RESOURCES
for the FUTURE

Policies for Scaling Up Carbon Dioxide Removal in the United States

Issue Brief 24-01 by **MIchael Toman**, **James Boyd**, **Alan Krupnick**, and **Emily Joiner** — April 2024

Carbon dioxide removal (CDR) involves the application of chemical or biological processes by which carbon dioxide (CO_2) can be removed from the atmosphere and stored in different reservoirs. Those reservoirs include soils, oceans, underground (geologic) storage sites, long-lived wood products, and living biomass like forests.

The 2015 Paris Agreement under the auspices of the 1992 United Nations Framework Convention on Climate Change established the aim of limiting the global average temperature increase from global emissions of greenhouse gases (GHGs) to less than 2.0°C, and as close to 1.5°C as possible, to limit dangerous impacts from climate change. Achieving that aim requires a concerted international effort to reduce GHGs to zero by mid-century. Many analysts have concluded that achieving the Paris temperature limits is infeasible without major increases in CDR, even with aggressive measures to limit GHGs (which have not yet been achieved).[1] Furthermore, net negative emissions removal (above and beyond what is achieved by a net-zero economy) will be necessary to reduce the stock of atmospheric CO_2 if, as is currently feared, emissions "overshoot" the trajectory for achieving the temperature limits.

Smith et al. (2023) describe the lack of national goals for CDR around the world, and the lack of adequate policies to engender rapid and significant advances in CDR capability followed by large-scale installation of CDR. In what follows we summarize what we believe are needed innovations in US CDR policy to achieve these goals.[2] A few basic principles underlie the policy suggestions. Public sector support for CDR research, development, and demonstration is needed. However, as technologies mature, public sector support should be scaled back in favor of policies relying on private sector incentives to finance the major buildup in CDR capacity needed. Policy should be based on technology performance and cost of CO_2 removal across a portfolio of approaches. However, negative side effects also must be identified and addressed in a timely way. Finally, CDR policy should be designed to take advantage of benefits from coordination with GHG mitigation measures.

1. Carbon Dioxide Removal Technologies and Costs

ARI (afforestation, reforestation, and improved forest management) consists of actions taken to expand the forest carbon sink, including carbon stored in soils. It also includes carbon stored in long-lived wood-based products.[3] ARI cost estimates range from $10–$100/

---

[1] Smith et al. (2023); Coalition for Negative Emissions (2021); Environmental Defense Fund (2021); Committee on Developing a Research Agenda for Carbon Dioxide Removal and Reliable Sequestration et al. (2019); IPCC (2018). These sources also provide background on the temperature goals; in addition, see IPCC (2018).

[2] These findings are based on research contained in a recent RFF report (Boyd et al. 2024).

[3] Additional carbon could also be stored in agricultural soils, but both the amount of feasible storage and its permanence remain unclear (Toman et al. 2022).

tCO_2 stored.[4] Within this range, there is no central cost estimate: forest-based CDR costs vary greatly because of differences in forest features and forest sequestration strategies (e.g., afforestation vs. changed harvest practices). The opportunity costs of land-use conversion to forests (e.g., its value in alternative uses, such as agriculture or range) and changes in forest management (e.g., the commercial opportunity costs of delayed harvests) also vary significantly.

BEC (bioenergy with carbon capture) is the production and use of plant biomass as a feedstock for supplying energy, through either combustion or fermentation and refining into fuel. BECCS (bioenergy with carbon capture and storage) adds transportation (by pipeline or other means) and long-term underground storage of the CO_2. Carbon capture and storage (CCS) is used to remove CO_2 from flue gas using various chemical reactions. Fuss et al. (2018) estimate that BEC via combustion costs \$80–\$200/tCO_2, without specifying feedstock. Sanchez et al. (2018) estimate that capture with bioethanol fermentation costs \$30/tCO_2, though there are also costs associated with producing the bioethanol from biomass feedstocks.

BiCRS (biomass carbon removal and storage) involves the capture of atmospheric carbon by plants, followed by putting the plant biomass in locations that inhibit decomposition, such as deep underground or deep in the ocean. Another BiCRS approach is ocean iron fertilization to promote phytoplankton CO_2 uptake; the storage occurs when the phytoplankton die and fall to the ocean floor. BiCRS costs are not as well-documented. Costs of transport from biomass sources to storage sites in the United States are \$20–\$40/tCO_2 (Stolaroff et al. 2021). A recent study estimates the cost of “wood vault” storage, where the decomposition of woody biomass is prevented via anaerobic containment options, to be \$10–\$50/tCO_2 (Zeng and Hausmann 2022).

DAC (direct air capture) uses chemical processes to remove CO_2 directly from the air. DACCS (direct air capture with carbon storage) adds transportation (by pipeline or other means) if needed and long-term underground storage of the CO_2. Because DAC facilities are designed to remove CO_2 in concentrations found in the air, they do not have to be located near sources of CO_2 emissions but could be located near storage facilities. DAC costs for the two most common removal strategies are \$90–\$220/tCO_2 for chemical processes using solid materials to absorb the CO_2 from the air and \$150–\$600/tCO_2 for chemical processes using liquids to dissolve the CO_2 out of the air (Hong 2022; McQueen et al. 2021; Ozkan et al. 2022; Sinha and Realff 2019). The cost difference between the two methods is driven by the higher thermal energy requirements of the latter approach, excluding transport and storage costs.

There are other methods, such as pulverizing certain types of rock to enhance CO_2 absorption through natural weathering or increasing the alkalinity of the ocean. However, these methods all are at earlier stages of development.

A crucial consideration for evaluating any CDR technology is measurement of its lifecycle emissions reductions—the reductions it creates minus GHG emissions created in the course of using the technology. For ARI, BECCS, and BiCRS, this entails accounting for emissions associated with growing the biomass, and for BECCS and BiCRS, emissions associated with collecting and transporting it. For BECCS and DACCS, lifecycle emissions reduction analysis entails accounting for emissions associated with the substantial electricity used to operate a facility.[5]

---

[4] For cost analyses, see Mendelsohn et al. (2012); Nielsen et al. (2014); Busch and Engelmann (2017); Griscom et al. (2017); and Austin et al. (2020). Forest sequestration cost estimates are higher than the cost of avoided deforestation (which is an emissions reduction strategy, not CDR).

[5] Underground storage with BECCS and DACCS involves the risk of CO_2 leakage back into the atmosphere. However, available evidence (e.g., from CO_2 injection into oil and gas wells) suggests that the risk is low, with underground storage duration anticipated to be tens of thousands of years (Kampman et al. 2016).

2. Policies for Increasing Afforestation and Reforestation

Federal programs administered by the US Department of Agriculture's Natural Resource Conservation Service provide cost-shares for afforestation and reforestation.[6] Notable infusions of new cost-share money were included in the Infrastructure Investment and Jobs Act in 2021 and the Inflation Reduction Act (IRA) in 2022.[7] Other programs are designed to stimulate innovation in wood product utilization and thus expand demand for forest products that could substitute for carbon-intensive products, such as cement and steel.[8]

The design of the IRA does not ensure that funding will be directed toward afforestation, the most effective land-based CDR investment. Moreover, a large amount of financing and land use change will be needed to increase land-based CDR. For example, Wear and Wibbenmeyer (2023) conclude that under a business-as-usual scenario, the US forest carbon sink between now and 2060 will remove 0.73 gigatons per year, on average (a decline from a 2021 yearly removal of 0.84 Gt). Adding 3 million forested acres to the landscape each year for 30 years, the amount removed increases to 0.95 gigatons per year, on average. In other words, expanding US forest cover by an area roughly equal to Montana increases annual CDR relative to 2021 by only 0.11 Gt. This would cost $5–$7 billion per year (roughly $17–24 per ton of CDR).

In addition, although reforestation and afforestation are well-known processes, several obstacles inhibit their application for reliable large-scale CDR:

Additionality. To measure the performance of policies designed to increase CDR investment, quantification of the investment and resulting emissions removal must be compared with a counterfactual business-as-usual outcome. For example, suppose a forest owner claims to have produced CDR credits by delaying a harvest by 10 years. The problem is that the owner may—for entirely commercial reasons—have chosen to delay harvest anyway.

Permanence. The duration of forest carbon sequestration is inherently impermanent because of trees' natural or harvested life cycle and the potential for fire, disease, and other risks.

Leakage. Leakage refers to the possibility that a CDR action taken in one location will trigger reduced storage in another location. For example, if managers of some forests delay harvests as a CDR strategy, that can create incentives for managers of other forests to accelerate their harvests. If agricultural land is afforested or switched to bioenergy cropping, other lands may be converted to agriculture. Quantifying leakage is difficult because it is determined by complex and often global market forces.

As a consequence, forest-based CDR removal claims are often met with skepticism, even in a governmentally regulated (as opposed to voluntary) forest carbon credit program (Greenfield 2023; Elgin 2021; IEMAC 2022). Thus, the key policy challenge is to devise improved methods for evaluating and, as needed, correcting for distortions in claimed forest-based CDR removal.

---

[6] These include the Forest Land Enhancement Program, Conservation Reserve Program, Environmental Quality Incentives Program, Healthy Forests Reserve Program, and Emergency Forest Restoration Program.

[7] Infrastructure Investment and Jobs Act, Pub. L. No. 117-58, H.R. 3684; Inflation Reduction Act of 2022, Pub. L. No. 117-19, H.R. 5376.

[8] Some emissions reduction regulations also create demand for increased forest carbon sequestration by allowing forest carbon credits to offset emissions. California's cap-and-trade program allows covered sources to meet a small percentage of their emissions reduction obligations through forest carbon credits and other types of emissions credits (California Air Resources Board 2021).

3. Improving the Capabilities of BECCS and DACCS

The key immediate challenge with BECCS and DACCS is improving their capabilities to remove CO_2 and lowering their costs. Market failures associated with early-stage innovation argue for government support for research, development, and deployment. One such failure is the non-appropriability of innovation's benefits (arising from the public-good nature of new information), which depresses the incentive to undertake early-stage innovation. The US government has supported research on carbon capture methods for BECCS and DACCS, and initial investment in demonstration plants.[9] As part of this, the 45Q tax credit for carbon sequestration was expanded by the IRA to support early investment in DAC and BEC (the latter through support for CCS).[10]

A broader challenge facing BECCS and DACCS is the need to increase the scale of investment beyond early pilot and demonstration projects. Taking investments to commercial scale provides new insights through "learning-by-doing" that are crucial for improving new technologies and reducing perceived financial risks. In addition, private capital markets can overestimate the risk associated with newly developed technologies or demand a high rate of return on investment in them because it is hard to diversify their risks . A new technology then must pass through a "valley of death" with scarce investment capital to advance toward market-level application.

Policies promoting greater scaling-up of DACCS and BECCS shift the focus from support of inputs (investments) to outputs (removed CO_2). Because such investments still face have cost risks that pose a barrier to private investment, advance market commitments (AMCs) can be used by the government (and "pioneer" private investors) to purchase specified quantities of removal using an emerging technology over a specified period at an agreed price.[11] Various mechanisms, such as a reverse auction, can be used to promote efficient procurement.[12] AMCs are better than grants for technologies at more advanced stages because they give developers incentive and time to build at scale to meet the commitments for ramping up these technologies. In principle, the tax breaks in the IRA could be changed over to publicly financed AMCs in a budget-neutral way.

4. Complementary Policies

The United States appears to have a solid regulatory base for addressing health and safety risks associated with pipeline transport of CO_2 removed and its long-term underground storage.[13] Much less has been done to consider regulatory reforms in land use management to ensure the facilities can be fairly and effectively sited. An additional concern is how the costs of transport and storage can be recovered, while limiting the ability of pipeline and storage facilities to set inefficiently high prices because of limited competition. Siting both capture facilities and CO_2 pipelines raises major distributional and equity concerns related to land use,

---

[9] Carbon Negative Shot, one of the US Department of Energy's Earthshot innovation efforts, was established in 2021 to promote research and development for engineered CDR. Its goals are to achieve the $100 per metric ton cost for CDR by 2030, establish rigorous life-cycle analysis accounting, develop cost estimates for monitoring, reporting, and verification with long-term storage, and increase CDR use to the gigaton removal scale. It is most applicable to DAC, but processed pellet or ethanol BEC configurations could also fall within the scope of the innovation target.

[10] CCS also benefits from the 48C tax credit, which subsidizes the production of equipment for carbon capture, transportation, and storage alongside other clean energy products.

[11] This type of approach has been used before in scaling up other pioneer technology, including in the medical field.

[12] In a reverse auction, participating entities offering CO_2 removal would submit bids with information on their desired price per ton of removal, estimated removal capacity, assessment of removal permanence, and any pertinent details associated with transport and storage. DOE would fund proposed removal projects starting with the lowest bid price and moving through projects with higher bid prices until the appropriation for the year is fully committed.

[13] In 2022, the Pipeline and Hazardous Materials Safety Administration released specific safety measures for pipelines transporting CO_2. These rules include instituting emergency preparedness plans for existing pipelines, providing advisory bulletins on pipeline safety, and funding further research on pipeline safety through a competitive academic grant (PHMSA 2022).

but CDR cannot be effectively and rapidly scaled up without a clear legal basis and workable approach to settling land-use disputes. Pricing of CO_2 transmission services must contend with the market power these pipelines would possess, which is the rationale for regulating natural gas pipelines today. It is possible that there will also be a limited number of storage sites available regionally or nationally. Yet, firms making enormous investments in transmission and storage facilities also must have some assurance that these costs can be recovered over time.

A critical issue for scaling up CDR is the consequences for local air pollution. Capture facilities could cause some increase in nearby air pollution. More significant is the potential increase in both local air pollution and GHGs due to increased use of fossil-fired electricity generation to meet the large electricity demands of CDR facilities, at least until the grid is decarbonized. Equally worrisome is the possibility that introducing CDR could reduce pressure for decarbonization and extend the operating lives of energy and industrial facilities that already impose a heavy pollution burden on disadvantaged communities. This is a major source of opposition to CDR, and it needs to be effectively addressed before large-scale CDR investment is undertaken by ensuring the offending facilities rapidly adjust to meet much more stringent air quality standards or shut down.

5. Policy Design for Mid-Century Decarbonization

To achieve net-zero emissions within a few decades, policy designs are needed that create incentives for financing massive CDR investment. The large costs of building up both CDR and GHG mitigation capacities emphasizes the need to do so cost-effectively. A key indicator of decarbonization cost-effectiveness is the difference between the marginal social costs of CDR and GHG mitigation, accounting for all spillover effects: if the marginal costs differ, then the same degree of reduction in net GHG emissions can be achieved by doing somewhat less (more) of the more (less) expensive option.

How can incentives for massive CDR investment and overall cost-effectiveness be pursued? One hypothetical option would involve the government taxing fossil fuels and other sources of emissions in relation to their GHG emission potential per unit of output. The higher the taxes, the more mitigation this would stimulate. The government then could use the tax revenue to finance CDR using efficient procurement methods (like the reverse auction mentioned in the previous section). The government would not accept any offer to remove CO_2 at a bid price above the tax on CO_2 emissions implied by the product taxes mentioned above, since higher bid prices for CDR would imply financing CDR at an incremental cost above the incremental cost of mitigation.[14] Leaving aside the intensely negative political climate for carbon-based taxes in the United States, this approach would require considerable institutional infrastructure to process bids and monitor CDR investment to ensure they comply with the quantities of CDR offered. Moreover, what if the cost-effective amount of CDR becomes larger than the amount that could be financed with the tax revenues as net emission caps decline, reducing tax receipts, while CDR technologies become less costly? (If it is smaller, the government in theory could bank the revenue for later use, but this would be hard to accomplish in practice.)[15]

An alternative would be to use a market-based approach for mitigation—some combination of tradeable allowances and targeted taxes where allowance trading is deemed to be problematic—and then allow the private sector to produce “removal credits” by financing its own CDR investments. Each ton of CO_2 removed could be used to offset a ton of CO_2-equivalent GHG emissions, in lieu of its mitigation (or purchasing emission mitigation allowances). Similarly, a CDR credit could be used to offset a tax liability for a ton of CO_2-equivalent GHG emissions. The capability to purchase and sell removal credits would provide the needed economic incentive for CDR investments—an incentive that would otherwise not

---

[14] The government also would have to adjust bid prices to account for any external effects of CDR.

[15] Somewhat similar challenges would arise if the United States decided to pursue net-negative emissions to lower atmospheric concentrations of GHGs in the wake of overshooting temperature limits. This would require government involvement in financing the additional CDR, which otherwise is a pure environmental public good.

exist—and it would ensure that whatever net emissions target was set could be achieved cost-effectively.[16]

CDR credits would still be useful in less incentive-based regulatory systems. Suppose, for example, that mitigation efforts were prescribed by performance standards (regulations on carbon intensities of economic activities) or even technology mandates. Provided that CDR credits could be used to offset regulatory compliance requirements, they could lower the overall cost of net emissions reductions—although the prescriptive mitigation requirements would yield an overall outcome that is not cost-effective. Even if CDR also was mandated, it is possible that CDR beyond what is required could offset higher-cost mitigation requirements (and vice versa for additional mitigation).[17]

A policy of incentive-based mitigation integrated with CDR credits also highlights the costs of reducing and removing GHG emissions, which is seen to be a political liability. However, other policy designs such as mandates (caps on the prices of emission allowances and CDR credits) will only raise costs further (albeit less visibly) or interfere with achieving net zero. A related problem arises as net emissions decline and only hard-to-mitigate emissions need to be addressed. The sectors with hard-to-mitigate emissions, like agriculture, might bear considerable costs, with consequences for consumer prices. In the interest of distributional equity, the overall effects of emissions mitigation and removal costs on different portions of the population need to be carefully assessed, with other tax and transfer policies used to the extent possible to soften distributional impacts seen as inequitable. This is preferable to resorting to less explicit and costlier measures, such as subsidies for CDR (or for mitigation).

6. Summary of Policy Implications

The key immediate challenge with engineered CDR is well-targeted financing for improving the technical capabilities of the technologies and lowering their costs.

A broader challenge facing BECCS and DACCS is the need to increase the scale of investment beyond early pilot and demonstration projects. Mechanisms like advance market commitments can provide the necessary financing for scaling-up CDR investment and thereby achieve further improvements in the technologies.

Complementary policies also are needed to deal with environmental side effects, health and safety concerns, and the siting of facilities.

Design of GHG mitigation and removal policies must include effective and timely ways to address distributional and environmental justice issues.

Ultimately, the incentives for needed large-scale CDR investments will depend on the coverage and stringency of policies for GHG mitigation.

One effective way to create incentives for private investment in CO_2 removal is to set net-emission targets and allow volumes of CO_2 removal to offset GHG mitigation requirements. In general, more cost-effective outcomes will come from coordinating mitigation and removal policies using incentive-based approaches.

---

[16] Andreoni et al. (2024) use an integrated assessment simulation model to show that introduction of CDR with a carbon price reduces total revenue and thus reduces the potential to improve income distributions through progressive redistributions of that revenue. Moreover, CDR (specifically, DAC) becomes fairly inexpensive over time in their analysis, but there is a binding constraint on its total application. As a result, larger economic rents accrue to higher-income individuals who own shares in CDR companies. The authors suggest that the inequality impacts may warrant operating CDR policy separately from mitigation policy, including the use of carbon tax revenues to finance public procurement of CDR. These findings warrant further study to refine estimates of potential inequality and improvements in cost-effectiveness through CDR deployment.

[17] One version of a CDR mandate that has received some attention is the proposal by Jenkins et al. (2023) for a Carbon Takeback Obligation, which emphasizes “extended producer responsibility.” The authors suggest that all emitters be required to pay for removal of a certain fraction of their total emissions each year. The percentage would start small to reflect the still-evolving state of CDR technology and grow over time. They do not address what would be the maximum percentage of removal required or how removal and emission reduction policies might be integrated.

References

Andreoni, P., J. Emmerling, and M. Tavoni. 2024. Inequality Repercussions of Financing Negative Emissions. *Nature Climate Change* 14 (January): 48–54. **https://doi.org/10.1038/s41558-023-01870-7**.

Austin, K. G., J. S. Baker, B. L. Sohngen, C. M. Wade, A. Daigneault, S. B. Ohrel, S. Ragnauth, and A. Bean. 2020. The Economic Costs of Planting, Preserving, and Managing the World's Forests to Mitigate Climate Change. *Nature Communications* 11(1): 5946. **https://doi.org/10.1038/s41467-020-19578-z**.

Boyd, J., E. Joiner, A. Krupnick, and M. Toman. 2024. *Policy Incentives to Scale Carbon Dioxide Removal: Analysis and Recommendations*. Report 24-03. Washington, DC: Resources for the Future (February). **https://www.rff.org/publications/reports/policy-incentives-to-scale-carbon-dioxide-removal-analysis-and-recommendations/**.

Busch, J., and J. Engelmann. 2017. Cost-Effectiveness of Reducing Emissions from Tropical Deforestation, 2016–2050. **Environmental Research Letters** 13(1): 015001. **https://doi.org/10.1088/1748-9326/aa907c**.

California Air Resources Board. 2021. California's Compliance Offset Program. **https://ww2.arb.ca.gov/sites/default/files/2021-10/nc-forest_offset_faq_20211027.pdf**.

Coalition for Negative Emissions. 2021. The Case for Negative Emissions. **https://coalitionfornegativeemissions.org/wp-content/uploads/2021/06/The-Case-for-Negative-Emissions-Coalition-for-Negative-Emissions-report-FINAL.pdf**.

Committee on Developing a Research Agenda for Carbon Dioxide Removal and Reliable Sequestration, Board on Atmospheric Sciences and Climate, Board on Energy and Environmental Systems, Board on Agriculture and Natural Resources, Board on Earth Sciences and Resources, Board on Chemical Sciences and Technology, Ocean Studies Board, Division on Earth and Life Studies, and National Academies of Sciences, Engineering, and Medicine. 2019. *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*. Washington, DC: National Academies Press. **https://doi.org/10.17226/25259**.

Elgin, B. 2021. A Top Seller of Carbon Offsets Starts Investigating Its Own Projects. *Bloomberg*, April 5. **https://www.bloomberg.com/news/features/2021-04-05/a-top-u-s-seller-of-carbon-offsets-starts-investigating-its-own-projects?leadSource=uverify%20wall**.

Environmental Defense Fund. 2021. Carbon Dioxide Removal: A Must-Have Tool for the Climate Challenge. **https://www.edf.org/sites/default/files/documents/CDR%20One-Pager_Final_Nov2021.pdf**.

Fuss, S., W. F. Lamb, M. W. Callaghan, Hilaire, F. Creutzig, T. Amann, T. Beringer, et al. 2018. Negative Emissions—Part 2: Costs, Potentials and Side Effects. *Environmental Research Letters* 13(6): 063002. **https://doi.org/10.1088/1748-9326/aabf9f**.

Greenfield, P. 2023. Revealed: More than 90% of Rainforest Carbon Offsets by Biggest Provider Are Worthless, Analysis Shows. Guardian, January 18, 2023. **https://www.theguardian.com/environment/2023/jan/18/revealed-forest-carbon-offsets-biggest-provider-worthless-verra-aoe**.

Griscom, B. W., J. Adams, P. W. Ellis, R. A. Houghton, G. Lomax, D. A. Miteva, H. Schlesinger, et al. 2017. Natural Climate Solutions. *Proceedings of the National Academy of Sciences* 114(44): 11645–50. **https://doi.org/10.1073/pnas.1710465114**.

Hong, W. 2022. A Techno-Economic Review on Carbon Capture, Utilisation and Storage Systems for Achieving a Net-Zero CO2 Emissions Future. *Carbon Capture Science & Technology* 3 (June): 100044. **https://doi.org/10.1016/j.ccst.2022.100044**.

IEMAC. 2022. 2021 Annual Report of the Independent Emissions Market Advisory Committee. California Environmental Protection Agency. **https://calepa.ca.gov/wp-content/uploads/sites/6/2022/02/2021-IEMAC-Annual-Report.pdf**.

IPCC Working Group III. 2018. Summary for Policymakers. In V. Masson-Delmotte, P. Zhai, H.-O. Portner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, et al. (eds.), *Global Warming of 1.5C: An IPCC Special Report on the Impacts of Global Warming of 1.5C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Policy*. Cambridge and New York: Cambridge University Press. **https://doi.org/10.1017/9781009157940.001**.

Jenkins, S., M. Kuijper, H. Helferty, C. Girardin, and M. Allen. 2023. Extended Producer Responsibility for Fossil Fuels. *Environmental Research Letters* 18 (011005). **https://doi.org/10.1088/1748-9326/aca4e8**.

Kampman, N., A. Busch, P. Bertier, J. Snippe, S. Hangx, V. Pipich, Z. Di, et al. 2016. Observational Evidence Confirms Modelling of the Long-Term Integrity of CO_2-Reservoir Caprocks. *Nature Communications* 7(1): 12268. **https://doi.org/10.1038/ncomms12268**.

McQueen, N., K. Vaz Gomes, C. McCormick, K. Blumanthal, M. Pisciotta, and J. Wilcox. 2021. A Review of Direct Air Capture (DAC): Scaling up Commercial Technologies and Innovating for the Future. *Progress in Energy* 3(3): 032001. **https://doi.org/10.1088/2516-1083/abf1ce**.

Mendelsohn, R., R. Sedjo, and B. Sohngen. 2012. Forest Carbon Sequestration. In Fiscal Policy to Mitigate Climate Change: A Guide for Policy Makers. International Monetary Fund. Chapter 5.

Nielsen, A. S. E., J. Plantinga, and R. J. Alig. 2014. New Cost Estimates for Carbon Sequestration through Afforestation in the United States. PNW-GTR-888. Portland, OR: US Department of Agriculture, Forest Service, Pacific Northwest Research Station. **https://doi.org/10.2737/PNW-GTR-888**.

Ozkan, M., S. P. Nayak, A. D. Ruiz, and W. Jiang. 2022. Current Status and Pillars of Direct Air Capture Technologies. *iScience* 25 (4): 103990. **https://doi.org/10.1016/j.isci.2022.103990**.

Pipeline and Hazardous Materials Safety Administration (PHMSA). 2022. PHMSA Announces New Safety Measures to Protect Americans from Carbon Dioxide Pipeline Failures after Satartia, MS Leak. May 26. **https://www.phmsa.dot.gov/news/phmsa-announces-new-safety-measures-protect-americans-carbon-dioxide-pipeline-failures**.

Sanchez, D. L., N. Johnson, S. T. McCoy, P. A. Turner, and J. Mach. 2018. Near-Term Deployment of Carbon Capture and Sequestration from Biorefineries in the United States. *Proceedings of the National Academy of Sciences* 115(19): 4875–80. **https://doi.org/10.1073/pnas.1719695115**.

Sinha, A., and M. J. Realff. 2019. A Parametric Study of the Techno-economics of Direct CO_2 Air Capture Systems Using Solid Adsorbents. AIChE Journal 65(7). **https://doi.org/10.1002/aic.16607**.

Smith, S. M., G. Nemet, M. Gidden, W. F. Lamb, C. Powis, R. Bellamy, M. Callaghan, et al. 2023. The State of Carbon Dioxide Removal: A Global, Independent Scientific Assessment of Carbon Dioxide. **www.stateofcdr.org**.

Stolaroff, J. K., S. H. Pang, W. Li, W. G. Kirkendall, H. M. Goldstein, R. D. Aines, and S. E. Baker. 2021. Transport Cost for Carbon Removal Projects Biomass and CO_2 Storage. *Frontiers in Energy Research* 9 (May): 639943. **https://doi.org/10.3389/fenrg.2021.639943**.

Toman, M. A., J. Baker, R. Beach, H. Feng, E. McLellan, and E. Joiner. 2022. Policies to Increase Mitigation of Agricultural Greenhouse Gas Emissions. Washington, DC: Resources for the Future. **https://www.rff.org/publications/issue-briefs/policies-to-increase-mitigation-of-agricultural-greenhouse-gas-emissions**.

Wear, D., and M. Wibbenmeyer. 2023. *Prospects for Land Sector Carbon Dioxide Removal in the United States*. Report 23–05. Washington, DC: Resources for the Future (June). **https://www.rff.org/publications/reports/prospects-for-land-sector-carbon-dioxide-removal-in-the-united-states/**.

Zeng, N., and H. Hausmann. 2022. Wood Vault: Remove Atmospheric CO_2 with Trees, Store Wood for Carbon Sequestration for Now and as Biomass, Bioenergy and Carbon Reserve for the Future. *Carbon Balance and Management* 17(1): 2. **https://doi.org/10.1186/s13021-022-00202-0**.

Resources for the Future (RFF) is an independent, nonprofit research institution in Washington, DC. Its mission is to improve environmental, energy, and natural resource decisions through impartial economic research and policy engagement. The views expressed here are those of the individual authors and may differ from those of other RFF experts, its officers, or its directors.

Michael Toman is a senior fellow at RFF.

James Boyd is a senior fellow at RFF.

Alan Krupnick is a senior fellow at RFF.

Emily Joiner is a research associate at RFF.