Carbon Capture Technologies and Natural Climate Solutions: 1+1 = 3

Lead Authors: Kathryn Fernholz, Harry Groot

Contributing Authors: Sarah Harris, Ed Pepke, Ph.D., Tamberly Conway, Ph.D, Dave Bubser

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Dovetail Partners

528 Hennepin Ave, Suite 703

Minneapolis, MN 55403

612-333-0430

info@dovetailinc.org

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Executive Summary

Carbon removal includes any activity that results in taking carbon dioxide out of the atmosphere. Carbon removal, or carbon dioxide removal (CDR), is accomplished through natural as well as engineered processes. Natural processes for CDR include absorption by oceans, photosynthesis by plants and trees, and additions of organic matter to soils. In addition to natural ways to accomplish carbon removal, there are also mechanical and chemical methodologies referred to as Carbon Capture and Storage (CCS) or Direct Air Capture (DAC). Examples of the use of these technologies include capturing carbon at stationary emission sources (such as power plants and other significant CO_2 emitting sources) or from the general atmosphere (ambient air) and storing it underground or using the captured carbon dioxide in manufacturing or other industries.[1]

In March 2023, the Intergovernmental Panel on Climate Change (IPCC) released its Sixth Assessment (AR6) report addressing climate science and actions to limit global warming.[2] As in past reports, the IPCC continues to indicate that staying below a temperature increase of 1.5°C may be out of reach, but temperatures can be brought back below the 1.5°C threshold by the end of the century if deep emission cuts are paired with additional deployment of carbon dioxide removal techniques, including both natural climate solutions and direct air and carbon capture facilities.[3]

This report provides an introduction to technologies for CDR, the policy and regulatory context, and the role of the forest and wood products sector. The investment in natural climate solutions has a direct impact on the forest and wood products sector as it can include investments in forestry, ecosystem maintenance and restoration, tree planting, and innovative wood products as strategies for sequestering carbon in the forest, storage in the built environment, and a more circular economic model with reduced climate impacts. Addressing climate change requires a robust menu of strategies being implemented, researched, and enhanced with all due haste.[4] Combining engineered solutions like CCS and DAC with widespread adoption of natural climate solutions is an essential strategy for addressing the full scope of economic, social, and ecological goals related to reducing the negative impacts of climate change. Natural climate solutions and carbon capture technologies working together are a 1+1=3 scenario that offers the greatest potential for making individual, community-based, and global changes.

[1]The US Department of Energy (DOE) refers to six approaches to Carbon Dioxide Removal (CDR), including direct air capture (DAC) coupled to durable storage, soil carbon sequestration, biomass carbon removal and storage, enhanced mineralization, ocean-based CDR, and afforestation/reforestation. Source: https://www.energy.gov/fecm/carbon-dioxide-removal#

[2]For a webinar recording addressing information from the IPCC report, see: Carbon Removal at Scale: A Call to Action from the IPCC Report (WRI, 2023) https://www.wri.org/events/2023/3/carbon-removal-scale-call-action-ipcc-report

[3]IPCC, 2023

[4]Natural CDR and select technologies with significant short-term drawdown potential (like biochar) can be deployed immediately while the development of more technically sophisticated methods are developed. A typical "new" technology may take 20 years or more to mature, where the 2030 target date for significant carbon removal is only 7 years from the date of this report, yet 5 years past the IPCC's initial warning.

Acronyms

BECCS - Bioenergy plus Carbon Capture and Storage

CDR - Carbon Dioxide Removal

CCS - Carbon Capture and Storage

CCUS - Carbon Capture, Utilization, and Storage

DAC - Direct Air Capture

DACCS - Direct Air Capture with Carbon Storage

GHG - Greenhouse gases

NbS - Nature-based Solutions

NCS - Natural Climate Solutions

NET - Negative Emission Technologies

PyCCS - Pyrogenic Carbon Capture and Storage[5]

An Introduction to Natural Climate Solutions, Carbon Capture and Storage, and Direct Air Capture

There are many recognized land management actions referred to as "Natural Climate Solutions" (NCS) that increase carbon storage and/or avoid greenhouse gas emissions (Table 1). Enhanced and expanded application of these land uses and management actions can contribute to greater natural capacity to reduce atmospheric GHG. It is estimated that 21% of net annual emissions in the US could be offset through greater application of NCS. Almost two-thirds (63%) of the NCS potential is attributed to increased carbon storage through trees and plants, and another 30% is associated with increasing carbon storage in soils (Fargione, 2018).

Table 1. Natural Climate Solutions (NCS) via Forests, Agriculture & Grasslands, and Wetlands

Habitat Type		
Forest	**Agriculture & Grassland**	**Wetland**
- Reforestation	- Biochar	- Coastal Restoration
- Avoided Forest Conversion	- Trees in Croplands	- Peat Restoration
- Natural Forest Management	- Nutrient Management	- Avoided Peat Impacts
- Improved Plantations	- Grazing - Feed	- Avoided Coastal Impacts
- Avoided Woodfuel	- Conservation Ag.	
- Fire Management	- Improved Rice	
	- Grazing - Animal Management	
	- Grazing - Optimal Intensity	
	- Grazing - Legumes	
	- Avoided Grassland Conversion	

Source: (Rice and Galbraith, 2008)

[5]Pyrolysis is the heating of organic matter in a low-to-no oxygen environment which can generate a high fixed-carbon end product for stable (long term) carbon storage.

Many of the NCS-related land management actions (Table 1) are well-established practices that are readily deployable and scalable within available knowledge and systems of practice. One notable cross-sector solution shown in Table 1 under the Agriculture and Grassland header is biochar. Biochar is a Pyrogenic Carbon Capture and Storage (PyCCS)[6] product made from any of the organic feedstock sources listed, including woody, grassy, waste (food processing, manure, biodigestate, etc.), and even seaweed. "Biochar" (coined from the combination of the words biological and charcoal) can be used in a variety of applications – both soil-based and in manufactured products. Biochar used in soil has significant co-benefits besides carbon sequestration, such as increased water retention, increased friability in clayey soils, providing habitat for microbiota and mycorrhizae, and leveling nutrient release (Groot, 2021; Schmidt, 2021). Biochar production is a standalone end product as well as a co-product of energy production, which also gives it standing as a Bioenergy plus Carbon Capture and Storage (BECCS) solution.

In addition to nature-based ways to accomplish carbon removal, there are also mechanical and chemical methodologies referred to as Carbon Capture and Storage (CCS) or Direct Air Capture (DAC) technologies. Examples include technologies to capture carbon at stationary emission sources such as power plants and manufacturing sites where carbon dioxide is in higher concentration than the general (ambient) atmosphere. Captured carbon dioxide may be stored underground, transported via pipelines, and utilized in fossil fuel extraction operations or a variety of manufacturing processes.

Although a DAC plant launched in 2017 has been reported as the first commercial operation of this type of carbon removal technology (European Commission, 2019), it is worth noting that the science of carbon dioxide removal is much older. The carbon removal technologies supported by the US federal government today are derived from innovations developed by NASA[7] and the space program to support the survival of astronauts many decades ago. Various types of carbon capture, filtering, and recycling technologies have been operational since the US space missions of the 1960s and the latest advances are in use today on the International Space Station (ISS) as well as being developed further to support missions to Mars (Cmarik and Knox, 2019).[8]

The Role of Carbon Removal in Climate Change Mitigation

Methods of mechanical and chemical carbon capture and storage have been around for many decades, continue to evolve, and are characterized by a few leading technologies. As shown in Figure 1., geoengineering[9] strategies for carbon capture and storage are diverse and offer a number of different approaches to carbon removal and the associated potential for scaling up.

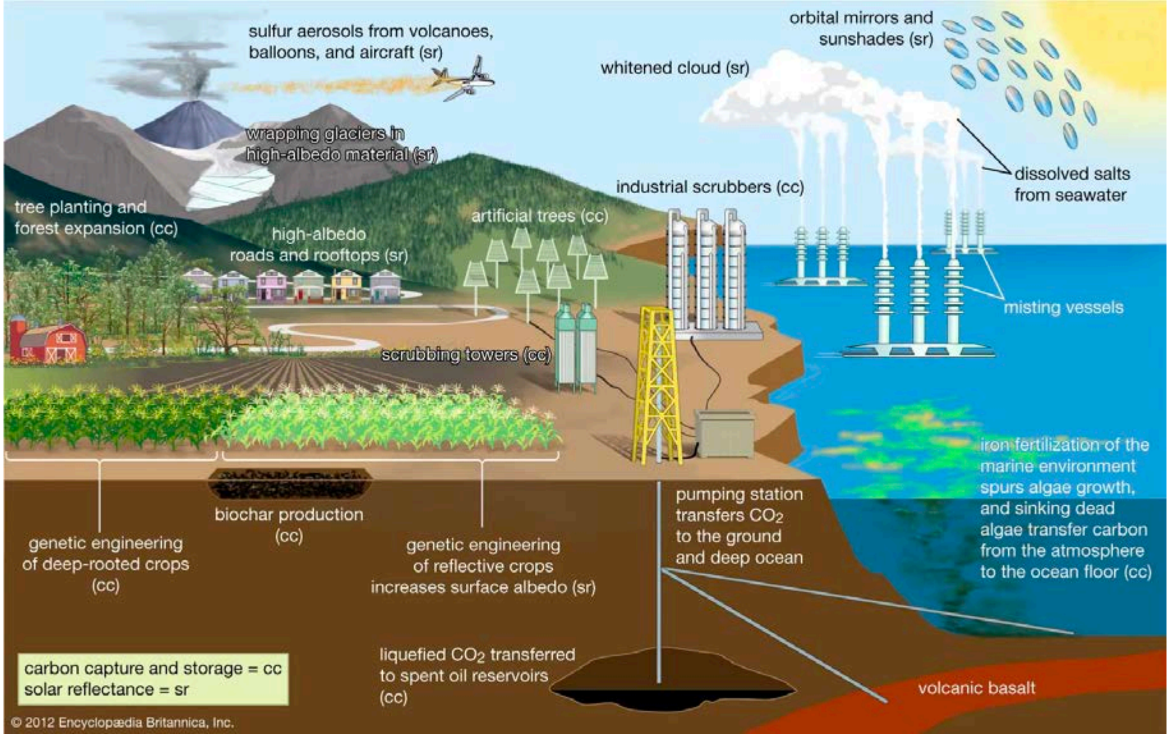
[6]PyCCS refers to the thermal treatment of biomass at temperatures of 350-900°C in an oxygen-deficient to anoxic atmosphere to generate carbonaceous products

[7]National Aeronautics and Space Administration

[8]Further discussion of the chemistry that is involved in this technology, including a classroom activity to explore the science of "Making Space Breathable" is available from the California Institute of Technology: https://www.jpl.nasa.gov/edu/teach/activity/the-air-up-there-making-space-breathable/

[9]Geoengineering is defined as " the large-scale manipulation of a specific process central to controlling Earth's climate for the purpose of obtaining a specific benefit" (Boyd, 2021).

Figure 1. Geoengineering: Various geoengineering proposals designed to increase solar reflectance or capture and store carbon.



Note: cc = carbon capture and storage sr = solar reflectance
Source: "Geoengineering", Encyclopedia Britannica, 2012

Examples of Carbon Removal Technologies and Methods:

DAC and DACCS - *Direct Air Capture and Direct Air Capture with Carbon Storage:* Using a machine for capturing carbon dioxide out of the atmosphere and injecting it deep underground (European Commission, 2019).

BECCS - *Bioenergy plus carbon capture and storage:* The combination of carbon capture and storage with the use of biomass as an energy source, and providing the potential to produce a negative emission technology (NET) (Fajardy, 2017).[10]

PyCCS - *Pyrogenic Carbon Capture and Storage:* The thermal treatment of biomass at temperatures of 350-900°C in an oxygen-deficient to anoxic atmosphere to generate carbonaceous products, including biochar, pyrolytic liquid (bio-oil), and pyrogases, offering some capacities for storage to produce negative carbon emissions (Werner, 2019).

CCUS - *Carbon capture, utilization, and storage (CCUS):* Involves the pumping of pressurized CO2 into suitable geological structures (i.e., with gas-tight upper layers to cap the buried carbon) deep underground or in the deep ocean. (Sakellariou, 2021)

Enhanced Rock Weathering - Rock weathering involves the chemical breakdown of silicate minerals to increase the capacity for a chemical reaction that results in removing carbon dioxide from the atmosphere and can be accelerated or enhanced by increasing the amount of silicate minerals exposed at any given time, such as by grinding up volcanic silicate rocks into a fine powder to increase the surface area available for reactions and applying the rock dust to croplands and other lands (Houlton 2020; Cosier 2021).

Ocean storage: Carbon dioxide removal and sequestration approaches conducted in coastal and open ocean waters, including: iron, nitrogen, or phosphorus fertilization; artificial upwelling and downwelling; seaweed cultivation; recovery of ocean and coastal ecosystems, including large marine organisms; ocean alkalinity enhancement; and electrochemical approaches[11] (National Academies of Sciences, Engineering, and Medicine, 2022; Lebling, 2022).

[10]For discussion of conditions for BECCS, see: The High Level Panel on BECCS Done Well, 2022. For a literature review addressing BECCS, see: Energy Futures Initiative. Surveying the BECCS Landscape. 2022.

[11]Electrochemical approaches to ocean-based CDR include using electricity to form carbonate rocks (limestone) from ocean water (Hirschlag and Schultz, 2021).

Each of these example methods, including Natural Climate Solutions, faces its own set of challenges as well as enabling conditions (Table 2). The estimated scale of climate benefit also varies considerably for the near and longer term.

Table 2. Enabling Factors, Barriers to Expansion, and Potential Climate Benefit of Carbon Dioxide Removal Methods

Carbon Dioxide Removal (CDR) Method	**Enabling Factors**	**Barriers to Expansion**	**Scale of Potential Climate Benefit**
Direct Air Capture (with Carbon Storage) (DAC, DACCS)	Building from existing technology; Attracting large public and private sector investments for innovation	Public opposition to pipelines and proposed storage strategies; energy intensive process	985 Mt CO2/year* *(by 2050)*
Bioenergy plus carbon capture and storage (BECCS)	Potential for negative emissions; baseload renewable electric and thermal energy production (including opportunities to decarbonize industrial processes)	Various risks for environmental, social, and economic impacts that require avoidance and/or mitigation	1,380 Mt CO2/year* *(by 2050)*
Pyrogenic Carbon Capture and Storage (PyCCS)	Low tech, utilizes diverse waste products or low-valued bio-based raw materials, use of existing equipment for application, currently available to scale-up	Sufficient markets to support expanded production; Standardization of use and application rates	1,800 Mt CO2/year**
Carbon capture, utilization, and storage (CCUS)	Existing market includes use for Enhanced Oil Recovery (EOR); geologic formations suitable for storage include depleted oil and gas reservoirs, deep saline formations, and unmineable coal seams	Public opposition to pipelines and proposed storage strategies, lack of diversified markets for utilization of captured CO2; enables continued reliance on fossil energy sources	5,245 Mt CO2/year* *(by 2050)*
Enhanced Rock Weathering	Low tech, utilizes waste products from mining operations, use of existing equipment for application	Pollution, including air quality and human health impacts from fine silicates	2,900 - 8,500 Mt CO2/ year*** *(by 2100)*
Ocean Storage	Low tech, scalable to extensive geographic areas with potential avoidance of land use conflicts	Carbon dioxide dissolved into the ocean causes seawater to acidify; risk of harm to ecosystems and coastal communities	2,000 - 3,000 Mt CO2/ year ****
Natural Climate Solutions (NCS)	Low tech, provides co-benefits to wildlife, water quality, ecosystem resilience, sustainable development, etc,; Provides carbon capture and storage and can be complemented with biochar addition.	Complexity of scaling up and customizing to local conditions, including considerations of land tenure and use rights and permanence.	23,800 Mt CO2/year *****

*Estimates derived from the Net Zero by 2050 Roadmap from IEA (IEA, 2021), available at: https://www.iea.org/reports/net-zero-by-2050 The IPCC scenarios have more use of CCUS in 2050. (IPCC scenarios generally include extensive use of both CDR and CCS, with CDR dominated by BECCS and sequestration on land, and relatively few scenarios using direct air capture with carbon storage (DACCS) and even less with enhanced weathering (EW) (AR6, Chap 3. IPCC, 2023.)

**Reported as 1.8 Pg CO2-C equivalent (CO2-Ce) per year (12% of current anthropogenic CO2-Ce emissions) by (Woolf, D., et al. 2010) 1 Pg=1 Gt; 1Gt=1000Mt]

*** Reported as 2.9 - 8.5 billion tonnes per year(Renforth, 2019).

**** Reported as 2-3 billion tons of CO2/year by WEC 2020.

*****Reported as 23.8 PgCO2e y−1 by Griscom, B., et al. 2017.

For perspective, annual global emissions can be estimated at 50 Gt CO2/year (50,000 Mt CO2/year).[12] The methodologies in Table 2 are significant, including the scale of potential climate benefit from NCS, but by themselves these strategies are not sufficient for reaching climate goals. Carbon removal and capture methods must be combined with the other strategies that directly address emission levels: energy efficiency, expanded renewable energy, and decarbonized electrification.[13]

Commercial Use of Captured CO2

The technology of Enhanced Oil Recovery (EOR) is listed in Table 2 as an enabling factor for carbon capture, storage and utilization (CCUS). Enhanced Oil Recovery includes the use of CO2 injection techniques that can add significant cost and complexity to operations, but EOR can result in the production of 30 to 60 percent more oil from a given site along with additional benefits and provides a market for captured CO2.[14] Data reported by the US Environmental Protection Agency (EPA) indicates 59% of the CO2 captured from industrial processes and 92% of the CO2 produced from natural sources is being used for EOR (US EPA, 2022). According to the same source, the top three producers of carbon dioxide captured from industrial processes were ethanol plants, natural gas processing facilities, and ammonia plants (i.e., fertilizer production). Finding commercial uses for captured CO2 contributes to the viability of these CDR technologies; however, finding uses which achieve permanence[15] while also lowering the overall atmospheric CO2 contribution of utilizing industries presents a significant challenge to the scaling of EOR.[16]

Global Development of Carbon Capture and Storage (CCS)

The Global CCS Institute's 2022 Global Status Report indicated a total of 30 CCS facilities in operation, 11 under construction, and 153 in development (Global CCS Institute, 2022). The operational capacity to capture carbon as of September 2022 was about 43 Mtpa (millions of tonnes per annum) and projected to reach 244 Mtpa if projects known to be in development become operational (Table 3). The growth in CCS reported in 2022 was an increase of 44% over the prior year; however, the Global CCS Institute estimates that 2,000 projects need to be operational by 2050 in order to achieve 2050 NetZero targets.

Table 3. CCS Facilities Globally, 2022

	Operational	Under Construction	Advanced Development	Early Development	Operation Suspended	Total
Number of Facilities	30	11	78	75	2	196
Carbon Capture Capacity (Mtpa)	42.5	9.6	97.6	91.8	2.3	243.9

Note: millions of tonnes per annum (Mtpa)
Source: Global CCS Institute, 2022.

As shown in Figure 2, the US Department of Energy (DOE) has envisioned a multi-faceted carbon management program that includes CCS and many approaches to carbon dioxide removal. The US has the most CCS development, with 34 new projects since 2021,[17] followed by Canada (19), the UK (13), Norway (8), and Australia, the Netherlands, and Iceland (6 each) (Global CCS Institute, 2022).

[12]Emissions are expressed in metric units. Pg = Petagram Gt = Gigatonne Mt = Megatonne 1 Pg=1 Gt and 1Gt=1000Mt https://ourworldindata.org/greenhouse-gas-emissions

[13]For discussion of the application of all four strategies to achieve net-zero pathways for the US, see: Williams, J. H., Jones, R., Haley, B., Kwok, G., Hargreaves, J., Farbes, J., et al. (2021). Carbon-neutral pathways for the United States. AGU Advances, 2, e2020AV000284. https://doi.org/10.1029/2020AV000284

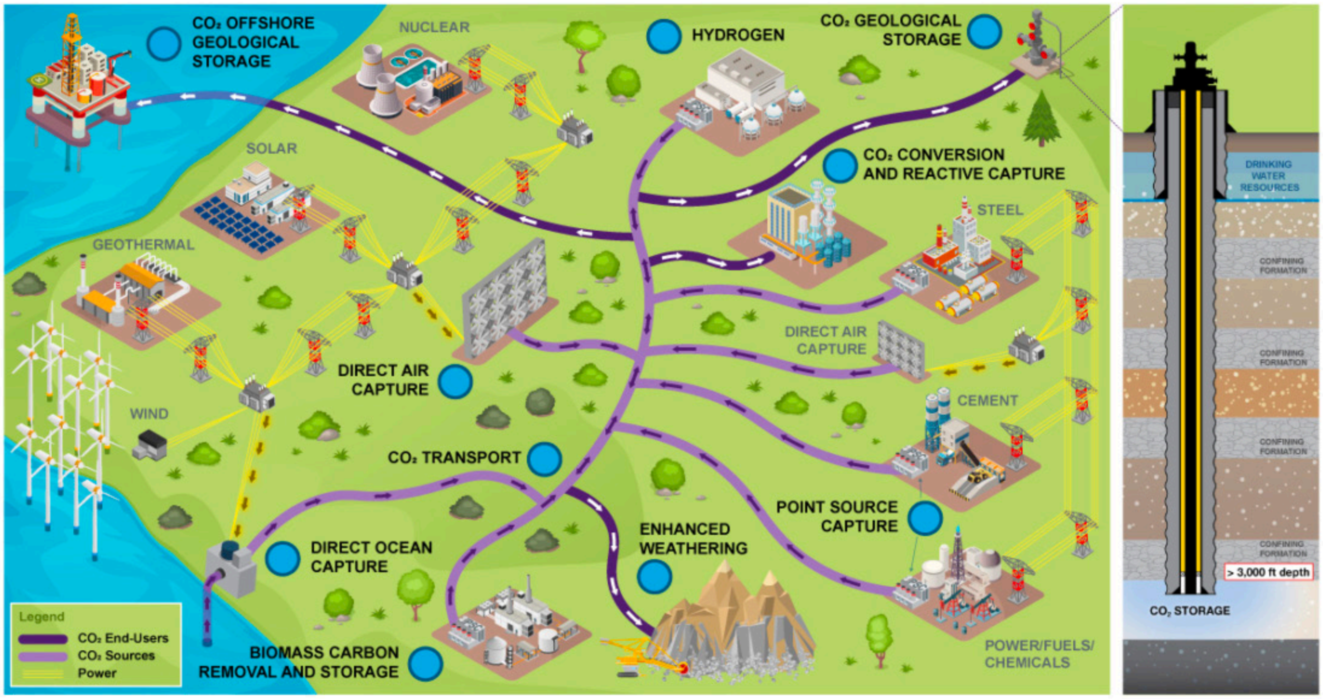
[14]https://www.energy.gov/fecm/enhanced-oil-recovery

[15]For discussion of considerations for carbon capture accounting and permanence for CCS, see: Carbon Capture and Sequestration Draft Accounting and Permanence Protocol, California Air Resources Board.

[16]Other examples of potential scalable commercial uses of captured CO2 include carbonation for beverages, manufacture of chemical and plastics, and production of cement and biofuels.

[17]US DOE has announced $2.52 billion in funding for carbon capture systems technologies, including transport and storage, and the funding includes two programs: Carbon Capture Large-Scale Pilots Program (CCLSPP) and Carbon Capture Demonstration Projects Program (CCDPP).

Figure 2. US Department of Energy, Carbon Management Programs



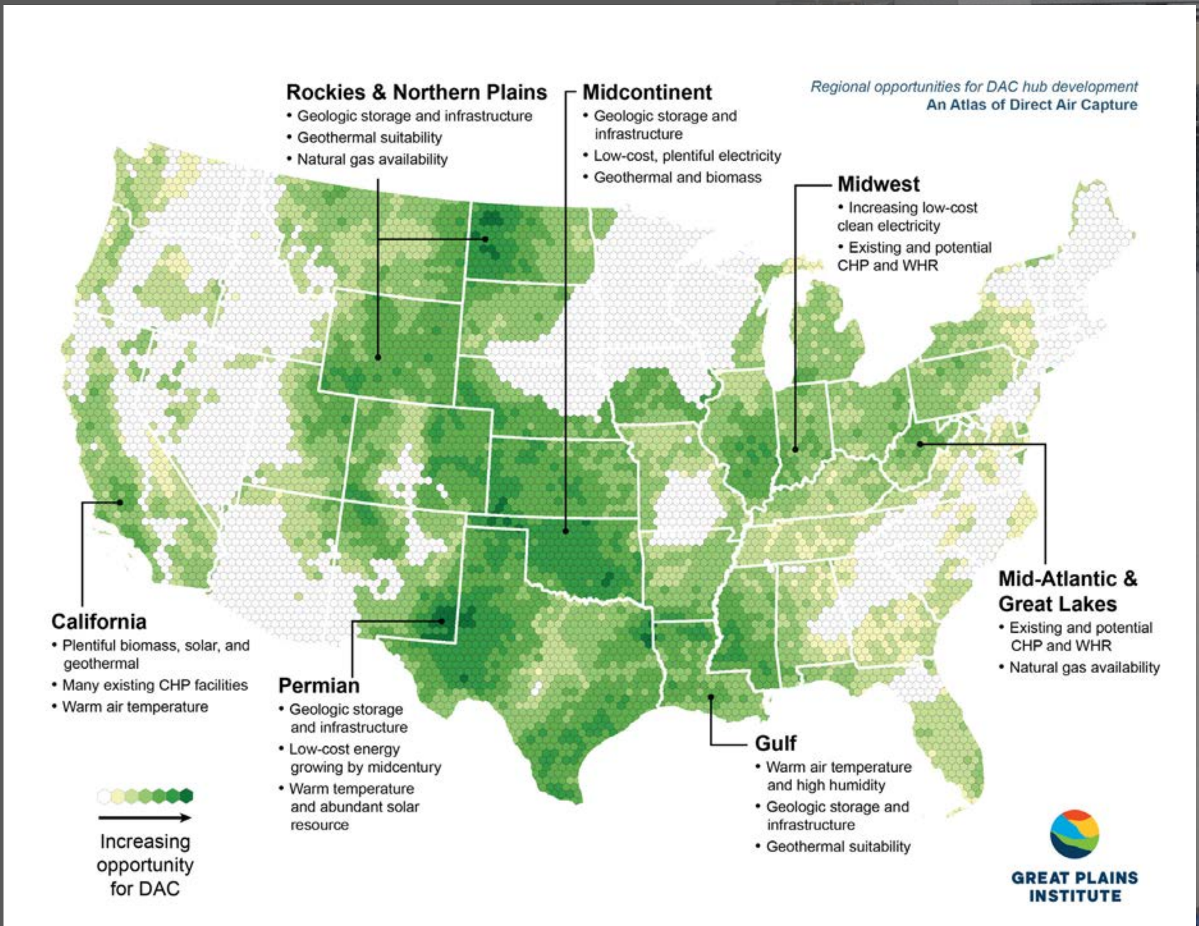
Source: US DOE, 2022.

The rate of CCS innovation and growth will be determined in part by the level of investment that occurs. The operational costs of DAC, and CCS in general, have been criticized as barriers to feasibility. In 2011, DAC was estimated to cost $600 -$1,360/tonne of CO2, and by 2018 the estimate had fallen to $94 - $232/tonne of CO2 (European Commission, 2019).[18] Research suggests that costs below $67/tonne of captured CO2 may be achievable by 2040 (Fasihi, 2019). It is estimated that one-third of the potential NCS climate benefit can be provided at a cost of $10/ tonne of CO2 or less (Griscom, B., et al. 2017).

[18]Study originally reported costs in euros and applied a fixed exchange ratio of 1.33 USD/€.

New Atlas Identifies Top US Regions for Direct Air Capture (DAC) Deployment

(1 March 2023): The Great Plains Institute (GPI) released a first-of-its-kind atlas that identifies seven regions in the US offering the best array of characteristics to house a DAC hub. The atlas examines key factors impacting regional suitability for development of DAC technology and associated infrastructure.



Source: GPI, 2023.

For analysis and mapping of global potentials for Carbon Capture, Utilization and Storage (CCUS), see: The world needs to capture, use, and store gigatons of CO2: Where and how? (McKinsey & Company, 2023)

The Policy Context

Development of CCS methodologies is occurring within the context of enabling policies including government incentives and protections. In the US, Section 45Q of the Internal Revenue Code of 1986, as amended, specifically targets CCS and eligibility for these tax credits has been extended to projects that begin construction before 2026 (Rodgers, 2021). Government policies and regulation can affect a number of aspects of CDR (Table 4).

Table 4. Regulation of Carbon Capture and Storage (CCS)

Category	Considerations
Research and Development (R&D)	Financing to address high development costs; Research oversight
Property Rights and Liability Rules	Ownership rules for subsurface storage; Liability and accountability for permanence
Monitoring/Verification	Addressing accounting and storage permanence; Alignment with emission reduction and removal targets and carbon markets and pricing
Public consultation	Social acceptability, legal obligations, and equity during research, development, and deployment

Source: Adapted from Craik, Hubert, and Daku, 2022

The policy considerations for CCS have also been recognized at the state level in the US. At least 21 states have enacted related legislation, including plans to conduct studies or prepare reports on CCS; tax incentives for CCS equipment, property, and projects; and/or establishing state-level geological regulations for storage (Cleveland, 2017). Complementary to the categories identified in Table 4, the National Conference on State Legislators reported the main areas addressed by US state legislation have included:

- liability,
- storage funds (funds established for the long-term management and monitoring of CCS storage sites),
- pore space ownership (e.g., establishing that the subsurface pore space belongs to the surface owner),
- unitization (the percentage of landowners required to agree to the project before it can proceed),
- carbon dioxide ownership (who owns and is responsible for the carbon dioxide after it is injected into the ground),
- primacy (e.g., establishing that mineral rights have primacy over CCS), and
- inter-state boundary issues.

In a global examination of the policy context, the International Energy Agency (IEA) concluded that CCS policy needs to address the creation of new markets, market barriers and failures, and promotion and regulation of infrastructure; furthermore, the appropriate policy for CCS will need to evolve as the technology matures (IEA, 2012).

Carbon Removal and the Forest and Wood Products Sectors of the US and Canada

The investment in NCS has a direct impact on the forest and wood products sector as it can include investments in forestry, ecosystem maintenance and restoration, tree planting, and innovative wood products as strategies for sequestering carbon in the forest, storage in the built environment, and to contribute to a more circular economic model with reduced climate impacts.[19] The forest and wood products sector also has a role to play in technological approaches to CDR.

The US and Canada are recognized as leading in the development of CCS (Global CCS Institute, 2022). Canada's Mid-Century Long-Term Low-Greenhouse Gas Development Strategy also identifies large-scale afforestation and BECCS as approaches to achieve negative emissions as well as areas for further research along with the increased use of wood products for carbon retention in buildings (Craik, 2022). The emissions-reduction potential of BECCS in the US has been studied and estimated to represent a pathway to achieving as much as one-third of the goal of net-zero GHG emissions by 2050 (Energy Futures Initiative, 2022). The US DOE has indicated that commercial deployment of CCS is essential to meeting the nation's climate goals (US DOE, 2021).

[19] For further discussion of these connections to the forest and wood products sector see: "Carbon Storage, Credit Markets, and Forests" and "An Introduction to the Circular Economy".

Carbon removal methods that relate to forests and wood products, including BECCS, are being developed within the context of existing and adapted forestry regulations. These laws throughout the US and Canada, as well as many other parts of the world, address conservation, sustainable forestry, and the protection of ecosystems and species (Braatz, 2003; Craik, 2022; USFS, 2023). Development of CDR methodologies that expand the use of wood and bio-based products, including mass-timber and biochar, also expand regulatory considerations to include impacts occurring beyond the forest. For example, biochar use as a soil amendment has relevance to regulation affecting the use and application of fertilizers, and the expanded use of mass-timber has required updates to building codes. Federal, state/provincial, and local laws will need to be updated and kept current with emerging CDR methodologies.

Emerging forest-based technologies and growing markets for wood products can be evaluated with consideration of climate and carbon benefits, economic cost and benefit, the potential scale of impact, and overall feasibility. In addition to the direct benefits to climate change mitigation, there is also a growing understanding that NCS provides a wide range of co-benefits. Actions to implement NCS commonly provide co-benefits to wildlife populations and habitats, soil conditions, water and air resources, recreation opportunities, human health and well-being, and the provisioning of diverse ecosystem services and benefits (Drever, et al. 2021; Fargione, et al. 2018). Forestry has the potential to mitigate climate change while also advancing other societal goals – reducing the risk and devastation associated with mega-fires, improving air quality, protecting biodiversity, enhancing soil productivity, providing for clean water, and better flood control (Living Forests, 2022).

From a business and economic security perspective, the co-benefits of investment in NCS may also result in supply chain resiliency. The Wildlife Habitat Council (WHC) reviewed actions and strategies undertaken by companies throughout the supply chain, from the extraction or harvesting of raw materials to the disposal of products at the end of their life cycles, and found that companies in supply chain tiers that are more likely to directly impact biodiversity and climate are seeking NCS solutions to these operational risks while others that primarily have indirect impacts are more likely to be working to support suppliers in adopting sustainable practices (WHC, 2022). The review concluded that individual companies and organizations should engage in actions that are locally appropriate, align with existing regional sustainability goals, demonstrate a commitment to transparency, and engage in regional, industry-wide and cross-sector coalitions that can help companies meet the expectations of consumers, investors, and regulators (WHC, 2022).

Industrial Decarbonization and the Forest and Wood Products Sector

With progress well underway in reducing the emissions of energy systems (expansion of renewables, clean energy, etc.) and transportation (electrification), the next major sector that needs to reduce its contribution to climate change is heavy manufacturing. Industrial decarbonization includes the reduction of carbon emissions and implementation of carbon capture for the production of cement, steel, and other materials that contribute significantly to global emissions. Decarbonization of these production processes is essential to meeting climate change mitigation goals and forest products are part of the solution.

The world's cement industry is responsible for about a quarter of all industrial CO2 emissions, and there are pathways to reducing these emissions by 75% by 2050 through a combination of energy-efficiency improvements, alternative fuels, material substitution, and new technologies (McKinsey, 2020). Similar strategies apply to the decarbonization of steel manufacturing and other industrial processes. The "Industrial Decarbonization Roadmap" for the US identifies four key technological approaches that could result in 100% of annual CO2 emissions from American manufacturing being mitigated. The four strategies are energy efficiency; industrial electrification; substitution of low-carbon fuels, feedstocks, and energy sources (LCFFES); and carbon capture, utilization, and storage (CCUS) (US DOE, 2021).

The forest and wood products sector contributes to industrial decarbonization by providing low-carbon fuels, feedstocks, and energy sources (LCFFES). Biomass energy and biofuels are able to provide electricity generation as well as renewable thermal heat required for many manufacturing processes. Carbon storing products like biochar can also be incorporated into industrial products like concrete, wall board, plastics, and asphalt. Research demonstrates biochar's potential as an effective CO2 storing material in cement-based applications, similar to its use as a soil amendment (Akinyemi, 2020). Steel is also targeted for decarbonization and is expected to experience marketplace and production system disruption in the next ten years (McKinsey, 2023). The climate impacts of cement and steel can also be reduced by utilizing wood-based alternatives in the built environment that lower the embodied carbon associated with construction material choices (Oregon Department of Forestry, 2022).

Concerns, Criticisms, and Urgency

There are a number of criticisms of CDR technologies. Criticisms of the various approaches include concerns that it is difficult to measure, storage may not be permanent, and atmospheric benefits may not be immediate or significant. Critics also assert that the strategies are unproven, not-scalable, too expensive, and have unknown long-term risks. These criticisms and others are valid and help raise awareness about areas of necessary assessment, caution, and continued research; but, it is important to maintain focus on the urgency of the situation and the level of innovation and action required. It is consistently reported that the world needs an all-of-the-above approach to avoid the worst outcomes of climate change. Significant reductions in emissions are needed this decade and technology will need to make dramatic advances by mid-century (see sidebar).

The Benefits of Near-Term Action, IPCC 2023

Deep, rapid and sustained mitigation and accelerated implementation of adaptation actions in this decade would reduce projected losses and damages for humans and ecosystems, and deliver many co-benefits, especially for air quality and health. Delayed mitigation and adaptation action would lock-in high-emissions infrastructure, raise risks of stranded assets and cost-escalation, reduce feasibility, and increase losses and damages. Near-term actions involve high up-front investments and potentially disruptive changes that can be lessened by a range of enabling policies. (IPCC, 2023)

There is some indication that the world's citizens have moved away from a position of climate change denial as the impacts become evident in communities and personal experience (Painter, 2023). However, there is a risk of people shifting their cynicism to a position of climate change "solution denial" with an amplified skepticism of the feasibility for fixing our problems or even being paralyzed by fear at the daunting challenge (Hayhoe, 2023). At the release of the UN's 6th IPCC report in March 2023, UN Secretary General António Guterres said, "In short, our world needs climate action on all fronts – everything, everywhere, all at once." The World Economic Forum (WEF) recommends the addition of "everyone" to this statement.[20] Abundant research, experience, and science demonstrate that solutions are available to us. We (everyone) just have to do the work (everything, everywhere), and the sooner the better (all at once).

[20] https://www.weforum.org/agenda/2023/04/address-climate-emergency-everyone-everywhere-all-at-once/

Bottom Line

No one solution is sufficient to avoid catastrophic climate change and also create the world we want. Carbon dioxide removal includes a full suite of strategies from diverse natural climate solutions to technological innovations, such as carbon capture and storage and direct air capture. Current technologies are insufficient in the short term and will take longer to bring to maturity than more natural solutions that are readily and immediately available, but these are all complementary innovations that create a holistic portfolio of available actions. The technological solutions and advances in decarbonization need to be nurtured in order to help restore the carbon balance (i.e., drawdown atmospheric carbon), and the forest and wood products sector has a role to play in their development and beneficial impact in both the short and longer terms.

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