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EXECUTIVE SUMMARY

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

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This is the executive summary of a Working Paper. The full Working Paper can be accessed at www.wri.org/publication/carbonshot-federal-policy-options-for-carbon-removal-in-the-united-states.

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.

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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

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.

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.
   - 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 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.

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.

- **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).

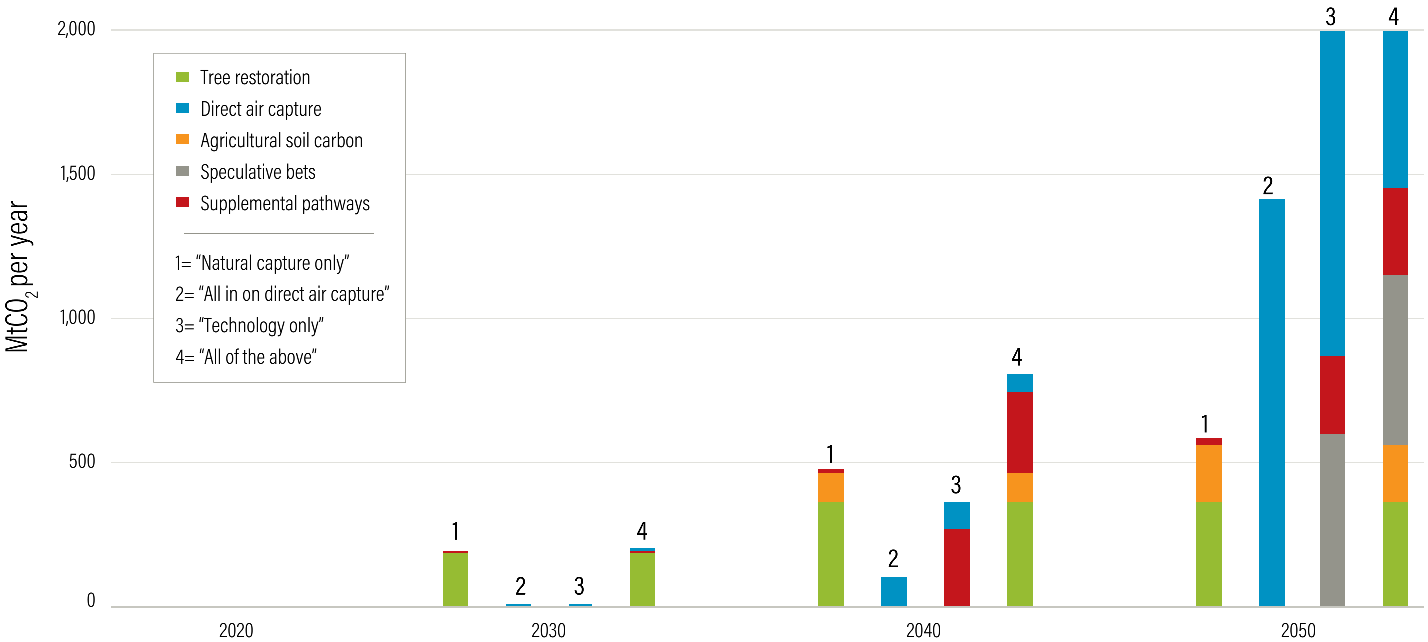
Similarly, Larsen et al. (2019) found a residual need for roughly 2 $GtCO_2$ per year in carbon removals to reach carbon neutrality by 2045. Considering a global need for as much as 10 $GtCO_2$ (or more) per year in carbon removals by 2050 and the clear importance of U.S. leadership in global mitigation 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.

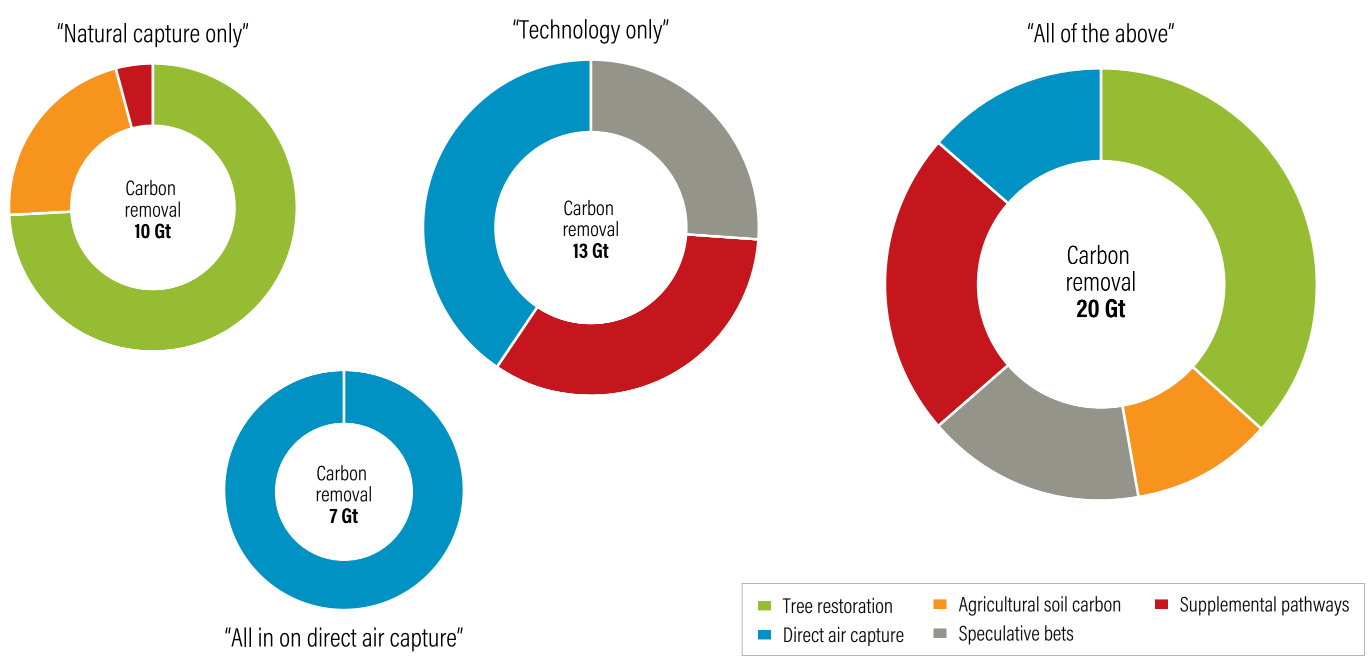
- **Tree restoration**: 180–360 $MtCO_2$ per year by 2040, sustained through 2050. This range represents tree restoration on one-third to two-thirds of suitable acres, given the possibility that landowner preferences may limit tree restoration in some portion of the available area.
- **Direct air capture**: 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

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.

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.

- **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.

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ABOUT WRI

World Resources Institute is a global research organization that turns big ideas into action at the nexus of environment, economic opportunity, and human well-being.

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.

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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.

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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.

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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.