes positive feedback loops (cracking)[a] that can allow for continued movement of CO_2 and more mineralization as opposed to when it instead causes clogging that can cut off the process.

The CarbFix project in Iceland has been injecting 12,000 tCO_2 per well per year (Cho 2018) and Wallula injected on the order of 14,000 tCO_2 per well per year (Blondes et al. 2019). Both have costs of \$10–30 per tCO_2 and provide proof of concept at the pilot scale. While no pilot tests have been done in peridotite (more reactive but less permeable rock than basalt), the National Academies estimate that storage potential is significant—potentially up to 3 $MtCO_2$ per year for a single 3 km deep borehole, with an estimated cost of \$10–20 per ton (NAS 2018a). Field testing will be needed to confirm this potential.

[a] As suitable rock reacts with CO_2 in fluid, the reaction forms a solid product with a larger volume than the reactants, adding pressure to the product, which leads to cracks that can then provide access to deeper areas of the rock, creating a positive feedback loop of reactions. Conversely, mineralization and creation of these solid products also has the potential to "clog" the pore space in reactive rock and prevent further mineralization. Understanding the conditions under which each type of process occurs will be key to scaling up its potential (Kelemen et al. 2018).

CO_2 Pipelines

The existing CO_2 pipeline network in the United States extends more than 4,500 miles[35] (Folger 2018) and is used mainly for transporting CO_2 from natural reservoirs in New Mexico and Colorado to Texas for enhanced oil recovery (Righetti 2017). Although the extent and location of the need for pipelines to support direct air capture—and the successful deployment of direct air capture itself—is uncertain (see Box 13), pipelines will also be needed to support carbon capture at point sources of emissions in the power and industrial sectors.

In early 2018, revisions to the 45Q tax credit for carbon capture, use, and storage (see Box 4) provided a more robust incentive for expanding the pipeline network. Although 45Q will mobilize buildout of the CO_2 pipeline network to some degree, the optimal footprint of a pipeline network suited to service future point source capture and direct air capture is unknown. Buildout under 45Q could connect the most economic near-term options for carbon capture—predominantly ethanol refineries in the Midwest and natural gas processing and fertilizer plants with capture costs in the range of \$20–\$30 per tCO_2 (EFI 2018). These new pipelines may or may not be useful

Box 12 | Class VI Permitting

Underground CO_2 injection and storage in saline aquifers[a] is subject to the permitting process for Class VI wells, required by the Environmental Protection Agency (EPA 2010) in order to protect drinking water resources. The Class VI rule has been in place since 2010, and to date the EPA has issued six permits to just two projects (each well requires a separate permit). Four permits, which have since expired, were issued to the FutureGen Alliance in Jacksonville, Illinois, and two permits to the Archer Daniels Midland (ADM) ethanol plant—a government-supported demonstration plant in Decatur, Illinois, that is capturing and sequestering 0.9 Mt per year (Zitelman et al. 2018).

The Class VI permitting process includes consideration of permitting, siting, construction, operation, monitoring, and site closure of Class VI wells, including postinjection monitoring for up to 50 years to ensure that injected CO_2 has stabilized and no longer poses a threat to drinking water (EPA 2016). It requires in-depth modeling and analysis to predict the behavior of and area affected by injected CO_2, as well as a plan of action in case the injected CO_2 does not behave according to expectations and endangers drinking water supplies (EPA 2013).

Typically, the permit is issued in stages, where the project operator first tests injection in accordance with the permit and submits a review report to the relevant regulatory agency. Only after the review is approved and adjustments made to relevant planning documents can injection begin. In the case of the ADM ethanol plant, the only Class VI permit still in effect, the Class VI rule was enacted after the initial permitting request was made, but even so, it did not become effective until February 2015, five years after the rules were finalized and seven years after the initial permit request (Locke et al. 2016).

In addition to applying to the EPA, individual states can apply for Class VI primacy to approve applications within their state independently. North Dakota is the only state with this authority, having applied in June 2013 and been granted primacy in April 2018 (Federal Register 2018).

[a] Injection of CO_2 for EOR is not subject to this permit since it is injected into already-drilled wells.

Box 13 | Pipelines and Direct Air Capture

One advantage of direct air capture is siting flexibility. Direct air capture facilities can be sited immediately adjacent to CO_2 use or storage facilities, negating the need for CO_2 transportation infrastructure. However, several factors related to siting optimization suggest that direct air capture at scale will indeed rely on a network of pipelines for transporting CO_2:

- Some of the low-hanging fruit for near-term deployment of direct air capture are locations where waste heat can be used as an energy source at little or no cost—for example, adjacent to nuclear and fossil power plants, geothermal facilities, and oil fields (Wilcox et al. forthcoming). Many of these prime locations may not coincide with use or storage endpoints, so pipelines would be needed.
- Early direct air capture facilities are likely to be built near use endpoints, rather than storage endpoints, to generate product revenue in the absence of sufficient public incentive for permanent storage. Some of these use endpoints may not coincide with storage endpoints, which will be needed if direct air capture is to provide net carbon removal at scale in the longer term.
- Direct air capture is energy-intensive. Clustering direct air capture facilities near prime storage endpoints may cause energy supply bottlenecks given existing electric transmission or natural gas pipeline capacity.
- Some of the best sites for accessing cheap low-carbon energy to power direct air capture—remote locations with high renewable energy resources but lacking electric transmission, or where renewable energy is subject to high rates of curtailment due to grid congestion—may not coincide with use or storage endpoints.

for carbon capture approaches further up the abatement curve, including direct air capture. Economies of scale for pipeline construction mean that the most cost-effective, efficient approach for CO_2 pipeline development would be to build a system that anticipates a larger, future need, rather than constructing it piecemeal and then scaling up later on (GCCSI 2011).

Comprehensive mapping and scenario planning could underpin further policy development to close gaps in policy incentives. For example, federal intervention may be warranted to enable pipeline buildout specifically to access the best areas for direct air capture deployment. Federal finance may also be warranted to oversize the capacity of near-term pipeline builds positioned to serve additional carbon capture in the future. Without government intervention, it is likely that private pipeline developers will size pipelines according to current and near-term demand, rather than longer-term needs, which may result in a system that is ill-equipped to handle future needs.

The 45Q tax credit itself could be strengthened to incentivize pipeline development. The date by which construction must begin under 45Q (January 1, 2024) provides a narrow window to take advantage of the incentive. Most large natural gas pipeline projects completed in recent years have taken more than two years from the permit application filing date to completion of construction, excluding time for siting and right-of-way access (Edwards and Celia 2018), and CO_2 pipelines can be more difficult to construct due to the need to maintain higher pressures, the potential of corrosion from water, the need to handle variable purity levels from different sources, and others. Additionally, the 12-year credit eligibility period is shorter than the lifetime of most pipelines. Both of these provisions could be extended to better incentivize CO_2 pipeline expansion (Larsen et al. 2019). Lastly, lowering the capture threshold for industrial facilities from 100,000 $MtCO_2$ per year to 10,000 $MtCO_2$ per year would provide a more favorable innovation environment for start-ups across all technologies (Larsen et al. 2019).

CO_2 Utilization

Captured CO_2 can be used as an input for commodities and products. Creating markets for economic uses of captured CO_2 can provide product revenue to carbon capture operations—including carbon removal technologies and natural carbon capture as well as capture at point sources of emissions—and a demand signal to entrepreneurs and investors. Some of these uses can provide long-lived storage, enabling net carbon removal, while others may provide emission reduction or other benefits. Initial markets can also provide learning opportunities to bring down the cost and support scale-up of early technologies and natural solutions, acting as a bridge to long-term storage (Wilcox et al. forthcoming).

Based largely on potential market size, some of the more promising uses for captured gaseous CO_2 include fuels and building materials, like aggregates and concrete, which together have the technical potential to use up to 3 $GtCO_2$ per year within the United States in 2050 assuming complete replacement with CO_2 utilization (CO_2U) alternatives and assuming that both markets continue to grow at current rates. Plausible potential would be a smaller portion assuming social and economic constraints around adoption of these alternative products. Billions of tons of building materials—aggregate and concrete—are used per year; they have long product lifetimes allowing for near-permanent storage; and they can be mineralized from CO_2 using little external energy (NAS 2018b). These are low-margin commodities, however, and may provide little economic value in offsetting the cost of operating direct air capture or BECCS facilities.

Fuels also have a very large market potential and are economically valuable but require significant added energy for production and would not provide long-lived storage but rather create carbon-neutral or less carbon-intense alternatives. Converting CO_2 to commodity chemicals generally involves electrolysis to combine CO_2 and hydrogen or photosynthetic or other biological processes to turn CO_2 into higher-order chemicals. The potential annual revenue for CO_2-based fuels is up to $250 billion globally in 2030, with the potential to use up to 2.1 $GtCO_2$ per year if supportive market, policy, and technology actions are taken (ICEF 2016). A number of companies are already developing CO_2U products in both of these markets (ICEF 2016) (see Boxes 14 and 15). For each of these approaches, the overarching challenge is developing processes that have low energy inputs and produce products that are economically competitive with existing technologies, without incurring offsetting GHG emissions.

Scaling up the market for these products will require continued basic research to optimize carbonation processes and resolve technical challenges, as well as policies to support market access and wider deployment.

The National Academies outline a comprehensive agenda for basic and applied research and development for a wide range of CO_2 utilization conversion pathways. Support for deployment could also come in the form of government procurement, mandates, and certification standards. Hezir et al. (2019) propose a portfolio of federally funded RD&D to advance CO_2 utilization approaches.

In addition to utilizing CO_2 that is captured in its gaseous form, natural carbon capture through photosynthesis creates an opportunity to use woody biomass in the form of harvested wood products. Significant restoration of U.S. tree cover may require growth in markets for harvested wood products to maintain the financial viability of replanting timber lands, and to avoid economic disruption

Box 14 | Selected Company Profiles: Mineralization for Construction and Building Materials

Blue Planet makes CO_2-sequestered synthetic aggregate by adding layers of synthetic carbonate over a substrate, using alkaline industrial waste as the reactant. They report that each ton of CO_2-sequestered concrete stores 440 $kgCO_2$, and its strength, performance, and cost are on par with those of standard quarried aggregates. The process can use dilute CO_2 waste streams, so it is best sited near fossil fuel power plants or cement plants.

Carbicrete is a Montreal-based company that produces concrete with cement made from steel slag, a waste product. The concrete is injected with CO_2 to add strength through carbonation activation, improving its mechanical properties and durability and lowering its material costs—the new material is estimated to have 50 percent greater compressive strength and to be around 20 percent less expensive (Bourzac et al. 2017). The company reports that it eliminates CO_2 emissions associated with production (typically around 2 $kgCO_2$ per block) and additionally stores around 1 $kgCO_2$ that is injected per block during curing.

CarbonCure injects CO_2 into wet concrete, where it reacts with calcium to form carbonates that are permanently embedded in the concrete and can also improve its compressive strength. This approach results in CO_2 uptake of less than 10 $kgCO_2$ for each ton of reactant, and is currently being implemented across a number of ready-mix concrete plants in the United States (NAS 2018b).

Carbon8 Systems produces synthetic aggregate through carbonation of sometimes hazardous industrial waste materials and air pollution control residues with nearly pure CO_2. It yields CO_2 uptake of around 120 kg CO_2 per ton of solid reactant, avoids landfill or alternative disposal costs for alkaline waste, and has reached commercial deployment in the United Kingdom (NAS 2018b).

Box 15 | Selected Company Profiles: CO_2-Based Commodity Chemicals and Fuels

Carbon Engineering, based in Canada, uses CO_2 captured in its direct air capture facilities combined with hydrogen electrolyzed from water using renewable electricity. The company claims that cost will be slightly less than $1 per liter at scale; however, the company has not published cost estimates for the CO_2-to-fuel conversion step (Tollefson 2018).

Carbon Recycling, based in Iceland, creates renewable methanol under the name Vulcanol at a commercial scale in Iceland using CO_2 from processing gas emissions of a geothermal power plant and hydrogen from electrolysis powered by hydro, geothermal, and wind power. Estimates point to a 90 percent reduction in life-cycle emissions compared to fossil fuels.

LanzaTech uses biological fermentation to produce ethanol from industrial waste gases containing carbon monoxide and hydrogen. Estimates indicate a 70 percent reduction in GHG emissions compared to petroleum fuels on a well-to-wheel basis and suggest that globally 150 $MtCO_2$ could be avoided by reusing steel mill gas residues alone (LanzaTech n.d.). In 2018, the company built its first commercial scale plant in Hebei, China, with a capacity of 46,000 tons (16 million gallons) of ethanol per year (LanzaTech 2018).

Sunfire, based in Germany, creates synthetic crude oil using co-electrolysis of CO_2 and water, which combines two steps, increasing efficiency and reducing costs. Its first commercial plant, which it is building in Norway, will produce 8,000 tons (10 million liters) of synthetic crude per year. It also aims to combine technologies with Climeworks (DAC), INERATEC (Fischer-Tropsch) and KIT (hydrocracking) into a self-sufficient facility by late 2019 (Sunfire 2019).

within the industry. Harvested wood products can also offer significant carbon storage benefits—but the magnitude of these benefits varies considerably depending on the durability and end-use of the product (Chen et al. 2008).

Mass timber is a promising avenue for the expansion of markets for harvested wood products. Mass timber includes several engineered wood products for commercial construction applications that use layering and glue to create structurally sound building materials. Cross-laminated timber (CLT) is a prominent mass timber technology that utilizes new machining methods to produce high-value products from lower-value wood stocks. There has been substantive growth in North American manufacturing of CLT—on the order of 35 percent per year between 2013 and 2018, which may provide an offtake pathway for timber as more traditional wood markets become saturated

(Pei 2016; PR Newswire 2019). Mass timber products can replace traditional large-scale building materials in most cases, with recent analysis showing that these technologies could replace up to 15 percent of the current building market (Beck Group 2018).

However, realizing this growth rate in the market for mass timber will require solving structural challenges to scaling up the technology as well as safeguards and strong accounting frameworks to ensure net carbon benefits and avoid ecological impacts. Despite updates to the International Building Code (2015) that now allow for the larger-scale utilization of CLT, adoption is still limited by other codes and standards. Mass timber production is also limited by a production bottleneck, with only five certified producers in the United States in 2018 (Beck Group 2018). Research into the challenges and opportunities of mass timber products has been spearheaded by the U.S. Forest Service's Forest Products Laboratory.

Natural Carbon Capture Monitoring

The federal system for monitoring carbon stock changes in tree biomass and soils is the foundation for any policy effort to safeguard and grow the natural carbon sink. Yet major deficiencies in the accuracy, timeliness, and spatial granularity of this monitoring system frustrate efforts to confidently track progress toward climate goals, evaluate the efficacy of past policies, and identify new policy interventions (McGlynn et al. 2019). Federal investments are needed to expand sampling networks, integrate field data with remote sensing tools, establish landscape-scale monitoring systems for carbon removal, and build out data platforms to facilitate data-sharing and transparency.

Robust scientific data on carbon stock changes in the United States are necessary to ensure that public investments in land management are translating into carbon removal results as expected—and if they are not, to inform course corrections to the nature and distribution of those investments (Mulligan et al. 2018a). Robust spatially explicit data can also inform policymaking and land management decisions at the state and local levels. Though the federal government currently collects statistical datasets on the U.S. land base, including the Forest Inventory and Analysis (FIA) and the National Resources Inventory (NRI), these datasets have limited utility for evaluating public investments or informing estimates of the specific effects of different carbon removal policy options (see Box 16).

Improvements and complements to these datasets using existing survey methods and remote sensing technologies could help advance understanding about the impacts of land management practices on carbon removal while fostering public confidence in efforts to incentivize carbon removal approaches. The federal government is well positioned to lead the creation of these improved and complementary datasets, given its ability to leverage existing federal data, the scientific capacity in agency offices and extension programs, and its current funding for national research efforts to benefit U.S. agriculture and forestry.

Key needs for land carbon monitoring relate to improved accuracy, timeliness, and spatial granularity of carbon removal estimates associated with the land sector. Improving on these data quality metrics requires that policymakers address the following components of a monitoring program:

- *Sampling networks*: Increase the data collection frequency, density of sites, and/or types of measurement collected.
- *Remote sensing tools*: Invest in regular data collection using aerial, satellite, and/or light detection and ranging (LiDAR) technologies, and integrate remote sensing products into sampling-based methodologies for carbon estimation.
- *Carbon removal practice monitoring*: Collect data on both the extent of adoption of key land management practices that promote carbon removal, and on the relationships between those practices and carbon removal outcomes.
- *Data systems*: Centralize data from sampling networks and remote sensing tools, along with supporting carbon estimation models, in a single system that is spatially explicit and accessible to nonfederal researchers and decision-makers.

Sampling networks

The greatest need for improvement in national sampling networks is on-farm measurement of soil carbon. On-site measurement of soil carbon could be added to a subset of the National Resource Inventory network's 800,000 sampling sites, which already support land-use and environmental monitoring. A partnership between the National GHG Inventory run by the U.S. Environmental Protection Agency and the U.S. Department of Agriculture National Resources Conservation Service (NRCS) had planned to collect soil sample data from 5,000 NRI survey sites

Box 16 | Federal Land-Based Datasets

Federal datasets offer the most robust publicly available information available on forests, soils, and other natural resources across the United States. The datasets described below underpin the most comprehensive monitoring system for natural carbon capture currently undertaken in the United States, conducted as part of the annual Inventory of U.S. Greenhouse Gas Emissions and Sinks. Understanding the methodologies and intended uses for these datasets is a critical foundation for improving land carbon monitoring data in the United States.

FOREST INVENTORY AND ANALYSIS

About: The U.S. Forest Service surveys a network of field plots across U.S. forest lands to collect data on area, tree, and other land-use attributes. Data on forest health indicators are collected from a subset of those field plots. Forest Inventory and Analysis (FIA) is the official data source for carbon flux on forest lands in the Inventory of U.S. Greenhouse Gas Emissions and Sinks.

Strengths: The field plot network that comprises FIA offers robust insights into how forests grow and change across the United States. The continuous annual data provided by FIA since 2001 enable research on temporal trends in the U.S. forest base to inform policy and management decisions.

Weaknesses: Although nationally aggregated FIA data are updated annually, individual field plots are measured only once every 5–10 years. FIA therefore cannot account for the impacts of sudden disturbances like fire, disease, or harvests in a timely fashion. Because data collection is confined to areas defined as forest, FIA does not survey trees in agricultural, urban, or peri-urban landscapes, which can offer significant additional carbon removal potential. FIA's sampling intensity—one plot for every 6,000 acres of forest—also limits its statistical power in estimating carbon fluxes at small spatial scales like counties or parcel maps.

NATIONAL RESOURCES INVENTORY

About: The USDA Natural Resources Conservation Service (NRCS) assesses land-use and management characteristics across all nonfederal lands in the conterminous United States, collecting data on soil, water, and related environmental resources from a stratified network of field plots. The National Resources Inventory (NRI) has been conducted annually since 1997, and previously was conducted every five years following its establishment in 1982. The NRI is the official data source for land use and land use change on nonfederal, nonforest lands in the conterminous United States and Hawaii, and is used to account for carbon fluxes in nonfederal agricultural lands, in the Inventory of U.S. Greenhouse Gas Emissions and Sinks.

Strengths: The NRI includes annual data on all land-use types, enabling research on land use change over time—a significant contributor to carbon flux in the land sector. The collection of soil and water data from field plots provides valuable on-the-ground data for agricultural producers.

Weaknesses: Measurements of soil carbon are not currently collected from NRI survey plots. As a result, the NRI cannot provide direct estimates of carbon removal from soils—those estimates can only be calculated by combining NRI land-use data with other data on the carbon impacts of those land uses. Additionally, because NRI data are not released until at least three years after collection, the dataset cannot provide timely estimates of year-to-year changes in land use or management practices.

NATIONAL LAND COVER DATABASE

About: The U.S. Geological Society (USGS) produces land cover data products based on Landsat satellite imagery. The National Land Cover Database (NLCD) is the official data source for the Inventory of U.S. Greenhouse Gas Emissions and Sinks for areas where gaps exist in FIA and the NRI, including federally owned nonforest land across the United States as well as nonfederal land in most of Alaska.

Strengths: The NLCD includes geospatial data on land cover across the entire United States, providing base layer data for land-use analyses down to a 30-meter spatial resolution.

Weaknesses: Data for the conterminous United States are available only from 1992, 2001, 2006, 2011, and 2016—and for Alaska and Hawaii even less frequently—so it isn't possible to observe trends in year-to-year land cover change. The NLCD is only made available on a time lag of three years or more, so the data are already somewhat stale by the time they are released.

but only collected data in 150 pilot sites before program funding was eliminated. A minimum sample size in the range of 5,000 sites nationwide is likely needed to provide adequate statistical power in calibrating the models used in the national inventory, and to ensure robust sampling from all regions and soil types. The National Academies have estimated that building out a soil carbon monitoring system on 5,000–7,000 NRI survey sites with sampling and analysis conducted on intervals of five to seven years would cost $5 million annually (NAS 2018a).

Reducing uncertainty in the estimates of annual carbon stock change in U.S. forests could also be achieved by increasing the sampling frequency for carbon pool measurements on Forest Inventory and Analysis plots (Mc Glynn et al. 2019). More intensive sampling can provide especially useful data on forest carbon dynamics immediately following disturbance events, as the current 5- to 10-year measurement cycle is not well suited to isolating sudden or short-duration changes in carbon stocks. Some states, including California and Minnesota, are already making FIA surveys more frequent within their borders to get more accurate state-level estimates of forest carbon stock changes. Other states are expanding FIA plots into urban forests to capture carbon stock dynamics that are excluded from the traditional FIA program. Using these state innovations as pilot sites, the federal government could assess where additional resources invested in improving FIA surveys could provide greatest value to national estimates of carbon stock change in tree biomass.

Remote sensing tools

Sampling networks, while critical to understanding how carbon stocks change over space and time in biomass and soils, tell only part of the story—they cannot represent every tree or patch of soil within the area of analysis. To assess carbon stock changes in a spatially explicit manner that can help prioritize and evaluate federal investments in natural carbon capture projects across the landscape, sampling networks must be paired with remote sensing tools. Data from satellite imagery, LiDAR, and digital aerial photography (also known as photogrammetry or "PhoDAR") can be used to estimate carbon in woody biomass across all land use types at a moderate to fine resolution.

To date, federal agencies' integration of remote sensing data into products related to land carbon has largely been through one-off projects—such as the Forest Service's Forest Carbon Management Framework (ForCaMF) for planning on national forest land, or the Global Ecosystem Dynamics Investigation (GEDI) mission, recently launched by the National Aeronautics and Space Administration (NASA), to produce global LiDAR maps—which are not currently designed to support long-term monitoring. Going forward, federal agencies should focus on regular collection of remote sensing data that can be calibrated with field data, including from FIA and NRI plots, to produce a high-resolution spatial dataset that shows how carbon stocks are changing over time and across the United States.

A number of possible avenues exist for leveraging remote sensing tools in federal monitoring of land carbon stocks:

- Perennially renewing the GEDI mission to collect regular national-level LiDAR data.
- Integrating LiDAR and/or PhoDAR data with FIA estimates of forest carbon to better assess year-to-year stock changes and incorporate trees outside of forests.
- Integrating the Soil Survey Geographic Database with soil carbon sampling data to produce a regularly updated national map of soil carbon.
- Collecting and analyzing new parameters in satellite data, such as ultraviolet reflectivity and greenness, to refine the modeled relationship between forest health or degradation and carbon stocks.

All of the remote sensing tools described here could have ancillary benefits aside from carbon monitoring, including planning for resilience to natural disasters such as fires, floods, and droughts. These benefits have led the Federal Emergency Management Agency to fund LiDAR data collection in the past and may open up future funding partnerships between agencies.

Practice monitoring

Tracking progress on terrestrial carbon removal requires national-scale monitoring of the extent and magnitude of impact of practices that affect carbon flux in the land sector, either through increased emissions (e.g., land use change) or increased removals (e.g., agricultural soil management). Data on the extent of land use change are available through NRI, and adoption of land management practices is already tracked through USDA surveys, including the Census of Agriculture, the National Woodland Owners Survey, and the Conservation Effects Assessment Project—though more regular updates of these data and greater accessibility to outside researchers could improve their utility. More data are needed to rigorously quantify the carbon impacts of land use change and most land management practices according to regional and time-specific conditions such as soil type, climate, temperature, or precipitation.

Data systems

Researchers often cite the inaccessibility and lack of transparency in government data as key hindrances in advancing knowledge on land carbon stock changes. A federal platform that serves as a repository and aggregator of geospatial and survey data on land carbon and land management practices could establish a common foundation of knowledge among agency, university, and external researchers to underlie future studies, calibrate process-based models, and inform policy. It could draw on existing field-based and remote sensing datasets, while helping researchers identify needs for future data collection.

The platform could be scaled nationally to estimate carbon removal trends over time and in relation to federal policies; it could also be downscaled to a state or regional level to track progress toward subnational goals, identify sources of regional variation, and inform state policies and markets. The National Academies have recommended annual funding of $5 million to support the build-out and operations of such a platform (NAS 2018a).

Land Use Efficiency

Global demand for food, fiber, and fuel affects the scale of opportunity for natural carbon removal through reforestation and grassland restoration. These competing demands for the use of land are projected to intensify as the global population grows in number and wealth (Searchinger et al. 2019). While the carbon removal potential from tree restoration quantified above is compatible with current and near-term land requirements for food, fiber, and fuel production, managing these competing global demands efficiently is nonetheless important to minimize land use conflicts in a future, more populated, world.

Increasing productivity on existing cropland, pasture land, and aquaculture systems, reducing food loss and waste, and encouraging plant-rich diets are important strategies for relieving pressure from food demand on prospects for natural carbon capture (Searchinger et al. 2019). These measures increase land use efficiency and can lead to significant carbon benefits. For example, the net carbon gain derived from making an acre of corn 6 percent more productive can be comparable to planting cover crops on the same acre, due to the land use change for expanding agricultural production that is avoided by instead increasing productivity.[36]

Increasing agricultural productivity allows more food to be produced with the same amount of land, liberating other land for restoration to more carbon-dense ecosystems. Even modest increases in the rate of productivity growth, if sustained over many years, would have a substantial effect on total agricultural output in the coming decades, as well as the competitiveness and profitability of U.S. agriculture. Furthermore, by exporting U.S. technology, these investments could bolster food security, boost productivity across the tropics where yields are often much lower, and enable greater deployment of natural carbon capture globally. Yet federal funding for research and development for agricultural productivity has stagnated in real terms since the mid-1980s.

Using land efficiently also requires protecting natural lands, which sequester significant quantities of CO_2 but can release CO_2 back into the atmosphere if disturbed. Existing U.S. forests sequester over 500 $MtCO_2$ per year on balance, but forest loss due to urban development and conversion to agriculture returns nearly 130 $MtCO_2$ annually into the atmosphere—fully one-quarter of the carbon removed by forests. Loss of grassland adds another 30 $MtCO_2$ per year in emissions (EPA 2019). Without measures in place to limit the conversion of natural lands, the resulting loss of carbon may offset carbon gains from tree restoration.

The federal government has a variety of tools at its disposal to promote the protection of natural lands under private ownership. The government can incentivize developers and agricultural producers to pursue “smart growth” on previously disturbed areas, rather than natural lands, through tax breaks or other subsidies. The Sodsaver provision in the 2014 Farm Bill, for example, incentivizes grassland protection in six Northern Plains states by cutting their federal subsidies for crop insurance on cropland that tills over native grassland. The government could also consider providing grants or other support and incentives to communities that adopt smart growth plans with provisions for protection of forest and native grassland. Conservation easement programs like the Agricultural Conservation Easement Program and Forest Legacy Program could work in tandem with smart growth planning by targeting natural lands that are particularly vulnerable to conversion. A suite of policies that systematically protects natural lands would ensure that other federal investments in natural carbon capture are not just mitigating carbon losses elsewhere on the landscape but also providing valuable carbon removal services to help the United States reach carbon neutrality.

CONCLUSION: 2050 AND BEYOND

A federal CarbonShot Initiative would position the United States to reach carbon neutrality on an accelerated time frame while backstopping the risk of failure in our efforts to reduce greenhouse gas emissions from every sector of the economy. CarbonShot would put real resources into the development of new technologies and new industries to scale them, while investing heavily in natural carbon capture pathways.

The portfolio of carbon removal pathways presented here offers promise, given the right investments in RD&D, to remove up to 2 $GtCO_2$ per year by 2050. Tree restoration and direct air capture are staples in this portfolio. Tree restoration offers both outsized potential and deployment readiness, and portfolio deployment scenarios that feature the largest investments in tree restoration garner the largest cumulative removals through 2050. As such, large-scale federal investment in tree restoration is warranted, with financial subsidies forming the core of the scaling strategy. Direct air capture, meanwhile, is necessary in all scenarios to reach the 2 $GtCO_2$ per year target and could scale up relatively quickly in the 2040–50 period provided concerted federal technology development and an expanded 45Q tax credit. Direct air capture could continue to scale beyond 2050 and could serve as a “backstop” should other pathways fail to scale.

Although these two pathways have unique value, pursuing a broader portfolio can reduce cost and risk. Cost-share subsidies for agricultural soil carbon management can provide immediate carbon removal benefits alongside substantial economic and environmental co-benefits. Foundational research and development could pay big dividends for carbon mineralization and enhanced root crops—more speculative carbon removal plays with significant theoretical potential although little proof of concept to date. Other pathways like BECCS, wood preservation, and extended timber rotations offer uncertain but likely modest potential for additional carbon removal. These pathways are therefore lower priorities for federal policymaking, though they may still contribute to a diversified portfolio.

Pursuing a broad portfolio also has merits in positioning the United States to maintain carbon neutrality beyond 2050. Natural carbon capture pathways together offer sizeable potential but are constrained by available land area, biophysical limits on removal rates, and—eventually—saturation points at which a given project no longer contributes incremental carbon removal value. For soils, this saturation point is thought to be on the order of several decades, with carbon removal rates attenuating in later years of implementation (NAS 2018a). Trees continue to sequester carbon throughout the more than 100-year lifespan of the tree in the absence of disturbance (Smith et al. 2006), but any restored trees slated for harvest will not contribute meaningfully to incremental carbon removal beyond the initial harvest cycle (typically 30–50 years) and must be replanted just to maintain prior carbon removal gains. These dynamics underscore the need for a long-term planning view in shaping an effective carbon removal portfolio for the United States, and the value of technological approaches to carbon removal.

Underlying many of these pathways is the need for investments in infrastructure, data, science, and markets to create a strong enabling environment. Key areas for enabling investments include low-carbon energy, life-cycle assessment, geological storage mechanisms for CO_2, CO_2 pipelines and utilization pathways, monitoring systems for natural carbon capture, and measures that increase the efficiency of land use, including enhancements to agricultural productivity.

Pursuing carbon removal pathways and enabling investments in tandem over the coming decade is an ambitious but necessary proposition in guiding the United States toward carbon neutrality—an imperative if the world is to limit global temperature rise to 1.5°C or even 2°C.

Although a CarbonShot Initiative is about positioning the United States and the world for a climate-secure future, it is also about creating economic opportunities now—on U.S. farms and in the country’s forests, factories, and businesses. The investments made now can help restore economic security to rural communities while incubating new industries, creating diverse employment opportunities, and promoting a healthy environment for generations to come.

APPENDIX A: ADDITIONAL INFORMATION ON TREE RESTORATION SUBSIDIES

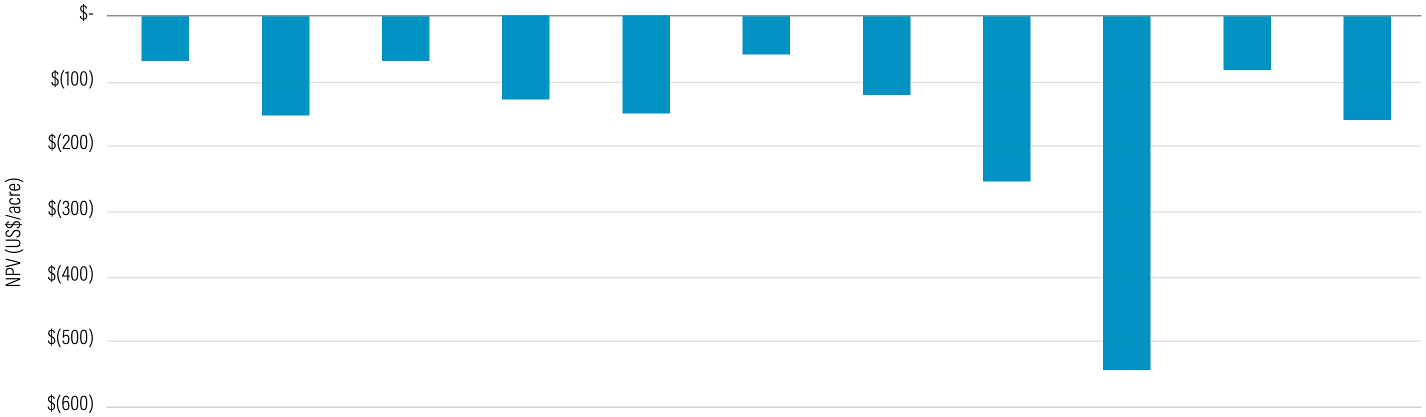
Assessing the Cost of Tree Restoration

The net costs of tree restoration will vary considerably from acre to acre depending on several factors, but under all circumstances restoration would require subsidies to make it economically attractive to the landowner. The federal subsidy would therefore need to cover 100 percent of the "hard costs" of tree restoration in order to achieve the full scale of carbon removal potential from this pathway. This assessment estimates the total cost of this subsidy based on the projected area available for each practice (Figure A1), but the actual cost to the federal government would depend on how many acres are enrolled in each.

The total cost of a federal subsidy would also be sensitive to landowners' net cost of tree restoration, which is influenced by the discount rate applied to future revenues from timber or forest product sales in restocked forests, silvopasture, and alley cropping systems.[37] These estimates assume roughly equal distribution of tree restoration opportunities on eastern lands and midwestern/western lands, but the regional distribution of tree restoration opportunities could impact funding needs as well—western forests require more costly site preparation and are typically stocked at lower densities than eastern forests (Bair and Alig 2006). Note that federal subsidies would leverage preferential tax treatment at the state level in several states for land held in forest. These state tax provisions and potentially other state policies could defray the total need for federal funding.

Table A1 shows the present value of upfront establishment costs, recurring maintenance costs, and potential private benefits that could result from timber harvest across selected tree restoration scenarios. These values are regional averages; significant variation may also occur within regions as a function of tree species, site conditions, and other factors. Though all private benefits are assumed here to come from timber harvest (including sawtimber and pulpwood), in reality other products like fruits or nuts may provide benefits to landowners in place of timber in some systems.

Figure A1 | **Economic Net Present Value of Tree Restoration Approaches on Nonfederal Lands**



LOW	HIGH	LOW	MIDDLE	HIGH	LOW	HIGH	LOW	HIGH	LOW	HIGH
$(68.04)	$(153.58)	$(68.85)	$(126.84)	$(147.30)	$(56.79)	$(121.49)	$(253.96)	$(543.35)	$(80.98)	$(159.44)
Silvopasture		Reforestation via Active Replanting			Reforestation via Natural Regeneration		Restocking		Cropland Agroforestry	

Note: Reforestation establishment costs are approximated using average cost estimates for afforestation on crop and pasture lands, under the assumption that site-preparation needs on nonforested, nonagricultural lands would be more similar to those on crop and pasture lands than on existing forest lands. Silvopasture cost estimates are based on afforestation of pastureland, while alley cropping estimates are based on afforestation of cropland, though actual costs in these systems will depend on the density and species of trees planted. Restocking cost estimates are based on active replanting on forest land. All monetary values are translated to 2019 dollars. Net present values (NPVs) assume that timber revenues (or equivalent revenues from other products) are captured in forest restocking, silvopasture, and alley cropping scenarios but not in reforestation. Establishment cost prices and tree density vary based on region, with high and low scenarios representing the highest- and lowest-cost regions. All costs and revenues are for softwoods; hardwoods would incur greater establishment costs and timber revenues, with a longer harvest cycle. NPVs are calculated over 35 years (the assumed length of one softwood harvest cycle) at a discount rate of 7 percent.

Source: Adapted from Bair and Alig (2006).

Table A1 | Total Costs and Private Benefits per Acre of Selected Tree Restoration Scenarios over 20 Years

	TOTAL COSTS PER ACRE[a]	PRESENT VALUE OF POTENTIAL TIMBER BENEFITS PER ACRE TO LANDOWNERS[b]	NET BENEFIT PER ACRE TO LANDOWNERS (PRIVATE BENEFITS MINUS COSTS)	NOTES
Reforestation via natural regeneration	Establishment: $43–$130 Maintenance: $25–$35	$158	With timber harvest: –$7 to $90 Without timber harvest: –$165 to –$68	Natural regeneration produces less sawtimber and more pulpwood at final harvest (Bair and Alig 2006). Regeneration will depend significantly on forest type and regional water availability.
Reforestation via active planting	Establishment: $104–$250 Maintenance: $55–65	$159–$306	With timber harvest: –$156 to $147 Without timber harvest: –$315 to –$159	Costs vary based on the species planted—establishment costs for hardwoods average about 10% more than costs for softwoods, due to greater planting costs but lower site-preparation costs—and region—establishment costs in western regions are roughly double those in the South (Stoots et al. 2017).
Silvopasture	Establishment: $114–$250 Maintenance: $55–65	$129	With timber harvest: –$186 to –$40 Without timber harvest: –$315 to –$169	Additional private benefits may accrue from greater animal production and offset costs—these benefits were not included in the baseline analysis (Mayerfeld et al. 2016).
Forest restocking	Establishment: $270–$600 Maintenance: $55–65	$79–$128	With timber harvest: –$586 to –$197 Without timber harvest: –$665 to –$325	Variation in cost based on species and region would be expected (Vasievich and Alig 1996).

Notes: High and low cost estimates represent differences in region and species type (softwood or hardwood). Future benefits from harvest are discounted at 7 percent per year. All costs and benefits are converted to 2019 dollars.

[a] Adapted from Bair and Alig (2006).

[b] Adapted from North Carolina State University (2019); Stoots et al. (2017); and Texas A&M Forest Service (2019).

Options for Structuring Subsidies for Tree Restoration

The federal government's tools for setting subsidy rates will look different depending on whether the program is structured as a direct payment program or a tax credit. Three options are available for setting direct payment rates:

1. **Competitive bidding process.** A competitive application process or reverse auction would incentivize applicants to minimize cost, maximize monetizable benefits, and seek out sources of cofunding to reduce the federal subsidy required. It would also allow USDA to engage in price discovery, providing better data on the true cost of project implementation and enabling more fiscally efficient policymaking in the future. However, operating well-functioning auctions poses several administrative challenges and may be susceptible to gaming. A competitive bidding process would also be better suited to large entities like states, municipalities, NGOs, and private companies than individual small landowners, given a more complex application process. This approach would require new spending authority and annual appropriations to USDA to implement.
2. **Cost-share rubric.** USDA could predetermine a range of cost-share rates based on a set of relevant factors—for example, whether active planting or natural regeneration will be used; typical planting costs and private benefits based on region, tree species type, or land use type; or whether the project is implemented by a private landowner or a public entity. Rates could be revisited based on uptake rates or as new information is collected. This type of approach is akin to rate-setting conducted now by USDA under the Environmental Quality Incentives Program.
3. **Flat cost-share rate.** The simplest and bluntest approach would be for USDA to set a flat rate—either a flat dollar value per acre or per tree, or a flat percentage of project costs.

Further characterization of the area identified for tree restoration—including total costs, private benefits to the landowner, and monetizable benefits to third parties—is needed to quantify the potential cost savings of tailored cost-share rates relative to flat rates.

Box A1 | Pay for Acres, Trees, or Tons?

A subsidy program for tree restoration can set rates on an area basis (dollars per acre), a volumetric basis (dollars per tree), or a performance basis (dollars per ton of CO_2 sequestered). This choice can affect the efficiency and scalability of the program, so it should be considered carefully.

PAY FOR ACRES

Current NRCS cost-share programs like the Environmental Quality Incentives Program (EQIP) and Conservation Reserve Program (CSP) pay landowners based on the number of acres enrolled in conservation practices. This approach is the simplest to implement, since the number of acres in a project is easy to monitor and verify. Because of the administrative simplicity of this type of program, it is easily scalable.

PAY FOR TREES

A pay-per-tree approach would rely on basic monitoring and verification of the number of trees planted on a given property. One advantage of the pay-for-tree approach over paying for acres is that it inherently rewards landowners who plant more trees on a property, which would likely translate to more carbon removal for a given parcel size. This approach would need to include limits, however, to ensure that payments for tree planting do not exceed ecologically appropriate tree densities or unduly increase the risk of disease outbreak or wildfire. Paying for trees may be the most equitable option for project types where trees are not evenly distributed across the project area, such as urban reforestation and some agroforestry systems, as this approach is not sensitive to where the project boundaries are delineated. If the payments can be structured to closely approximate the value needed to induce tree planting—and no more—this approach also offers greater economic efficiency than paying a set rate per ton of CO_2 sequestered.

PAY FOR TONS

The pay-for-tons approach has been modeled by the California greenhouse gas cap-and-trade program, which issues offset credits to forest carbon projects according to the amount of CO_2 they sequester. Paying for tons carries the advantage of incentivizing landowners to maximize carbon sequestration on their land, but it also involves the greatest level of program complexity and transaction cost due to monitoring and verification needs. For this reason, paying for tons can entail high administrative costs, and may be prohibitively expensive for smaller projects. Private landowners may also be less likely to enroll in a pay-for-tons program due to the added uncertainty around the value of payments they would receive for a given tree restoration practice. A pay-for-tons approach would be most appropriate for programs designed to incentivize only a small portion of the total potential, where it is important to cultivate the "low-hanging fruit" (the cheapest opportunities for carbon sequestration).

OTHER CONSIDERATIONS

In addition to scaling subsidy payments by acres, trees, or tons, payment rates could be set to vary by region, previous land use type, species planted, or other factors. Variable payment rates of this sort are already employed in farm support programs like EQIP, where rates are set regionally and differ depending on crop type and farmer characteristics. Adjusting per acre or per tree payments according to other variables that affect carbon sequestration potential could make the incentive structure for landowners more closely resemble actual direct and hidden costs but would introduce some additional administrative costs.

Paying a percentage of incurred costs is another common structure for cost-share programs. Unlike the other approaches, however, pay-for-cost programs (where the cost-share is less than 100 percent of costs) cannot compensate landowners for "hidden costs" like transaction costs or opportunity costs. Given the significance of these hidden costs to many landowners with opportunities for tree restoration on their lands, a pay-for-cost approach is unlikely to succeed in capturing most of the potential in this pathway.

For a tax credit, rate-setting tools like competitive bidding or complex rubric evaluations would be unworkable within the context of the tax code and the capacity of the Treasury Department. Tax credit rates would therefore likely be less efficient in incentivizing tree restoration at the lowest cost. Three feasible options for setting tax credit rates could be considered:

1. **Increasing rates over time.** A tax credit that starts at a modest rate and ratchets up over time is likely to be more efficient than a rate that starts high, as it allows the Treasury Department to engage in price discovery and optimize rates upon reauthorization of the tax credit.
2. **Tiered rates.** The Treasury Department could offer different tax credit rates based on project attributes that are linked to either the cost of the project or its expected carbon removal value. For example, the Treasury might offer lower rates for trees slated for harvest. Note that this approach is more applicable if the tax credit is distributed on a per acre or per tree basis rather than a per ton basis (see Box A1).
3. **Flat tax credit rate.** As with a cost-share program, the simplest and least efficient approach would be for the Treasury to set a single rate for tree restoration, and revisit that rate only during reauthorization of the tax credit.

In either a direct payment program or a tax credit, the metric on which the subsidy is based can also affect the subsidy's efficiency in producing carbon removal. Box A1 presents a variety of options for how the subsidy amount may be measured for a given tree restoration project.

The temporal structure of federal subsidies also contributes to the subsidies' effectiveness and efficiency for motivating tree restoration. A program that provides a subsidy upfront will facilitate project finance, responsive to the needs of many landowners for immediately available capital to support their operations (Butler 2008). However, if the entire subsidy is awarded upfront, the federal government may then bear some of the risk of failed project implementation.

Phasing the subsidy over time instead would likely require the use of private or other nonfederal sources of finance to cover upfront costs, thereby increasing total cost of implementation, but would allow the federal government to peg subsidy payments to implementation milestones. In this way, the subsidy could operate like the Conservation Reserve Program, dispensing regular payments over a set contract period as long as the conservation practice (in this case, tree growth) remains in effect, with a repayment obligation and financial penalty if the practice is terminated early. A hybrid approach could entail a percentage of the subsidy awarded upfront to the project operator as start-up funding, with the remainder distributed in increments throughout the contract period or withheld until project milestones are met.

Any of these approaches could be implemented in a direct subsidy program or a tax credit program. A direct subsidy program lends itself to a more adaptable approach, in which USDA could evaluate project risk and negotiate terms with applicants to balance the landowner's need for upfront certainty in financing with the government's interest in ensuring successful project implementation.

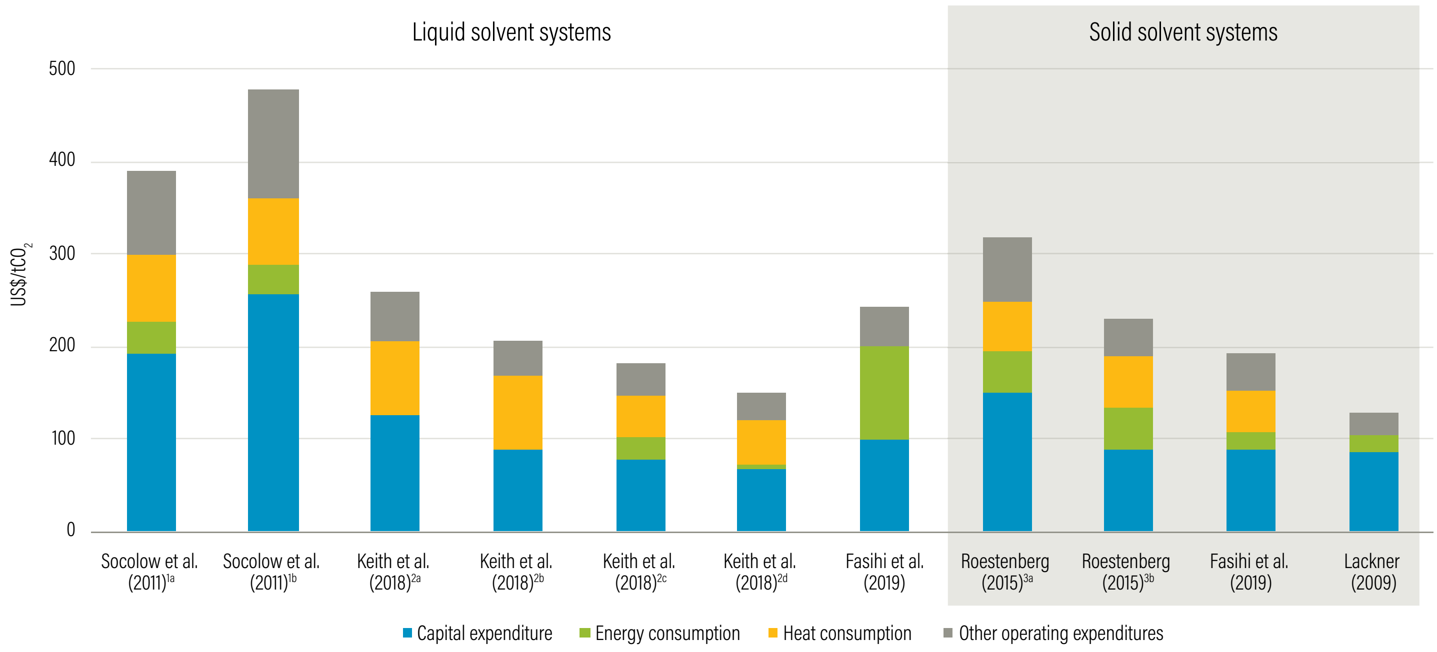
APPENDIX B: COSTING DIRECT AIR CAPTURE

Many factors need to be considered when comparing costs reported in the literature:

- Whether the estimate is the cost of CO_2 captured versus the cost of net CO_2 removed from the atmosphere.
- Which life-cycle costs are included (e.g., capital costs vs. operating costs, and which specific costs are included (i.e., whether including compression, transportation, sequestration, or other steps of the process).
- Whether costs are for a first-of-its-kind demonstration pilot plant or for a mature "nth" plant.
- Whether the estimates are based on a specific technology versus theoretical efficiencies and energy requirements.
- The heat and electrical energy required, and energy source assumed.
- Whether the system is a solvent-based system or a sorbent-based system.[38]
- The purity of the stream of CO_2 produced.
- The cost of the materials and design configurations, including plant size. Examples include the following:
    - *Designs maturing*: For example, the NAS (2018a) notes that designs assumed in earlier studies (e.g., APS et al. 2011) are no longer broadly applicable. The flow configuration can be altered to reduce the pressure drop, and accordingly reduce capture costs (Keith et al. 2018; NAS 2018a).
    - *Cost declines*: For example, the National Academies (NAS 2018a) show that the current costs of industrial calciners can halve earlier (APS 2011) estimates.
    - *Alternative materials*: For example, Keith et al. (2018) describe how polyvinyl chloride (PVC) packing, alongside a cross-flow configuration, could lower costs significantly when compared with metal packing, coupled with a counterflow configuration (NAS 2018a). The structural materials chosen for the air contractor play a key role in determining the capital costs as this is the largest component of a direct air capture system. A seemingly small detail such as using plastic instead of steel could lead to significant cost savings (ICEF 2018), although it remains to be seen whether the PVC packing can be durable enough over time (NAS 2018a).
    - The National Academies find that, accordingly across the literature, the range of ***capture costs*** (which do not include costs associated with any transport, injection, and storage or usage of carbon dioxide) for a generic direct air capture system that can remove 1 Mt per year CO_2 yield range from
        - \$147–\$264 per tCO_2 for a natural gas–fueled liquid solvent system; to
        - \$317–\$501 per tCO_2 for a liquid solvent system that is based on solar photovoltaics and electrolytic hydrogen; to
        - \$88–\$228 per tCO_2 for a generic solid sorbent system (NAS 2018a).
    - For ***net carbon removal costs***, which take into account the emissions associated with any burning of fossil-based energy sources, costs range from
        - \$199–\$357 per tCO_2 for a natural gas-fueled liquid solvent system; to
        - \$320–\$506 per tCO_2 for a liquid solvent system that is based on solar photovoltaics and electrolytic hydrogen; to
        - \$89–\$877 per tCO_2 for solid sorbent-based systems, depending on the adsorption design (NAS 2018a).

The broader literature has produced a wide array of cost estimates as well. Figure A2 shows the cost breakdown between capital expenditure, heat consumption, energy consumption, and other operating expenditures (opex) among systems described in the literature.

Figure A2 | DAC Cost Composition per Ton of CO_2 Captured



Notes:

[1a] Optimistic assumptions for capital and operating costs.

[1b] Pessimistic assumptions for capital and operating costs.

[2a] Baseline gas-fired plant with CO_2 output under high pressure (15 megapascals [MPa] or 2,175 pounds per square inch [psi]).

[2b] Same as baseline plant, but with improved capital and construction costs reflecting an "nth" plant.

[2c] Gas and electricity with CO_2 output under high pressure (15 MPa or 2,175 psi).

[2d] Gas and electricity input with CO_2 output under low pressure (0.1 MPa or 14 psi) and assuming zero-cost O_2.

[3a] Power input scaled to 5 MW.

[3b] Power input scaled up to 500 MW.

The two Socolow et al. (2011) systems have been normalized to a 25-year lifespan (rather than 20 years) and represent a baseline technical feasibility study; the four Keith et al. (2018) models are based on a pilot plant; the two Fasihi et al. (2019) models are developed based on the other models presented; the Lackner (2009) model is theoretical and assumes a lifetime of 10 years.

Source: Fasihi et al. (2019).

ENDNOTES

1. While oceans are the largest natural sink for CO_2, this paper focuses only on terrestrial carbon removal approaches.
2. This estimate of potential accounts only for the direct impact of carbon sequestration and not other possible climate impacts from trees, such as reduced albedo, energy redistribution due to evapotranspiration, volatile organic carbon (VOCs), or emissions of other greenhouse gases. The net effects of these noncarbon climate effects from tree restoration are regionally variable and highly uncertain for the United States, though most sources agree that tree restoration in the eastern United States has a net cooling effect on the climate (Popkin 2019; Bright et al. 2017; Bonan 2008; Snyder et al. 2004). This approach differs from that employed by Fargione et al. (2018), which discounted carbon sequestration rates in coniferous forests by 50 percent to account for the reduction in albedo associated with conifer restoration. In our view, the net magnitude and even directionality of noncarbon climate effects from tree restoration is not sufficiently resolved in the literature to support such a discount factor.
3. Poorly stocked forests were included in the restocking potential estimation only where forest cover exceeds 25 percent, in order to avoid double-counting with potential opportunities for reforestation (Sohngen unpublished). Restocking potential was only quantified for the eastern United States (North and South regions, according to Oswalt et al. 2014), where patterns of carbon uptake and storage in forests are expected to remain relatively unchanged under most climate warming scenarios through 2050, without the accelerated negative effects of wildfire, disease, and other disturbances anticipated to occur in western forests (Vose et al. 2012). Some of this carbon removal potential may also be accessible with forest management interventions that do not affect tree density, such as selectively harvesting to increase a forest's structural complexity (Ford and Keeton 2017) or increasing tree species diversity within a forest (Woodall et al. 2011).
4. Increasing tree density on timberlands would continue a decades-long trend: from 1987 to 2007, U.S. timberlands increased in density by an average of 0.60 percent per year (Rautiainen et al. 2011). However, it is unclear whether this rising density has impacted all timberlands equally, or whether it has been concentrated in well-stocked, high-value productive timberlands. The estimate of carbon removal potential from restocking eastern timberlands assumes no net increase in tree density under business-as-usual conditions. Assuming baseline restocking rates of 0.60 percent per year across understocked forests would only reduce the average carbon removal potential by less than 15 $MtCO_2$ per year.
5. Riparian buffers may offer additional carbon sequestration potential on croplands, but the magnitude of potential for this practice has not been estimated in the literature.
6. In systems where trees are likely to be harvested for timber, such as current timberlands that are restocked to full density or some silvopastures, landowners have clear private benefits to gain from tree restoration in the form of timber sales. Even so, in many cases upfront costs exceed the present value of these future private benefits for landowners, which would not begin to accrue until 15–25 years after planting.
7. Funding estimate is based on per acre establishment and maintenance costs adapted from Bair and Alig (2006), multiplied by the number of acres included in the technical potential for each tree restoration approach. Maintenance costs are assumed to begin the year after establishment, with 5 percent of all acres being established in each year. The low end of the funding estimate assumes that all reforestation occurs via natural regeneration; the high end assumes that all reforestation requires active replanting. For more details on cost assumptions, see Figure 5.
8. Carbon removal benefits are assessed using the current-year social cost of carbon as published by the U.S. Environmental Protection Agency under the Obama administration in 2016. The social cost of carbon is expected to increase through 2050 and beyond, which would increase the economic value of public benefits compared to what is presented here. The comparison with the present value cost of tree restoration is made using a consistent discount rate.
9. Notably, other analyses based on Forest Inventory and Analysis (FIA) data have found significantly larger opportunities for tree restoration on federal lands than these conservative estimates (Sample 2017; U.S. Forest Service unpublished; Wear and Coulston 2015). Those analyses, however, did not account for background rates of natural regeneration or minimum area requirements for reforestation projects to be feasible. Further analysis may help reconcile the differences between previous findings based on FIA data and more recent findings based on remotely sensed geospatial datasets.
10. This level of funding is based on establishment costs for active replanting on forest land (Bair and Alig 2006) multiplied by the total acreage available for reforestation on federal lands (Cook-Patton forthcoming), with the range of funding needs accounting for the lowest- and highest-cost regions. Establishment costs for forest land are used in calculating total costs on federal land because these reforestation opportunities are assumed to occur mostly on postdisturbance sites that still maintain woody debris—rather than on previously cleared land, as is assumed for nonfederal reforestation opportunities. The federal funding need for maintenance costs on federal lands is assumed to be zero, as forest management is generally covered through in-kind contributions from the U.S. Forest Service.
11. In addition to chemical separation, there are also cryogenic processes in which the carbon dioxide is removed via freezing, and processes involving membranes, which include the exchange of ions and reverse osmosis (Sandalow et al. 2017).
12. For more information, see Mulligan et al. (2018c).
13. This range is for the lower-bound solid sorbent (excluding the lowest bound of that estimate) and upper bound for a natural-gas-powered liquid solvent capture costs. This range does not include estimated costs for a liquid solvent system that is based on solar photovoltaics and electrolytic hydrogen, which is substantially higher, as noted in Box 3.

14. If $30 million per year were allocated to this phase for a decade, the National Academies estimate that 30 projects per year in several areas could be funded for three years with $1 million per year (NAS 2018a).
15. In addition to chemical separation, there are also cryogenic processes in which the carbon dioxide is removed via freezing, and processes involving membranes, which include the exchange of ions and reverse osmosis (ICEF 2018).
16. For example, in 2017, the U.S. electricity generation sector created 25 quads of waste heat, and while not all of it is at a suitable temperature for DAC, a significant portion is a candidate for DAC use. ICEF et al. (2018) suggest that just 1 quad of waste heat could supply sufficient thermal energy for a 150 $MtCO_2$/year DAC facility. Climeworks and Global Thermostat already use waste heat to regenerate their sorbent (ICEF et al. 2018).
17. Federal procurement could also be for concrete and aggregate. While this would not be a primary means for scaling direct air capture, it could still support up to 3 million metric tons of DAC capacity (Larsen et al. 2019).
18. Direct air capture CO_2-EOR operations could generate $110–$165 per ton from the sale of oil (assuming two to three barrels of oil produced per ton of CO_2 captured and injected and the current $55 per barrel price of oil), and capture the $35 per ton tax credit for CO_2-EOR under 45Q. The combined $145–$200 per tCO_2 could compare favorably to costs of some direct air capture systems.
19. One ton of CO_2 is converted to 88.1 gallons of diesel based on molar and mass conversions. One gallon of diesel production from CO_2 costs $8.91 based on assumed Fisher-Tropsch efficiency of 85 percent (adopted from (Tremel et al. 2015). CO_2 can be converted to methanol for an estimated $3.74 per gallon or $718 per ton captured CO_2. Methanol can be sold at a market price of $1–1.50 per gallon or for $288 per ton captured CO_2 (adopted from Tremel et al. 2015).
20. The estimated cost of conversion ($719 per ton) less the product revenue ($355 per ton) equates to a $364 subsidy required just to convert a ton of CO_2 to fuel. This compares to $100–$180 per ton required to incentivize direct air capture with storage.
21. This estimate does not include avoided upstream emissions from synthetic fertilizer production or changes in nitrous oxide (N_2O) emissions from cropland soils as a result of soil management practice implementation or the addition of nitrogen-fixing crops. It also excludes any mitigation feedback effects (positive or negative) from albedo changes.
22. This acreage target is consistent with establishing 5,000 sampling sites nationally across cropland and grasslands for each of ten different soil management practices (Conant and Paustian 2002). This is the minimum sampling size recommended to estimate average levels of soil carbon stock change with 95 percent confidence within each of the USDA Major Land Resource Areas (Spencer et al. 2011). These sites could ideally be co-located with existing NRI sites, which are each 160 acres (Nusser and Goebel 1997).
23. This number considers only mineralization via construction aggregate production; assumes use of basalt, which can contain up to 25 percent CO_2 based on (NAS 2018a); and assumes linear scale-up from 0 to 33 percent market share in 2050.
24. Suitable rocks are those with sufficient alkalinity, usually in the form of Ca or Mg, and include mantle peridotite, basaltic lava, and ultramafic intrusions that are generally found deep in the earth's interior, but have been brought to the surface in some locations (NAS 2018a).
25. Carbon sequestration rates are initially high but fluctuating (peaking at 8 tCO_2/acre/year and then declining to 1.7 tCO_2/acre/year) in the first five to seven years after crop planting. The initially high levels are due to establishment of the plant and carbon sequestration associated with its growth. In the longer term, sequestration rates level off to eventually include only net carbon additions to the soil, and are expected to be on the order of 0.5–0.7 tCO_2 per acre per year (de Oliveira et al. 2018; Deng et al. 2016).
26. Depending on how they are cultivated, the data show that annual wheat varieties can be a small carbon sink or a CO_2 emitter (Chi et al. 2017).
27. There are two main ways to develop perennial versions of major crop species: (1) hybridization, which includes crossbreeding conventional crops with related perennials, or (2) domestication, which includes identifying perennial analogs of annuals and breeding them to produce higher yields over time (Crews and Cattani 2018).
28. A rotation extension of less than 25 years, as considered in other analyses of this pathway (e.g., Sohngen and Brown 2008), would sequester incremental carbon at a lower rate and remove less total carbon than the scenario considered here.
29. Assumes 85 percent capacity factor and $800 per ton (of annual capacity) average capital cost.
30. Energy inputs may come from forms other than electricity. For example, natural gas with capture could provide thermal energy.
31. This includes 249 million acres planted with corn, soy, wheat, cotton, sorghum, barley, sunflower oilseeds, and rice (USDA 2019b).
32. Assumes net removal of 1.13 tCO_2 per MWh generated, cost of BECCS power generation of $119 per MWh, and a subsidy required to cover the difference with solar photovoltaic levelized cost of power of $30 per MWh.
33. Assuming an average cost to the federal government of $10 per ton for tree restoration, $40 per ton for agricultural soil carbon, and $50 per ton for extended timber rotations.
34. Assuming the same cost/ton in the previous notes as well as $40/ton for mineralization, $15/ton for enhanced root crops, and $70/ton for BECCS and wood waste preservation.
35. Even though an extensive natural gas pipeline system is already in place in the United States, CO_2 pipelines have different design requirements to accommodate the higher pressures that CO_2 is under, and thus are not interchangeable.

36. A 6 percent increase in corn productivity would on average produce about 10 more bushels per acre, or about 0.26 metric tons per acre (Widmar 2018). Assuming a "carbon opportunity cost" for corn production of 2.1 tCO_2 per ton of production, the increase in productivity would theoretically avoid 0.54 tCO_2/acre for every year that the added productivity is maintained (Searchinger et al. 2018). Because of elastic demand for corn, however, the actual carbon opportunity cost would likely be about 10–20 percent lower, thereby avoiding annual emissions of 0.45–0.49 tCO_2/acre (Searchinger et al. 2015; Berry 2011). This estimate of avoided emissions is comparable to the average carbon removal rate attributed to cover crops (Poeplau and Don 2015).
37. The 7 percent discount rate used here is consistent with the assumption by the Office of Management and Budget (OMB) of pretax rates of return on private capital. This rate has been used for cost-benefit analyses of most federal programs since 1992, pursuant to OMB Circular A-94.
38. In a liquid solvent direct air capture process, an aqueous solution (potassium hydroxide solution) reacts with the carbon dioxide from the air to form water and potassium carbonate. The potassium carbonate solution is then reacted with calcium hydroxide to form a precipitate of calcium carbonate. Water is removed from this precipitate and then is heated to about 900°C to form solid calcium carbonate and a high-purity carbon dioxide gas (NAS 2018a). In a solid sorbent system, air is blown through a solid adsorbent that is contained within an air contractor. The solid adsorbent adsorbs the carbon dioxide, emitting CO_2-depleted air in the process. It is then heated or vacuumed to release the carbon dioxide from the adsorbent. The adsorbent is then regenerated.

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ABOUT WRI

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Our Challenge
Natural resources are at the foundation of economic opportunity and human well-being. But today, we are depleting Earth's resources at rates that are not sustainable, endangering economies and people's lives. People depend on clean water, fertile land, healthy forests, and a stable climate. Livable cities and clean energy are essential for a sustainable planet. We must address these urgent, global challenges this decade.

Our Vision
We envision an equitable and prosperous planet driven by the wise management of natural resources. We aspire to create a world where the actions of government, business, and communities combine to eliminate poverty and sustain the natural environment for all people.

Our Approach
COUNT IT
We start with data. We conduct independent research and draw on the latest technology to develop new insights and recommendations. Our rigorous analysis identifies risks, unveils opportunities, and informs smart strategies. We focus our efforts on influential and emerging economies where the future of sustainability will be determined.

CHANGE IT
We use our research to influence government policies, business strategies, and civil society action. We test projects with communities, companies, and government agencies to build a strong evidence base. Then, we work with partners to deliver change on the ground that alleviates poverty and strengthens society. We hold ourselves accountable to ensure our outcomes will be bold and enduring.

SCALE IT
We don't think small. Once tested, we work with partners to adopt and expand our efforts regionally and globally. We engage with decision-makers to carry out our ideas and elevate our impact. We measure success through government and business actions that improve people's lives and sustain a healthy environment.