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Carbon Dioxide Removal in California

A Practical Guide for Policymakers and the Public

the climate center

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A Practical Guide for Policymakers and the Public

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Executive Summary

California is entering a pivotal moment in its fight against the climate crisis, one that demands not only accelerating the reduction of greenhouse gas emissions, but also confronting carbon pollution left behind since the Industrial Revolution. These long-lived legacy emissions will continue to impact the climate, even when society has successfully decarbonized across sectors. Removing legacy emissions is no longer optional. It is essential to restoring climate stability and safeguarding our future.

With statutory commitments to reach net-zero emissions by 2045 and net-negative emissions thereafter, California cannot rely on emissions reductions alone. The United Nations Intergovernmental Panel on Climate Change (IPCC) has made it clear that, in order to stabilize our climate, society will need to both greatly reduce emissions (45 percent below 2010 levels by 2030) and also remove hundreds to thousands of gigatons (billions of tons) of carbon dioxide already released into the atmosphere.[1]

Meeting California's goals will therefore require a coordinated, dual strategy:

1. **Accelerating decarbonization across all sectors**, and
2. **Responsibly scaling carbon dioxide removal (CDR)** to remove residual and legacy carbon emissions.

Carbon Dioxide Removal (CDR) encompasses nature-based, hybrid, and industrial methods that remove legacy emissions from the atmosphere and store them in products or in geological, terrestrial, and aquatic reservoirs. CDR is *not* the same as Carbon Capture and Sequestration (CCS), although some infrastructure and risks associated with certain CDR strategies can be similar. While CCS methods purport to capture carbon emissions at a pollution source (e.g., a smokestack), CDR aims to draw down past emissions already present in the atmosphere.

For centuries, California's forests, soils, and wetlands have removed carbon from the atmosphere. But climate stressors including wildfires, drought, pests, and land-use changes now undermine our lands' ability to durably store carbon.

At the same time, emerging industrial and hybrid CDR approaches such as direct air capture (DAC), biomass carbon removal and storage (BiCRS), and enhanced rock weathering (ERW) show potential for durable carbon storage. However, they remain

[1] https://www.ipcc.ch/sr15/

expensive, technically complex, and resource-intensive, and any effort to scale them must come with strong guardrails to protect communities and the environment.

With its ambitious climate mandates, strong research institutions, and comprehensive regulatory tools, California is uniquely positioned to develop a high-integrity, equitable model for carbon removal. Our state has the potential to build a diverse CDR portfolio that supports ecosystems, promotes durable, engineered solutions, and keeps environmental justice at the forefront.

A Portfolio Approach

CDR can be described as a ‘dial, not a switch,’[2] as estimates of how much CDR will be needed rely on how quickly society can decarbonize. In addition, no single CDR approach can deliver the volume, durability, and reliability of carbon removal California needs on its own. A successful approach will:

- **Scale proven, nature-based solutions (NBS)** such as reforestation, wetland restoration, and sustainable agricultural practices. These offer near-term, low-cost carbon removal as well as significant ecosystem and community benefits. However, they also face durability challenges and will require strong monitoring to ensure long-term performance.

- **Advance hybrid approaches** like biochar and enhanced rock weathering, which use technology to enhance natural carbon sequestration processes. Further research on impacts, scalability, and long-term outcomes is required.

- **Research, pilot, and cautiously expand industrial CDR,** including direct air capture (DAC) and biomass carbon removal and storage (BiCRS). These technologies are capable of durable carbon storage, but require strong guardrails around safety, siting, energy use, and community protection to ensure the responsible deployment of these approaches.

Policy Context

California has established ambitious goals through AB 1279 (Muratsuchi, 2022), SB 905 (Caballero, 2022), SB 27 (Skinner, 2021), AB 1757 (C. Garcia and R. Rivas, 2022),

[2] https://carbon180.org/blog/carbon-removal-and-the-path-back-to-1-5c/

and the 2022 CARB Scoping Plan. Yet California still lacks a unified roadmap for the equitable, responsible, and effective deployment of CDR.

Achieving this vision requires a coordinated effort among state agencies, tribal governments, community organizations, labor partners, academic institutions, environmental justice leaders, and responsible private-sector actors. Transparent decision-making, rigorous monitoring and verification, and genuine community participation are paramount to avoid repeating past environmental injustices from industry.

Priority Recommendations

To ensure the responsible deployment of CDR in California, The Climate Center recommends the following policy priorities for state decision-makers:

1. **Keep CDR separate from emissions reductions.** Count CDR solely toward California's dedicated carbon removal targets (7 million metric tons by 2030; 75 million metric tons by 2045), not toward the state's 85 percent emissions-reduction requirement.

2. **Strengthen Community Benefits Agreements for industrial CDR.** Include community rights of refusal and restitution, protections for frontline communities, multilingual notices and opportunity for input, and best-practice engagement standards.

3. **Adopt strict regulations on the transport and storage of carbon dioxide in all of its states.** Require science-based setback distances from industrial CDR projects and carbon dioxide pipelines, odorized carbon dioxide, and clean-energy powered operations. Uphold bans on Enhanced Oil Recovery (EOR), require strong emergency response planning and leakage remediation plans, limit transport distance, and require a full CEQA review, including cumulative impacts.

4. **Increase funding for CDR research and development.** Support studies that clarify impacts, risks, and potential pathways to scaling effective CDR solutions.

5. **Continuously fund and expand investment in nature-based solutions (NBS).** Advance AB 1757 targets to scale NBS and deliver statewide carbon removal

and resilience benefits.

6. **Refine Monitoring, Reporting, and Verification (MRV).** Ensure MRV protocols for all CDR strategies provide accurate, additional, and transparent carbon removal accounting.

7. **Develop long-term, fossil-free funding mechanisms for CDR.** Establish financing tools — such as compliance markets, extended producer responsibility, procurement, and tax incentives — that do not rely on offsets or perpetuate the use of fossil fuels.

8. **Fund ongoing partnerships with environmental justice and community organizations.** Support community engagement throughout the lifecycle of CDR projects to ensure industrial CDR delivers meaningful local benefits and centers the local community.

Financing

Today's CDR financing landscape — including voluntary markets, philanthropy, federal and state programs, and tax incentives like 45Q — has spurred early innovation. However, current financing opportunities are not enough to support the quantity and quality of carbon removal needed. Public programs with strong safeguards will be necessary to help effectively scale carbon removal while also preventing unintended consequences.

For California to continue making real progress, the state needs financing systems that are sustainable over time, prioritize community interests, and do not perpetuate the use of fossil fuels.

Path to Success

California's success in carbon removal will depend on **acting early, acting cautiously, and acting collaboratively** with various stakeholders across the state. By pairing aggressive emissions reductions with a thoughtful, justice-centered approach to CDR, the state can protect frontline communities, strengthen its economy, restore ecosystems, and demonstrate what responsible, high-integrity climate leadership looks like for the nation and the world.

Introduction

The Intergovernmental Panel on Climate Change (IPCC) concluded in its 2018 landmark Global Warming of 1.5 C Report that, in order to stabilize our climate, we must cut 45 percent of emissions by 2030 and also remove 100-1,000 gigatons (billion tons) of greenhouse gas (GHG) emissions already in the atmosphere, known as **legacy emissions**, throughout the 21st century.[3] One gigaton (Gt) of carbon dioxide is roughly equivalent to the annual carbon dioxide output of approximately 233 million gas-powered cars.[4]

As part of the **Climate-Safe California Campaign**,[5] The Climate Center has focused on rapidly scaling up nature-based solutions to draw down legacy carbon emissions. However, recent reports[6] have made it evident that nature-based solutions alone are not sufficient to achieve established net-zero and net-negative commitments. Therefore, a variety of **Carbon Dioxide Removal (CDR)** strategies, including nature-based solutions, must be deployed at scale to reach these targets and stabilize the climate.

Since the field of Carbon Dioxide Removal (CDR) is relatively nascent, it is important that community members and policymakers understand the impacts of CDR strategies before they are scaled up. While the CDR field is promising, some nascent CDR approaches carry substantial risk and are still in the early stages of design, requiring further research and development before they can be effectively deployed. Furthermore, nature-based solutions and other CDR approaches will need to work in tandem to create resilient communities and stabilize the climate.

This paper explores key topics in the world of Carbon Dioxide Removal, from various CDR pathways to potential financing mechanisms and how environmental justice must be the guiding principle for future policies and projects. The world of CDR is nuanced and complicated. Readers are encouraged to learn more about this topic after reading this paper.[7]

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[3] https://www.ipcc.ch/sr15/
[4] https://www.epa.gov/greenvehicles/greenhouse-gas-emissions-typical-passenger-vehicle
[5] https://theclimatecenter.org/climate-safe-california/
[6] https://www.pnas.org/doi/10.1073/pnas.1710465114
[7] Refer to the Further Resources section of the paper in the Appendix

The Climate Center, in partnership with Project 2030[8] and California Environmental Voters,[9] established preliminary guidelines for responsible CDR deployment as context for advocacy efforts:

1. Removing past climate pollution from the atmosphere is essential to stabilizing our climate,
2. The reduction of greenhouse gas (GHG) emissions and phase out of fossil fuels must be accelerated,
3. CDR is not a substitute for direct emission reductions,
4. CDR projects should be community-centered and designed with meaningful input from communities,
5. CDR projects should not exacerbate existing pollution and other environmental problems, and
6. Nature-based CDR is critical with its many co-benefits.

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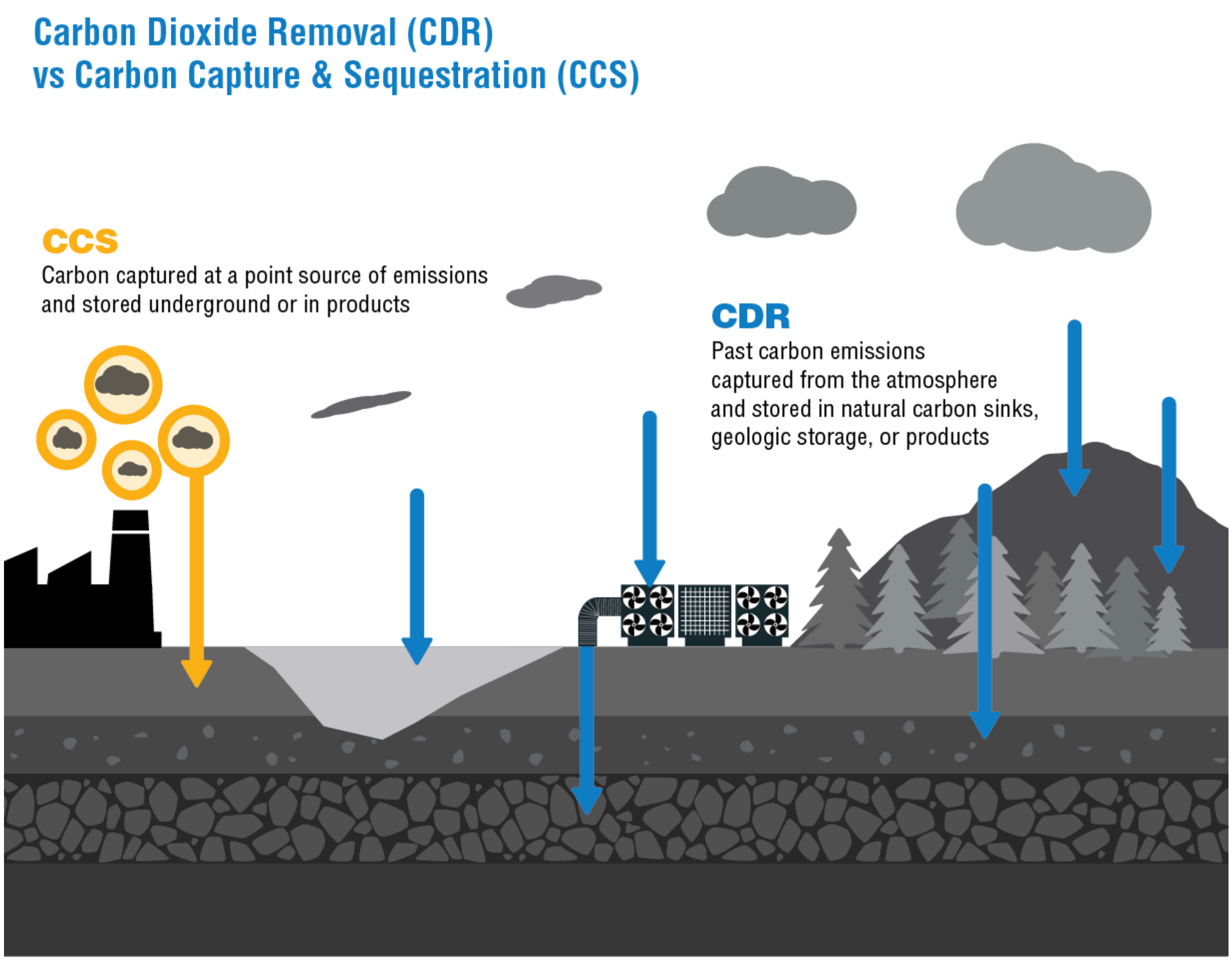
[8] https://project2030.blog/about-us/
[9] https://envirovoters.org/

What Is Carbon Dioxide Removal? Why Is It Important?

Carbon Dioxide Removal (CDR) refers to strategies that remove legacy carbon dioxide pollution from the atmosphere and store it in products or in geological, terrestrial, and ocean reservoirs. Carbon Dioxide Removal is *not* **Carbon Capture and Sequestration (CCS)**, though some of the infrastructure and risks for certain CDR strategies can be similar. Whereas CCS methods purport to capture carbon emissions at a source of pollution (e.g., at a smokestack), CDR seeks to draw down past emissions from the atmosphere, also known as **legacy emissions**, as part of a larger effort to mitigate the worst effects of climate change.



Legacy emissions have increased carbon dioxide levels above what is considered safe to support human society. Current atmospheric carbon dioxide levels exceed 420 parts per million (PPM), far above the safe 350 PPM threshold,[10] highlighting the necessity of a net-negative emissions goal. The dramatic increase in atmospheric carbon dioxide, along with the increase of other greenhouse gases such as methane (CH_4) and nitrous oxide (N_2O), is a key driver of the catastrophic climate change society faces today. Since carbon dioxide is the most common greenhouse gas[11] and has a long atmospheric lifespan,[12] carbon dioxide removal is necessary. However, CDR must be scaled up without slowing decarbonization efforts and without further harming frontline communities and the environment.

The latest climate science[13,14] is clear that CDR is "required to achieve global and national targets of net-zero carbon dioxide and greenhouse gas (GHG) emissions."[15] The IPCC report finds that, in order to limit global warming to 1.5 degrees Celsius with limited or no overshoot, CDR strategies must be deployed over the course of the 21st century.[16] Planned and current levels of CDR are insufficient to support this goal, underscoring the urgent need to invest in research and the development of a CDR portfolio.

Almost all current carbon drawdown comes from natural carbon sinks.[17] These solutions trap about 2 gigatons of carbon dioxide per year globally. In contrast, the use of fossil fuels emitted 37.4 gigatons of carbon dioxide in 2024.[18] Nature-based solutions can and must be scaled up. However, climate change is already impacting ecosystems across the world, reducing their ability to sequester the amount of carbon needed to achieve climate stabilization.[19] This demonstrates the need for a multitude of coexisting CDR pathways that can support more stable and longer-term CDR. Currently, these novel CDR projects are only 0.1 percent of drawdown efforts.[20]

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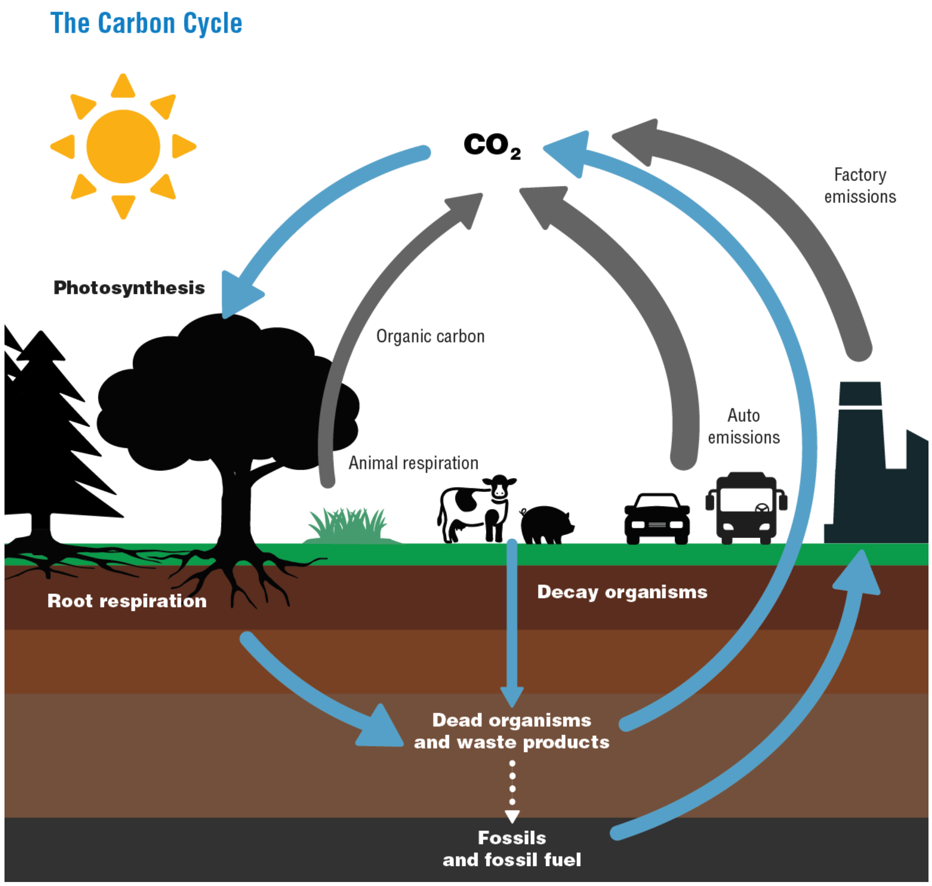
[10] 350 PPM is a generally accepted "safe" threshold of carbon dioxide concentration, however, the pre-industrial level of carbon dioxide concentration was about 280 PPM: https://www.noaa.gov/news-release/
[11] https://www.eia.gov/tools/faqs/faq.php?id=81&t=11
[12] https://science.nasa.gov/earth/climate-change/greenhouse-gases/
[13] https://wedocs.unep.org/bitstream/handle/20.500.11822/43922/EGR2023.pdf
[14] https://static1.squarespace.com/static
[15] https://www.ipcc.ch/report/ar6/wg3/downloads/outreach/IPCC_AR6_WGIII_Factsheet_CDR.pdf
[16] https://www.ipcc.ch/sr15/chapter/spm/
[17] https://carbongap.org/sizing-up-the-gap
[18] https://static1.squarespace.com/static
[19] https://www.theguardian.com/environment/2024/oct/14/nature-carbon-sink-collapse
[20] https://carbongap.org/sizing-up-the-gap

The Carbon Cycle and Sequestration



Carbon is an essential element for life on Earth,[21] as it is the core chemical in the organic compounds that make up the cells and structures of organisms. The carbon cycle is the flow of carbon through land, water, living organisms, and the atmosphere via photosynthesis as well as fire, fossil fuel use, weathering, and volcanic activity.[22] When more carbon is drawn down from the atmosphere into a natural or artificial reservoir than is released, this can be understood as a **carbon sink**. Examples of carbon sinks include forests and oceans, which absorb carbon through photosynthesis.

Carbon sources — such as the burning of fossil fuels, deforestation, and other land-use changes — release carbon dioxide into the atmosphere. In the case of fossil fuel use, the carbon dioxide released is *ancient* carbon that was sequestered naturally

[21] https://www.noaa.gov/education/resource-collections/climate/carbon-cycle
[22] https://oceanservice.noaa.gov/facts/carbon-cycle.html#transcript

millions of years ago and is being abruptly released back into the atmosphere.[23] While carbon is essential to life on Earth, carbon dioxide is a greenhouse gas with a long lifespan in the atmosphere, ranging from 300 to 1,000 years.[24] For context, carbon dioxide released during the Industrial Revolution in the 1800s is still lingering in the atmosphere today. These legacy carbon dioxide emissions increase the global atmospheric carbon dioxide level, which leads to increasing global temperatures. As the climate rapidly changes, the ability of forests, oceans, and soils to sequester carbon decreases. To counter these effects, efforts are ramping up to expand the ways atmospheric carbon dioxide can be captured and stored.

As society works to slash emissions and scale up CDR technology such as Direct Air Capture (DAC), nature-based solutions (NBS) will be critical to avoid both the worst effects of climate change and to draw down carbon dioxide in the short term while nascent CDR approaches are researched and scaled. For example, supporting healthy soil practices such as compost application and no-tillage will increase the soil's ability to sequester carbon, reduce local emissions from pesticides and fertilizer, and ensure food systems are resilient in the face of prolonged drought or other climate impacts. Although nature-based solutions (NBS) may not store carbon for thousands of years, they can still capture carbon for long periods of time and help ecosystems increase their capacity to absorb more carbon.

At this point, many ecosystems are not able to sequester as much carbon as they did previously. Some ecosystems are now a net source of carbon dioxide as opposed to a net sink.[25,26] For example, in 2001, trees globally sequestered almost 10 gigatons (Gt) of carbon dioxide per year. In 2025, forests globally sequestered less than 2 Gt of carbon dioxide. This map from the World Resources Institute demonstrates how forests globally can be either a carbon source or a carbon sink. Notably, forests in California are behaving as a carbon source primarily due to wildfire.[27]

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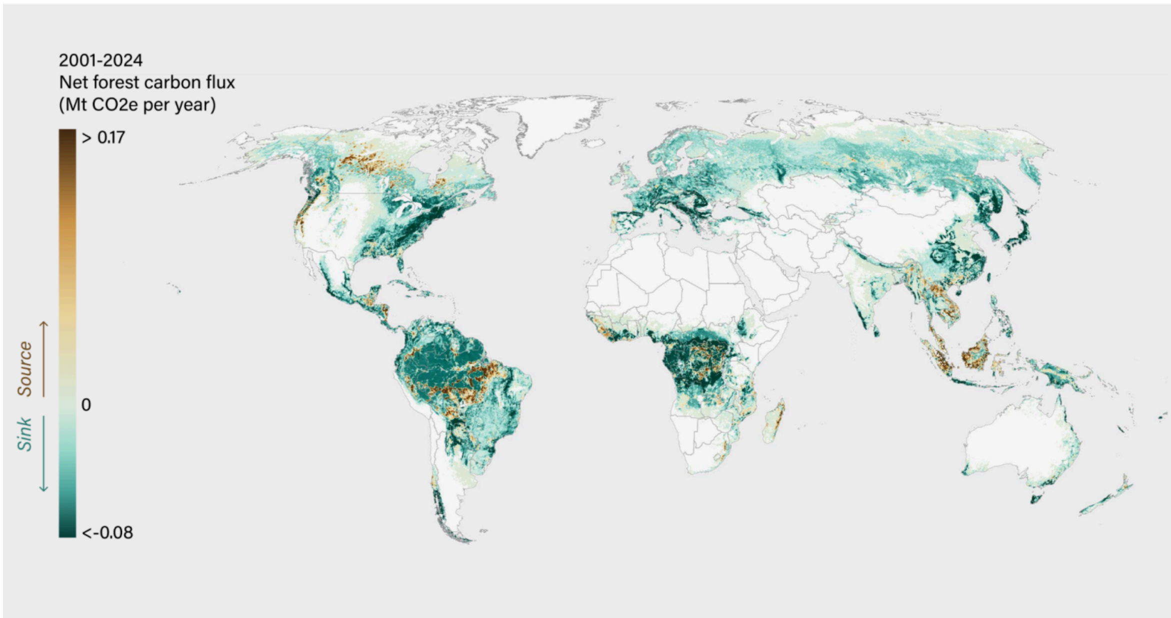
[23] https://www.eesi.org/topics/fossil-fuels/description
[24] https://science.nasa.gov/earth/climate-change/greenhouse-gases
[25] https://arxiv.org/pdf/2407.12447
[26] https://www.newscientist.com/article/2489663
[27] https://www.wri.org/insights/forest-carbon-sink-shrinking-fires-deforestation

Net carbon flux in global forests



Source: WRI, Gibbs et al. 2025 (updated with 2024 tree cover loss). WORLD RESOURCES INSTITUTE

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How Does Carbon Dioxide Removal Work?

The fight against climate change, an existential threat to life as we know it on our planet, requires a comprehensive approach that utilizes all tools available to curb the worst effects, protect communities, and sustain ecosystems.

CDR approaches can be understood as a spectrum. On one end of the spectrum are nature-based solutions, such as reforestation, that utilize the power of ecosystems to draw down carbon while also benefiting people and the environment.[28] On the other end of the spectrum are industrial CDR technologies, such as Direct Air Capture, that employ technology to remove carbon from the atmosphere. In the middle of the spectrum are hybrid approaches such as biochar or enhanced rock weathering, which use technology to enhance natural carbon sequestration processes. These approaches are further explained in Table A. These approaches also vary in terms of carbon storage time scales, costs, maturity of technology, and risk factors. **Further research and**

[28] https://www.wri.org/insights/what-exactly-are-nature-based-solutions

development is needed to identify which CDR approaches will be the most beneficial, affordable, equitable, safe, and scalable solutions.

A responsible CDR project broadly contains the following characteristics:

1. It can store carbon dioxide durably and in a way that can easily be monitored, measured, reported, and verified;
2. It is scalable and can contribute to the portfolio of CDR practices needed to achieve net-negative commitments;
3. It does not create or exacerbate societal or environmental harm and engages local communities in the planning process when appropriate;
4. It is cost-effective at scale; and
5. It ultimately results in net-negative emissions, considering a full life-cycle analysis including land use changes, upstream manufacturing of components and chemicals and downstream leaks, energy usage, and grid impacts.

CDR can be described as a 'dial, not a switch',[29] as estimates of how much CDR will be needed vary. Returning global temperatures below the 1.5 degrees Celsius threshold in the industrial era, or remaining under the 2 C threshold, depends on how fast and how much current emissions are reduced. If the world manages to stay below 1.7 C of warming, then current levels of CDR, mainly from nature-based solutions, could be sufficient. However, if the world surpasses 1.7 C of warming, then increased carbon removal capacity will be needed.[30] Given limited progress toward emissions reductions, current models suggest we will need CDR removals of 7 to 9 gigatons per year globally by 2050 to meet Paris Agreement targets.[31]

According to the 2022 California Air Resources Board (CARB) Scoping Plan, CDR levels from nature-based methods are estimated to sequester about 1.5 million metric tons (MMT) of carbon dioxide per year in California, far below the 7 to 75 MMT levels of CDR needed for the state to achieve its climate goals.[32] However, it is imperative to continue scaling up nature-based solutions, as they provide multiple CDR pathways while also creating more resilient communities and ecosystems in our rapidly worsening climate. For example, well-managed forests sequester carbon, protect

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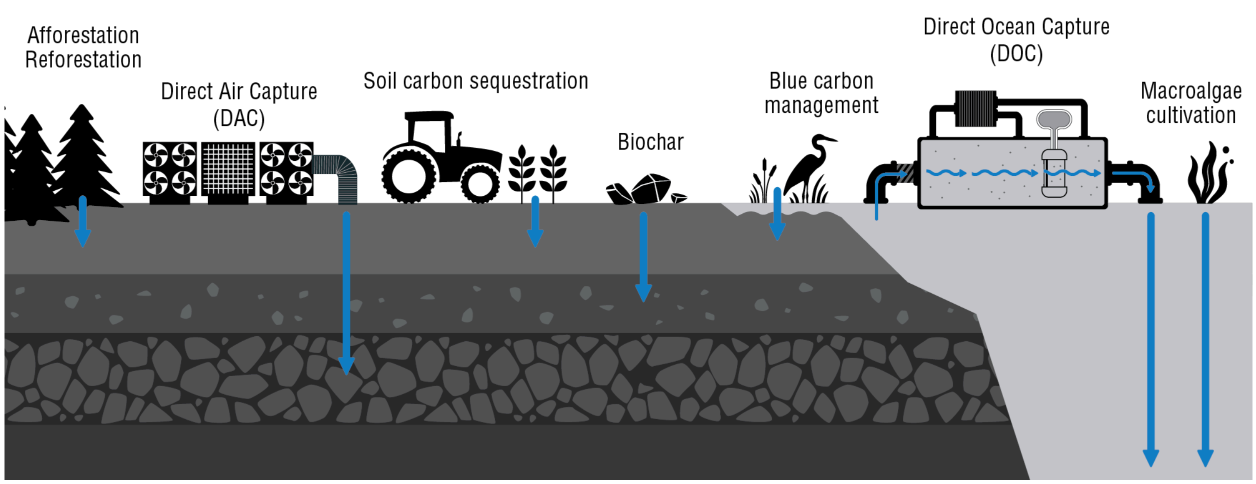
29 https://carbon180.org/blog/carbon-removal-and-the-path-back-to-1-5c/
30 Ibid.
31 https://www.stateofcdr.org/
32 https://ww2.arb.ca.gov/our-work/programs/ab-32-climate-change-scoping-plan

against deadly wildfires, and provide opportunities for recreation. Similarly, creating green streets in urban areas removes carbon, supports clean air, and protects people from extreme heat. If California's natural and working lands are properly stewarded, they could once again be a carbon sink rather than a carbon source.

Rapid decarbonization must remain central to climate action to reduce environmental injustice and limit reliance on unproven CDR technologies. As communities and countries decarbonize, funding research and development of novel CDR approaches will be critical, since it typically takes decades to develop and scale these efforts. CDR is a "valuable, but limited"[33] resource and will not solve the climate crisis on its own.

To ensure decarbonization remains central to climate action strategies, California can set separate targets for emissions reductions, nature-based solutions, and novel CDR approaches with appropriate oversight. Without proper oversight and regulation, the promise of CDR could defer critical decarbonization efforts, thereby allowing climate change to continue unchecked.

Select Carbon Dioxide Removal Approaches



Please note that The Climate Center does not endorse all Carbon Dioxide Removal pathways. The table below is intended as an overview of current CDR strategies, not as a recommendation for further research or policymaking.

[33] https://carbon180.org/blog/carbon-removal-and-the-path-back-to-1-5c/

This table highlights the benefits and risks of many of the most prominent CDR strategies, underlining the need for the utilization of a portfolio of solutions. Policymakers must carefully consider these factors when supporting a portfolio of CDR options and work to maximize co-benefits such as improving air quality, mitigating extreme heat, and increasing community resilience to climate change.[34] Lifecycle analyses of these strategies can help identify the risks and benefits of each pathway.

Table A[35]

LEGEND

COST/ T CO_2	TYPE OF TECH	STATE OF TECH
$ — $ 0-100	Nature-Based	In development (blue)
$$ — $ 101-500	Hybrid	In small-scale pilot and research state (yellow)
$$$ — Greater than $ 500	Industrial	Ready to be scaled (green)

Afforestation, Reforestation and Forest Management	**Durability**	
Forest management practices include forest conservation, afforestation (planting trees in new areas), reforestation (restoring forests with new trees), and management practices to make forests more wildfire resilient	10-100s of years	$
	Nature-Based	Ready to be scaled

BENEFITS	RISKS
❖ Clean air ❖ Preserve habitat ❖ Protect biodiversity ❖ Provide recreation opportunities	➔ Wildfire and land use change can result in carbon dioxide being released back into the atmosphere

[34] https://carbonherald.com/new-report-says-cities-have-a-key-role-to-play-in-carbon-removal/
[35] Sources cited in this table can be found in the appendix of the paper

Soil Carbon Sequestration

Using measures to restore soil carbon and sequester carbon dioxide through various land management practices, such as no-till farming, cover crops, and applying compost

Durability

30-40 years

$

BENEFITS

- ❖ Improve soil health
- ❖ Increase climate resilience for food supply chains
- ❖ Reduce fertilizer and pesticide use
- ❖ Improve water retention in soil and reduce need for irrigation

RISKS

- → Soils can become saturated with carbon and will not be able to sequester it after a certain point
- → Carbon can be released if soils are disturbed
- → MRV is difficult for soil carbon sequestration
- → No-till is typically accomplished by increasing herbicide use, which can also release greenhouse gas emissions and pose risks to community health

Blue Carbon Management

The carbon stored in sediments and plants underwater is known as "blue carbon." Restoring coastal and marine habitat (mangroves, seagrass, saltmarsh) is a way of expanding carbon dioxide capture from the atmosphere

Durability

1000+ years

$

BENEFITS

- ❖ Support local food supplies
- ❖ Provide habitat for marine life
- ❖ Support tourism
- ❖ Help reduce acidification in the ocean
- ❖ Extreme weather resiliency

RISKS

- → Proving additionality can be difficult
- → Reversibility of carbon sequestration when land use changes or is disturbed
- → MRV can be difficult

Biochar

Burning biomass feedstocks (wood, crop residues) in high temperatures and oxygen-controlled pyrolysis units. The resulting biochar is then applied to the soil and used as an amendment.

Durability 100-1,000s of years

$-$$

BENEFITS

- ❖ Improve soil quality, reduce the need for fertilizer, and provide a potential energy source when converting biomass
- ❖ Potential uses in soil remediation as part of brownfield cleanup

RISKS

- ➔ Reversible, if soil with biochar is disturbed, it can be released back into the atmosphere
- ➔ Air pollution is a concern with biochar, as the pyrolysis process can release pollutants such as particulate matter (PM), nitrous oxide (NOx), volatile organic compounds (VOCs), carbon monoxide (CO), and carbon dioxide
- ➔ MRV can be challenging
- ➔ Has the potential to release more carbon than it stores if proper guardrails are not implemented. I.e. feedstock production and upstream land use change, transportation from diesel trucks and trains, and energy needs

Enhanced Rock Weathering

Spreading crushed minerals to absorb carbon dioxide from the atmosphere

Durability 1,000+ years

$-$$

BENEFITS

- ❖ Improves soil fertility and has the potential to help reduce ocean acidification
- ❖ The reuse of mine tailings, or the waste from mining practices, allows the reuse of a waste product
- ❖ Can be integrated with other agricultural practices

RISKS

- ➔ Complicated MRV
- ➔ Potential for trace metals to end up in soil, and for the alkalinity of groundwater and rivers to change
- ➔ Greenhouse gases related to the sourcing and transportation of materials

Ocean Alkalinity Enhancement	Durability	$-$$
Adding alkaline materials, such as limestone, to the ocean to enhance the ocean's natural carbon sink capabilities	100,000 years	

BENEFITS

- ❖ Counter ocean acidification
- ❖ Co-production of hydrogen

RISKS

- ➔ Some alkaline materials have trace metals, which can accumulate in food sources
- ➔ High energy use
- ➔ Unknown risks of this type of early-in-development geoengineering may negatively impact ocean ecosystems and natural cycles

Ocean Fertilization	Durability	$-$$
Iron or nitrogen and phosphorus fertilization to the ocean to increase the growth of phytoplankton that take carbon dioxide and turn it into organic carbon	100+ years	

BENEFITS

- ❖ High potential for carbon removal (1-5 gigatons annually)

RISKS

- ➔ Only works if the organic carbon sinks to the bottom of the ocean
- ➔ Potential for mismanagement due to low-cost mining for iron
- ➔ Unintended consequences such as negative impacts on ecosystems, changes in water quality, changes in nutrient cycles, potential for deoxygenation, harmful algal blooms, and a decrease in fish populations

Kelp Cultivation and Sinking	Durability	$-$$
Intentionally growing and sinking kelp in the open ocean to store carbon dioxide in the deep ocean	100-1,000s of years	

BENEFITS

- ❖ Can help mitigate ocean acidification and improve water quality by absorbing nutrient pollution

RISKS

- ➔ May not sequester as much carbon dioxide as promised, there are unknown consequences of dumping seaweed on the ocean floor, requires a lot of mass to reach 1 Gt of carbon dioxide equivalent, and can disrupt nutrient flow in the surrounding ecosystem

Artificial Upwelling (AU) and Downwelling (AD) *Marine CDR approach that uses vertical pipes to cycle water between the surface and the deep ocean. Upwelling water supports the growth of phytoplankton, and downwelling takes this carbon-rich water down into the deep ocean*	**Durability** 10-100 years	**$$**

BENEFITS	RISKS
❖ AU could cool the surface water temperatures in warmer regions ❖ Can help increase fish populations and enhance seaweed growth	➔ AU has a large termination effect. I.e. if this is stopped, the temperature could be higher than if this tech were never used ➔ AU can lead to changes in rainfall and drought patterns and can contribute to ocean acidification ➔ Can conflict with the shipping and fishing industry at scale

Direct Ocean Capture (DOCS) *Seawater is drawn into a tank, where a small portion of the water is diverted and undergoes electrodialysis to separate water molecules into an acid and a base. The acid is added back into the tank to convert inorganic carbon into carbon dioxide, which is then passed through a chamber where the gas is captured. The carbon-dioxide-free water is held in another tank where the base is added back in to neutralize the acidic seawater. The carbon-dioxide-free, neutralized seawater is returned to the ocean.*	**Durability** 10,000 years	**$$-$$$**

BENEFITS	RISKS
❖ Easier to separate carbon dioxide than DAC due to higher concentration in water. Carbon removal can potentially counter ocean acidification, can be integrated with desalination plants	➔ Can increase ocean noise pollution, disrupt ocean ecosystems, and produce chlorine gas

Direct Air Capture (DAC) *Filtering carbon dioxide out of the air and storing it underground or using it to produce commercial products like construction materials and chemicals*	**Durability** In Materials: 10-100s years Geologic Storage: 10,000- 1,000,000s years	**$$-$$$**

BENEFITS	RISKS
❖ Siting flexibility: does not require arable land ❖ MRV is more precise ❖ Employment opportunities for former oil and gas workers	→ Extremely energy-intensive and requires the use of water → Used in other states for Enhanced Oil Recovery → Transportation and geologic storage of carbon dioxide may result in leaks that pollute local water sources, harm communities, or induce seismicity → Unlikely to benefit from economies of scale because the main cost is energy use

Biomass Carbon Removal and Storage (BiCRS) *BiCRS involves capturing carbon dioxide from plants. These plants (biomass) can be buried to store carbon or heated to create byproducts, such as biochar, bio-oil, and carbon dioxide. Carbon dioxide is stored in geologic formations or carbontech products.*	**Durability** 100-1,000s of years	**$$**

BENEFITS	RISKS
❖ Energy source for biofuels and a way to help clean up woody biomass waste from forest floors to help reduce wildfire risk ❖ Can provide economic benefit for farmers' agricultural residue	→ Without proper safeguards, feedstock sourcing can impact food security and prices due to land use requirements, result in biodiversity loss, use up water resources, increase fertilizer and pesticide use, and result in soil carbon loss → Can increase air and water pollution from transportation via diesel truck → The use of pipelines to transport carbon dioxide can be risky to local communities → The processing of biomass can increase criteria and toxic air pollution

Advantages and Challenges of Nature-Based Carbon Dioxide Removal

Scaling up nature-based solutions (NBS) is critical not only to achieve our state climate targets, as outlined in AB 1279 (Muratsuchi, 2022), but also to create resilient communities and ecosystems in the face of climate change. Sustainable agriculture practices can sequester carbon and protect crops from drought. Protecting forests can sequester carbon and reduce wildfire risk and spread. Restoring wetlands, meadows, and other ecosystems will sequester carbon and provide spaces for biodiversity, food, and recreation.

The importance of nature-based solutions has been recognized worldwide. In 2022, 190 countries signed on to the Kunming-Montreal Global Biodiversity Framework, agreeing to protect 30 percent of the world's land, coastal, marine, and inland water by 2030.[36] California has committed to the 30X30[37] goal as well, and has currently conserved 26.1 percent of its land and 21.9 percent of coastal waters as of June 2025.[38] These worldwide commitments demonstrate the importance of protecting ecosystems and scaling up NBS.

Even amid the increasing extremes from climate change, California communities can be resilient and ready if nature-based solutions are deployed at scale. Shade trees along sidewalks can protect individuals from extreme heat, carefully managed agricultural soils support resilient food networks, and conserving natural lands such as mountain meadows protects against natural disasters and provides essential recreation opportunities for all California residents.

While most CDR is currently achieved through nature-based solutions, major challenges remain.[39,40] Wildfires, drought, heat, floods, and pests are all expected to increase due to climate change, raising questions about how durable nature-based solutions are in terms of carbon sequestration. For example, when wildfires burn through forests, the carbon that was sequestered in the trees is released back into the atmosphere.

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36 https://www.nature.org/en-us/what-we-do/our-priorities/protect-water-and-land
37 https://www.californianature.ca.gov/
38 https://resources.ca.gov/-/media/CNRA-Website/Files/2025-30x30-Pathways-Progress-Report.pdf
39 https://10insightsclimate.science/year-2023/4-over-reliance-natural-carbon-sinks-risky-strategy/
40 https://10insightsclimate.science/wp-content/uploads/2023/12/10NICS-2023-Report_digital.pdf

Case Study: Nature-Based Solutions on the Sierra-Cascade Landscape[41]

Monitor Pass in Alpine County. Image by Sierra Nevada Conservancy.

Nature-based solutions (NBS) leverage the power of nature to address the climate crisis by removing atmospheric carbon dioxide and creating resilient communities and landscapes. Examples of how nature-based solutions support resilient ecosystems and communities can be found in Sierra Nevada Conservancy (SNC) funded projects across the Sierra-Cascade mountain region.

In the South Yuba River Canyon, fuel-reduction treatment and prescribed burns reduce the risk of wildfire, protecting forests and nearby communities from harm. In Butte County, a large forest restoration project after the Camp Fire helped prevent a large-scale conversion of the landscape from forest to shrubland. This project reintroduced native species and collaborated with the local Maidu tribe to incorporate traditional ecological knowledge in the reforestation project. This also demonstrates how nature-based solutions can help communities rebuild from climate disaster and protect against future climate impacts. In Alpine County, a meadow restoration project ensured the landscape did not change from a meadow to a forest. This effort helps protect hydrologic benefits, conserves habitats for a variety of plants and animals, and lowers the risk of high-intensity wildfire.

[41] https://sierranevada.ca.gov/nature-at-work-building-climate-resilience-in-the-sierra-cascade/

This has already impacted California's progress toward its climate goals. The intense wildfires of 2020 alone made up 30 percent of the state's greenhouse gas emissions and were two times greater than the emissions reductions achieved from 2003 to 2019.[42] The 2025 Los Angeles fires released more carbon pollution than all passenger vehicles in the state emit in a single month.[43]

Monitoring, Reporting and Verification (MRV) is an essential aspect of any CDR project as it can assess the efficacy of a CDR approach, therefore supporting transparency and accountability in this growing field. MRV refers to the activity of measuring carbon removal, reporting this information to buyers, and having a third party verify its accuracy. Therefore, consistency among MRV standards is critical to establishing credible carbon removal credits,[44] a challenge due to the complexity of ecosystems and the need to account for site-specific conditions.[45] Determining the additionality of NBS projects can also be difficult. For example, if a project claims it is conserving a forest that would have otherwise been subject to logging when that forest was never actually intended for logging, then there is no additional benefit to the practice.

It is important to note that NBS can be integrated into established CDR frameworks and is an important part of the CDR portfolio. To address the issue of permanence, NBS credits can be vertically or horizontally stacked. Horizontal stacking of NBS refers to buying multiple short-term credits over a period of time, whereas vertical stacking refers to the purchase of multiple credits upfront. Innovative financing mechanisms such as The Permanence Trust[46] or insurance[47] can help ensure these solutions are scaled in a way that supports more permanent carbon sequestration.

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[42] https://news.uchicago.edu/story/wildfires-are-erasing-californias-climate-gains-research-shows
[43] https://www.forbes.com/sites/kensilverstein/2025/08/03
[44] https://www.wri.org/technical-perspectives/measurement-reporting-verification-of-carbon-removal
[45] https://www.sciencedirect.com/science/article/pii/S2590332224004196
[46] https://www.forestfoundation.org/permanence-trust/
[47] https://www.carbonpool.earth/

Advantages and Challenges of Hybrid and Industrial Carbon Dioxide Removal

While there are many emerging CDR technologies, DAC, BiCRS, and mCDR have an outsized footprint in California. **Direct Air Capture (DAC)** uses chemical reactions to filter carbon dioxide from the atmosphere.

These chemicals are either liquid solvents or solid sorbents and they react with atmospheric carbon dioxide. This combination is then heated to separate the captured carbon dioxide and store it underground or in products.[48] MRV for DAC is relatively straightforward, as a project owner can directly measure how much carbon dioxide is captured in the process, and there is a significant opportunity for scaling up deployment.

As DAC technology matures and scales up, costs are projected to decline. Expansion of DAC is a common feature of almost all net-zero carbon plans at the state,[49] federal,[50] and even international levels.[51] However, DAC is expensive and resource-intensive. A solvent DAC system has a water evaporation rate of up to 50 tons of water per ton of carbon dioxide captured. To capture a ton of carbon dioxide, a DAC system will use 2,000 kilowatt-hours of energy, more than double the average U.S. household's monthly electricity consumption.[52] Once DAC reaches 8 million metric tons of removal a year, it is estimated to use up to 0.4 percent of the total electricity generation in the United States.[53] While this is a small percentage of total energy use in the United States, these impacts will be felt acutely at the local level.[54] DAC plants need to be powered by clean energy sources to ensure net carbon removal.

48 https://www.wri.org/insights/direct-air-capture-resource-considerations-and-costs-carbon-removal
49 https://www.gov.ca.gov/2022/11/16/california-releases-worlds-first-plan-to-achieve-net-zero-carbon
50 https://www.sustainability.gov/pdfs/united-states-nzgi-roadmap.pdf?ref=newsletters.holoniq.com
51 https://www.ipcc.ch/site/assets/uploads/sites/2/2022/06/SR15_Chapter_2_LR.pdf
52 https://www.eia.gov/tools/faqs/faq.php?id=97&t=3
53 https://www.wri.org/insights/direct-air-capture-resource-considerations-and-costs-carbon-removal
54 https://carbon180.org/blog/energy-and-water-use-for-dac/

Case Study: First in the Nation - Heirloom Direct Air Capture (DAC) Facility

An Heirloom engineer at America's first commercial DAC facility. Image by Heirloom.

The Heirloom Direct Air Capture[55] (DAC) facility in Tracy, California, uses limestone to draw carbon dioxide out of the atmosphere. A fan moves ambient air over trays of limestone, which absorb carbon dioxide. The limestone is then heated in a kiln powered by local, renewable energy to extract the carbon dioxide. The captured carbon dioxide is used in the production of concrete or stored underground, and the limestone returns to the stacks of trays, where the process repeats. Heirloom focused on utilizing limestone as this is an abundant[56] and easy-to-process material,[57] reducing total operational costs. This facility is the first commercial DAC project in the United States and strives to adhere to responsible CDR deployment practices set by the company. Their four High Road Carbon Removal principles[58] were created with input from a variety of stakeholders and provide baseline best practices for other CDR companies to follow. These principles include not taking money from oil and gas companies, not allowing captured carbon to be used for Enhanced Oil Recovery (EOR), using MRV as a tool for transparency, and co-creating Community Benefit Agreements (CBAs). Moreover, the facility was built with union labor, and Heirloom has facilitated a community governance model in which they meet quarterly with community groups in San Joaquin County to address concerns and find ways for the community to benefit from this project.

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[55] https://www.heirloomcarbon.com/news/heirloom-unveils-americas-first-commercial-direct-air-capture
[56] https://www.mdpi.com/2076-3298/11/12/28
[57] Ibid.
[58] https://www.heirloomcarbon.com/news/the-new-climate-economy-needs-rules-of-the-road

In addition, communities have raised concerns about the use of pipelines to transport carbon dioxide after it is captured. Carbon dioxide is an asphyxiant, so when a carbon dioxide pipeline falters, it can drastically harm the surrounding community and environment. DAC can be built directly on top of a geologic storage site, negating the need for miles of pipelines. In addition, shorter carbon dioxide pipelines also carry less financial risk from construction and operations.[59] In order to avoid public health hazards from ruptured pipelines or geologic storage sites, proper setback criteria and other protections need to be established to ensure carbon dioxide transportation and storage is deployed responsibly. Recent research has created a 'hazard risk'[60] equation for carbon dioxide pipelines that could provide a starting point in establishing meaningful setbacks between carbon dioxide transport and communities. As of right now, some DAC projects are proposed by fossil fuel companies, undermining climate and CDR goals.[61]

Biomass with Carbon Removal and Storage (BiCRS),[62] which is also referred to as **BECCS (Biomass Energy with Carbon Capture and Storage)**, describes processes that extract carbon dioxide from plants and algae using an engineered process (gasification, pyrolysis, combustion, etc.) to remove carbon dioxide from the atmosphere and put it in long term storage, or create products that replace fossil fuels.[63] BiCRS replaces the end use of the BECCS process from maximizing energy output to prioritizing carbon dioxide removal.[64]

BiCRS could potentially help California address its waste biomass challenge. Each year, California is estimated to have 54-56 million bone dry metric tons (BDT) of waste biomass.[65] This includes biomass waste from forests, agriculture, sawmills, and other sources. If left alone, this waste biomass will release carbon dioxide back into the atmosphere as it decomposes or burns. Therefore, BiCRS presents an interesting opportunity to turn waste into carbon removal. However, this CDR approach is also

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59 https://www.sciencedirect.com/science/article/abs/pii/S175058362200055X
60 https://www.sciencedirect.com/science/article/pii/S2667143324000751?via%3Dihub
61 https://www.epa.gov/uic/r9-uic-permits#class-vi
62 https://www.icef.go.jp/pdf/summary/roadmap/icef2020_roadmap.pdf
63 https://www.wri.org/insights/sustainable-biomass-carbon-removal
64 https://carbon180.org/pathway/biomass-carbon-removal-and-storage/
65 https://str.llnl.gov/past-issues/januaryfebruary-2022/path-carbon-neutral-california

very expensive,[66] energy-intensive, and creates community concerns regarding air pollutants, the use of carbon dioxide pipelines, and where biomass is sourced from.

BiCRS may have lower costs than DAC at first, but this technology may not benefit from economies of scale due to the limited availability of feedstocks.[67] BiCRS technology is in its infancy, and it remains to be seen how it will develop and scale.[68] To ensure BiCRS projects store more carbon than they emit, there must be strict regulations governing this technology. This includes limiting feedstock to waste biomass to ensure forests are not logged and farmland is not converted for the purpose of providing inputs for BiCRS projects. There are many negative impacts of utilizing purpose-grown biomass, including the decrease of soil organic carbon, an increase in harmful land use change, and an increase in fertilizer and pesticide use for growing feedstocks.

Since DAC and BiCRS are often energy-intensive technologies, it is essential to ensure that they are run on clean energy and do not divert these resources away from California communities. Co-locating clean energy at a DAC or BiCRS facility can help address this concern by ensuring that these projects are not straining the grid and result in net-negative emissions.

Enhanced Rock Weathering (ERW) refers to the process of spreading crushed minerals across land to speed up the natural carbon cycle and absorb carbon dioxide. Depending on the mineral used, ERW has the potential to introduce trace metals such as nickel and chromium into soil, which can be harmful. These trace metals can also change the alkalinity of groundwater and rivers. Moreover, mining rocks for ERW carries risks of land disturbance, carbon dioxide emissions from mining operations, and a large land-use requirement.

Marine Carbon Dioxide Removal (mCDR) is a topic that is currently being heavily researched as it holds immense capacity to sequester carbon, yet can risk impacting the broader marine ecosystem. Additionally, as the ocean warms, ocean stratification and carbon transport will be altered, impacting the efficacy of mCDR approaches that rely on these natural processes to sequester carbon in the deep ocean.[69] mCDR encompasses many nascent approaches that have the potential to change ocean

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[66] https://isometric.com/writing-articles/biomass-carbon-removal-and-storage-explained
[67] https://link.springer.com/article/10.1007/s40518-025-00252
[68] https://carbon180.medium.com/carbon-removal-at-county-scale-adbfeab95836
[69] https://carbon180.org/blog/carbon-removal-and-the-path-back-to-1-5c/

biochemistry, negatively impact marine food systems, and deplete subsurface oxygen.[70]

Some mCDR approaches, such as Ocean Iron Fertilization, are currently banned on a commercial level under the London Protocol.[71] Others, such as artificial upwelling and downwelling (AU/AD), are not recommended for deployment in California due to natural upwelling processes off the coast.[72] It is imperative to ensure that in the push for more CDR, there are no significant negative effects on surrounding ecosystems.

Note on Geologic Storage

Whether the end use of captured carbon dioxide from DAC, DOC, or BiCRS is for utilization or underground storage, a project must consider durability, safety, transportation costs, and transparency in life-cycle assessments (LCAs). If carbon dioxide leaks from geologic storage, this could reverse the climate benefits of CDR and harm local ecosystems and communities. For example, carbon dioxide that leaks into underground aquifers can acidify the water by creating carbonic acid, which then releases heavy metals such as arsenic and lead, contaminating the water supply.[73] As previously mentioned, carbon dioxide is an asphyxiant and could drastically harm communities in the event of a pipeline rupture. Induced seismicity is another concern that may be remedied through careful site selection, site assessment, monitoring, and corrective action.[74,75]

Storing carbon dioxide in long-lived products, such as concrete, is another effective end use of captured carbon that may not elicit as much concern from community members. Concrete can use carbon dioxide from a DAC facility or biochar to decarbonize its production and store the carbon dioxide on meaningful timescales. If 10 percent of all global concrete production is used to store carbon dioxide, it could store 1 gigaton of carbon dioxide.[76]

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[70] https://www.climate.gov/news-features/understanding-climate/carbon-dioxide-removal-noaa
[71] https://wwwcdn.imo.org/localresources/en/KnowledgeCentre
[72] https://opc.ca.gov/wp-content/uploads/2025/02/Item-7-mCDR-Informational-Item-508.pdf
[73] https://www.sciencedirect.com/science/article/abs/pii/S1750583609000255
[74] https://sccs.stanford.edu/sites/g/files/sbiybj17761/files/media/file/induced-seismicity-hazard
[75] https://climate.mit.edu/ask-mit/there-danger-pumping-liquid-carbon-dioxide-underground-could-have
[76] https://www.ucdavis.edu/news/storing-carbon-buildings-could-help-address-climate-change

The potential risks of nascent CDR approaches demonstrate the need for further research and development of these strategies, as well as a need for comprehensive regulations, safeguards, and community engagement plans.

Financing of Carbon Dioxide Removal Projects

Despite calls to scale up Carbon Dioxide Removal (CDR), funding for these projects is a major barrier to their development. Many CDR strategies are new and have uncertain outcomes in terms of feasibility, scalability, and duration of storage, so investing in these pathways can be risky and unattractive. However, the threat of the climate crisis underlines the urgent need to expand financing mechanisms for CDR.

Contracts for differences, or fixed price contracts, such as the Carbon Contracts for Difference in the United Kingdom,[77] are an example of innovative financing agreements that can attract funds and promote CDR at the levels needed to reach net-zero and net-negative targets. Other financing strategies are outlined below.

Voluntary Carbon Markets

Voluntary carbon markets (VCM) refer to avoided or removed carbon emissions traded through a private sector-run marketplace to help companies meet their climate goals.

More than 8,000 companies have publicly committed to net-zero emissions due to pressure from consumers, stakeholders, and the labor market.[78] Since there are generally hard-to-avoid emissions in a company's supply chain or operations, businesses have an incentive to purchase carbon credits, which pay another entity to draw carbon dioxide out of the atmosphere.[79] For example, Frontier[80] is a coalition of companies (Meta, Shopify, and others) that have set an advance market commitment to buy $1 billion worth of carbon credits to offset residual emissions on their pathway to net-zero. This voluntary carbon market has supported the first phase of scaling up

[77] https://www.carbonfuture.earth/magazine/government-as-catalyst-strategic-financing-paths-for-scaling-carbon-dioxide-removal
[78] https://www.forbes.com/sites/phildeluna/2024/04/09/
[79] Ibid.
[80] https://frontierclimate.com/

CDR, but it is not enough to support the necessary scale of meaningful carbon removal. In addition, carbon credits sold in the VCM do not always accurately represent the claimed tons of carbon removed due to integrity issues such as additionality, leakage, or overcounting[81]. These projects do not always have established high quality standards for protecting communities and ecosystems.[82] This shortcoming of the VCM highlights the need for regulations around financing CDR projects to ensure they are effectively drawing down carbon.

In Europe, the Carbon Removals and Carbon Farming Certification (CRCF) aims to develop MRV protocols for CDR that can be used to generate carbon removal certificates that verify whether an eligible carbon removal or carbon farming project does indeed remove carbon dioxide.[83] This regulatory certification framework[84] was approved on February 20, 2024. This is the world's first carbon removal certification strategy. Certification is voluntary, and only certified carbon removal units can be used to satisfy the European Union's climate objectives.

Philanthropy

Philanthropy has a unique opportunity to provide funding for CDR projects. Similar to venture capitalists and startups, philanthropic organizations can take on larger degrees of risk with their investments. Since philanthropies are not designed to receive a return on their investment, they can invest in a wider array of CDR initiatives including research and development. Philanthropic organizations can also utilize their influence to legitimize and lead on this issue area.[85] Philanthropy has played a pivotal role in the past in scaling other new markets, such as the global health market of the early 2000s via the Gates Foundation.[86]

Compliance Markets

Compliance markets are markets mandated and regulated through a government entity, such as **California's Cap and Invest Program**. Cap and Invest sets annual

[81] https://policyintegrity.org/files/publications/Regulating_the_Voluntary_Carbon_Market_Report_vF.pdf
[82] Ibid.
[83] https://climate.ec.europa.eu/eu-action/carbon-removals-and-carbon-farming_en
[84] https://www.euractiv.com/section/climate-environment/news
[85] https://greatunwind.substack.com/p/whos-got-next
[86] https://gcgh.grandchallenges.org/history

limits (caps) on emissions that decrease over time until a final emissions target is reached. Companies that emit climate pollution are required to purchase allowances that equate to one ton of carbon dioxide equivalent (CO_2e) emissions.[87] These allowance purchases are then reinvested back into communities across California through the Greenhouse Gas Reduction Fund (GGRF).

There are many nature-based solutions funded through Cap and Invest, such as the Wetland and Watershed Restoration and Wildfire Prevention Grants. Some GGRF funds go toward more nascent CDR approaches such as DAC through the Carbon Removal Innovation Support Program (CRISP). It should be noted that many environmental justice advocates and community groups oppose the use of Cap and Invest funding to invest in industrial CDR due to the risks these technologies pose to frontline communities.

The **Extended Producer Responsibility (EPR)** framework is another potential compliance market mechanism. The paper, "Extended producer responsibility for fossil fuels"[88] lays out a framework in which fossil fuel producers "take responsibility for" the pollution from their fossil fuel production by agreeing to deal with the resulting waste from these activities. The origins of a mandatory carbon buyback proposal can be found in French legislation from 1975[89] that mainstreamed the idea of EPR, where "producers, importers, and distributors may be required to contribute to the disposal of waste from their products." It was applied for the first time in 1992 to household waste. California has established a number of EPR programs, including ones for plastic bottles, electronics, and mattresses.

Applying the EPR principle to fossil fuel producers can help create a carbon buyback obligation. Instead of fossil fuel emissions being freely dumped into the atmosphere, extractors and importers of fossil fuels would be responsible for the permanent disposal of carbon dioxide waste via geologic sequestration, utilization, or nature-based solutions. A carbon buyback program does not require high carbon prices, supporting the creation of a financially attractive market for CDR.

Establishing a CDR market may dilute incentives to directly reduce carbon dioxide emissions. Therefore, it is imperative to frame CDR as a portfolio of options to deal with

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87 https://theclimatecenter.org/wp-content/uploads/2023/12
88 https://iopscience.iop.org/article/10.1088/1748-9326/aca4e8/pdf
89 https://journals.openedition.org/factsreports/6557

only residual emissions, or emissions still being released even when net-zero is reached,[90] and legacy emissions.

Tax Credits

Financing tools such as tax credits can help de-risk investments as well as reduce the high capital and operational costs of new CDR projects.[91] The **federal 45Q Tax Credit** was first established in 2008, expanded in 2018 and 2022, and was recently amended in 2025 through H.R. 1 (Arrington, 2025), the One Big Beautiful Bill Act.[92] This tax credit incentivizes the sequestration of carbon dioxide, carbon monoxide, and carbon suboxide[93] through geological sequestration, Enhanced Oil Recovery (EOR), or utilization. DAC was included in this tax credit in 2018, and project investments can receive a tax credit of $180/ton of carbon dioxide if the carbon dioxide is geologically stored, utilized, or used for EOR.[94]

This is the most significant federal incentive for an industrial CDR approach.[95] While the 45Q Tax Credit supports the scale-up of CDR efforts, it should be noted that EOR should *never* be an end use of CDR projects, as this incentivizes the continued use of fossil fuels. California has already banned the practice of using captured carbon for EOR within the state through SB 1314 (Limon, 2022)[96] and SB 905 (Caballero, 2022).[97]

Government Procurement

Government procurement refers to the direct purchase of carbon credits or direct investment in carbon removal projects by the state and/or federal government. CDR can be seen as a type of 'waste management' service. In the same way trash is collected and disposed of to keep communities healthy, removing carbon dioxide from the atmosphere reduces greenhouse gas levels and mitigates climate change. In this sense, CDR is a public good the government can support. Any CDR projects

[90] https://www.wri.org/insights/residual-emissions-carbon-removal
[91] https://www.weforum.org/stories/2025/01/cost-of-different-carbon-removal-technologies
[92] https://www.congress.gov/bill/119th-congress/house-bill/1/text
[93] Carbon suboxide, also known as tricarbon dioxide, is a chemical compound with the formula C_3O_2.
[94] https://media.rff.org/documents/Report_24-03.pdf
[95] https://carbonherald.com/what-is-45q-tax-credit/
[96] https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=202120220SB1314
[97] https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=202120220SB905

subsidized by taxpayer dollars, whether this is a tax credit or direct procurement, must have rigorous community engagement, labor, and environmental standards.

The Carbon Dioxide Removal Purchase Pilot Prize, funded by the Department of Energy under the Biden administration, provided up to $35 million for CDR projects across the country.[98] Government support of CDR through policy, initiatives, and investments will help spur innovation, develop comprehensive research, and establish the confidence and credibility needed for further private investment.[99]

In California, the Carbon Removal Innovation Support Program (CRISP) provides financial support to Direct Air Capture projects across the state that are in the testing and piloting phases and have community engagement plans.[100] SB 643 (Caballero, 2025) proposed a Carbon Dioxide Removal Purchase Program, which would have allowed the California state government to directly invest $50 million into CDR projects across the state by 2035 through a competitive grant process, but was vetoed by Governor Gavin Newsom.

Community Protections and Guardrails

CDR is a new and rapidly expanding industry, which should avoid the mistakes of other industries as it scales up as a credible climate solution. The negative effects of CDR in communities cannot be justified in the larger race to fight climate change.

CDR technologies such as DAC and BiCRS in particular are seen to pose potential threats in frontline communities due to air quality and safety concerns regarding the combustion of biomass, the use of pipelines to transport carbon dioxide, and the geologic storage of carbon dioxide. In addition, questions have been raised about whether funding these technologies is as beneficial as funding emission reduction projects.

Since oil and gas companies were early investors in many CDR technologies, some environmental and environmental justice groups view CDR technology as justification for oil companies to continue business as usual. Today, oil and gas companies are

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[98] https://www.energy.gov/articles/doe-announces-12-million-accelerate-americas-carbon-dioxide-removal
[99] https://www.weforum.org/stories/2024/07/why-carbon-dioxide-removal-needs
[100] https://www.caclimateinvestments.ca.gov/carbon-removal-innovation

proposing the buildout of both CCS and some DAC hubs in California. These entities have proven to be untrustworthy partners on climate, the environment, and public health, and therefore any proposed projects must be strictly regulated.

The moral hazard problem, as it relates to CDR, refers to the idea that scaling up CDR will diminish the emissions reductions efforts critical to curbing both climate change and air pollution. In addition, environmental justice organizations are concerned that CDR will not be used to draw down legacy emissions, but instead will be used to only offset ongoing emissions. Occidental Petroleum CEO Vicki Hollub has stated that DAC technology will preserve the oil industry for up to another 80 years.[101] ExxonMobil CEO Darren Wood has claimed scaling up DAC, rather than reducing emissions, will be the easiest way to reach net-zero.[102] Oil and gas companies have also used captured carbon from CDR processes to extract hard-to-reach oil reserves through a process called Enhanced Oil Recovery (EOR), which is banned in California. However, the state continues to incentivize the use of captured carbon for EOR outside of California through the Low Carbon Fuel Standard.[103] Using captured carbon for EOR releases four times more carbon than was initially captured, undermining CDR, climate, and air quality goals.[104] **The use of CDR to justify continued oil production and pollution will continue to drastically harm frontline communities and the planet.**

California is in a unique position. There are enough underground geological formations, with the right geologic makeup, for underground carbon sequestration in the San Joaquin Valley.[105] However, many of these communities have faced decades of harm from industries like oil and gas, among others. Stockton and Kern County are among the most polluted areas in the entire country.[106] The impact from the oil and gas industry also undermines trust in the claim that there is enough geologic storage in the San Joaquin Valley, due to unplugged and abandoned wells that have not been accounted for.[107] These wells could allow for captured carbon dioxide to be reintroduced into the atmosphere. Now, these same communities are identified as critical sites for nascent CDR technologies that could have unintended negative consequences.

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[101] https://www.eenews.net/articles/oil-companies-want-to-remove-carbon-from-the-air
[102] Ibid.
[103] https://leginfo.legislature.ca.gov/faces/billTextClient.xhtml?bill_id=202120220SB1314
[104] https://pubs.acs.org/doi/10.1021/es902006h
[105] https://gs.llnl.gov/sites/gs/files/2021-08/getting_to_neutral.pdf
[106] https://www.pbs.org/newshour/nation/california-has-some-of-the-worst-air-quality
[107] https://www.fractracker.org/2019/03/failing-abandoned-wells/

In addition, even though California has slowed down its oil and gas production, this rate of decline has been slower near racially and socio-economically marginalized communities.[108] For example, the proportion of Black residents living near active wells was 42-49 percent higher and the proportion of Latinx residents near wells is 4-13 percent higher than their respective statewide populations.[109] Pollution from oil and gas operations includes diesel exhaust, volatile organic compounds, air toxics, polluted groundwater, and light and sound pollution from machinery.[110] As a result, frontline communities are at a higher risk for adverse health effects, including increased blood pressure,[111] asthma, preterm birth, and lung and heart disease, as well as an increased risk of dying from COVID-19.[112]

There are real and prolonged impacts to these pollution burdened communities if CDR is used to delay the reduction of fossil fuel production and use. Policymakers, businesses, and community organizations must prioritize decarbonization to curb climate change and ensure CDR is complementary, not deleterious, to those efforts.

Communities have already experienced catastrophic impacts when carbon storage projects go wrong. In Satartia, Mississippi, a carbon dioxide pipeline ruptured, forcing 200 people to evacuate and 45 people to be hospitalized.[113] First responders were not able to reach anyone as the released carbon dioxide caused their combustion engines to stop working. Community members were unaware of the carbon dioxide pipelines near their homes. Other frontline communities in Texas and Louisiana were not included in community benefit agreement conversations when DAC hub plans were introduced.[114] Moreover, if a carbon dioxide pipeline ruptures, the gas can contaminate groundwater. Since the San Joaquin Valley is both an estuary and utilizes the Sacramento-San Joaquin River Delta waters for agriculture, this carbon dioxide pollution could harm a resource depended on by individuals across the state, nation, and world.

The passage of SB 614 (Stern, 2025)[115] lifted the moratorium on carbon dioxide pipelines in California. Since carbon dioxide pipelines can be integral to the design of

[108] https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2022GH000690
[109] Ibid.
[110] Ibid.
[111] https://pmc.ncbi.nlm.nih.gov/articles/PMC10850428/
[112] https://news.stanford.edu/stories/2021/10/living-near-oil-gas-wells-increases-air-pollution-exposure
[113] https://www.npr.org/2023/05/21/1172679786/carbon-capture-carbon-dioxide-pipeline
[114] https://www.eenews.net/articles/false-promise-does-carbon-removal-plans
[115] https://calmatters.digitaldemocracy.org/bills/ca_202520260sb614

some DAC and BiCRS facilities, local communities must understand the associated risks and maintain a right of refusal. To ensure project information is properly disseminated, project developers and governments should work with local community organizations to reach as many community members as possible.

U.S. Department of Energy (DOE) funded projects under the Bipartisan Infrastructure Law (BIL) originally required projects to incorporate Community Benefits Plans (CBPs) [116] in project applications. CBPs, while not legally binding, are commitments from the project developer to demonstrate the local benefits a project will provide to the community. Agreements usually include language about employment, local tax revenue, and environmental guardrails for the local community.[117] The requirement to include CBPs in projects was eliminated under the Trump administration.[118]

Other models for community engagement include the Community Alliance for Direct Air Capture (CALDAC),[119] led by the Center for Law, Energy & the Environment (CLEE) and Lawrence Berkeley National Laboratory. This project tested novel governance structures to ultimately give the participating communities voting power over a CDR project. This collaborative community involvement pilot modeled how projects can be community or publicly owned and operated, but the project was defunded by the Trump administration.

These important reform efforts are critical to ensure local communities have agency in protecting their livelihoods, health, and wellbeing.[120] If successful, these efforts will yield significant shared benefits and provide a model for the required development of CDR infrastructure in the coming decades. Community agency enables residents to ensure their community will receive economic and environmental benefits. It is crucial that communities also have a right of refusal, allowing them to reject proposed CDR projects such as DAC or BiCRS from being sited in their communities.

The CDR industry can take inspiration from well-designed projects to implement meaningful community engagement. Urban design projects such as those documented on the Social Economic and Environmental Design (SEED) Network[121] or renewable

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[116] https://www.wri.org/insights/community-benefits-agreements-us-clean-energy
[117] https://www.resources.org/archives/improving-community-benefits-plans-can-optimize-local-outcomes/
[118] https://earthjustice.org/wp-content/uploads/2025/01/doe-memo-suspending-cbp.pdf
[119] https://newscenter.lbl.gov/2023/08/24/california-group-exploring-viability
[120] https://www.filesforprogress.org/memos/advancing-equitable-deployment-of-regional-dac-hubs.pdf
[121] https://seednetwork.org/about/mission/

energy projects such as those implemented by EDPR North America[122] demonstrate how community engagement can be meaningful to both the community and project developer. These projects engage the community in early project development phases, find multiple opportunities at relevant locations to speak with residents, and incorporate feedback into their projects. Going even a step further, some of these projects invest money into the communities where the project is sited, similar to what would be a part of a Community Benefit Agreement. If even after best practices are implemented and a community rejects a CDR project, then this right of first refusal needs to be respected.[123]

CDR also has the potential to provide significant employment opportunities. Five of the aforementioned CDR pathways (ERW, BiCRS, DOC, OAE, and DAC) have the potential to create an estimated 95,000 to 130,000 jobs per year nationwide once they have been collectively scaled up to the 100 million metric ton-level of carbon drawdown.[124] Each individual pathway will provide different levels of employment. For example, DAC is projected to provide 5,000 to 7,000 operation and management (O&M) jobs, whereas ERW can provide up to 22,000 to 29,500 O&M jobs.[125] The knowledge of workers employed by oil and gas companies will be critical to the operation of some CDR facilities and skilled labor from trade unions will be needed to successfully build out CDR operations.[126] The scale-up of this industry creates an opportunity to support union labor, displaced oil and gas workers, and provide new career paths in the transition away from fossil fuels.

California is standing at the precipice of these new technologies. While CDR is needed to achieve climate targets, it cannot be deployed in a way that will further harm communities and the environment. In every phase of the project planning process, communities must have a say, including a right of first refusal. The Environmental Justice Advisory Committee (EJAC) of the California Air Resources Board published a letter to the U.S. Department of Energy in 2023 outlining concrete steps to equitably deploy DAC hubs.[127] Some of these ideas are reflected in the list below, along with other recommended strategies to protect communities.

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[122] https://www.edp.com/en/north-america/na/projects
[123] https://www.latitudemedia.com/news/direct-air-capture-has-arrived-at-the-community-buy-in-hurdle /
[124] https://rhg.com/research/the-benefits-of-innovation-an-assessment-of-the-economic-opportunities
[125] Ibid.
[126] https://carbonactionalliance.org/wp-content/uploads/CM-and-Labor-Backgrounder.pdf
[127] https://www.filesforprogress.org/pdfs/DAC_hubs_DOE_letter.pdf

1. **Stringent Protections and Guardrails**
    a. Ensure CDR technology is used to address legacy and hard-to-abate emissions and is not sold as an offset or credit to oil, gas, and other companies to allow continued pollution.
    b. Establish meaningful setbacks between a community and a CDR operation.
        i. Support research and establishment of a safe distance from carbon dioxide pipelines.[128]
    c. Add odorants to the carbon dioxide sequestered to warn people of leaks.
    d. Do not use fossil fuels to power CDR operations.
    e. Do not allow CDR to be used for Enhanced Oil Recovery (EOR).
    f. Pipeline systems must be new and strictly regulated at the state and federal level. This includes different regulations for carbon dioxide in a liquid, gas, and supercritical state.[129] Plans to protect carbon dioxide pipelines from water intrusion must be created to minimize risk of explosion.
    g. Invest in effective emergency response practices to prepare for potential leaks, including rapid communication and electric first responder vehicles.
    h. Ensure analysis of the impacts of the project to the environment and public health, including exposure to toxic materials, hazardous waste, and energy and water use.
2. **Community Ownership and Governance**
    a. Public funding for the development for DAC and other CDR projects should not go to oil and gas companies.
    b. Codify the right of refusal for a community.
    c. Conduct meaningful community outreach before a site is chosen for a CDR project, throughout the development process, and after operations begin.
    d. Work with the community to create a robust, legally binding Community Benefit Agreement document with a scope of work that directly benefits impacted communities.
    e. Work with unions and labor groups to create project labor agreements for the construction and operation of a CDR project.

[128] https://pstrust.org/wp-content/uploads/2022/10/CO2-Regulatory-and-Knowledge-Gaps-1.pdf
[129] https://pstrust.org/carbon-dioxide-pipelines-dangerous-and-under-regulated/

The Role of Carbon Dioxide Removal in California Climate Policy

California is one of the first states to introduce policies related to carbon removal.[130] AB 1279 (Muratsuchi, 2022) codified California's carbon neutrality and net-negative goals. This bill also set a goal to reduce state emissions by at least 85 percent below 1990 levels by 2045. This means that CDR can counterbalance up to 15 percent of remaining emissions, ensuring CDR does not replace critical emissions reductions efforts. The 2022 California Air Resources Board (CARB) Scoping Plan outlines specific carbon dioxide removal targets of 7 million metric tons (MMT) by 2030 and 75 MMT by 2045.[131] These targets are designed to help the state reach its carbon neutrality goals by 2045. Most of the carbon removal targets are currently expected to be reached using DAC, BiCRS, and CCS.[132,133] Natural and working lands are expected to deliver net removals of 1.5 MMT by 2045,[134] although other estimates are much higher than that.[135,136] AB 1757, enacted in 2022,[137] codified nature-based solutions targets[138] that will contribute to the larger CDR portfolio.

To address the aforementioned moral hazard problem of CDR, state policy must carefully address how CDR is used in offsetting hard-to-avoid emissions and drawing down excessive carbon dioxide. The IPCC has stated that humanity must cut carbon emissions to net-zero by 2050 and achieve net-negative emissions thereafter to account for the warming effects of legacy emissions.[139] Therefore, CDR policy will play a role in achieving both goals. While CDR can support the decarbonization of hard-to-avoid emissions from industry, it is imperative that CDR is reserved for offsetting only truly hard-to-decarbonize industries, such as cement, steel, and chemical production. Even in these situations, CDR should be viewed as a temporary

[130] https://www.wri.org/insights/california-carbon-dioxide-removal-policies#
[131] https://ww2.arb.ca.gov/our-work/programs/ab-32-climate-change-scoping-plan/2022
[132] Ibid.
[133] The Climate Center recommends that CCS only be counted towards state emission reduction goals and not carbon removal goals. Additionally, CCS should only be used for specific industrial applications where carbon emissions are hard to avoid. https://theclimatecenter.org/fossil-fuels
[134] Ibid.
[135] https://gs.llnl.gov/sites/gs/files/2021-08/getting_to_neutral.pdf
[136] https://theclimatecenter.org/carbon-sequestration/setting-an-ambitious-sequestration-goal-for-california
[137] https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=202120220AB1757
[138] https://resources.ca.gov/-/media/CNRA-Website/Files/Initiatives/Expanding-Nature-Based
[139] https://www.sciencedirect.com/science/article/pii/S2590332224004226

support while research is conducted for ways to permanently decarbonize these industries.

While on the path to net-zero, CDR can be deployed to draw down residual carbon dioxide emissions from the atmosphere and, once net-zero is achieved, continue to draw down legacy emissions to achieve net-negative goals.

Legislation has been introduced in recent years to facilitate and develop novel CDR technologies, and scale up nature-based solutions. The chart below outlines a few key pieces of CDR legislation in California since 2020.

Carbon Dioxide Removal Legislation in California

AB 1279 **California Climate Crisis Act** *Muratsuchi, 2022*	Codifies a net-zero and net-negative target for the state, including an 85 percent emissions reduction target from 1990 levels by 2045.
SB 905 **Carbon Sequestration: Carbon Capture, Removal, Utilization and Storage** *Caballero, 2022*	Sets up a regulatory framework for carbon sequestration technologies. The regulatory requirements include an MRV plan, strategies to minimize co-pollutants, establishing rules for financial responsibility for projects and geologic carbon dioxide injection sites for a minimum of 100 years, and prohibits use of projects for enhanced oil recovery.
SB 27 **Carbon Sequestration and Climate Resiliency Project Registry** *Skinner, 2021*	Establishes the Natural and Working Lands Climate Smart Strategy, directs the California Air Resources Board (CARB) to include CDR targets in the Scoping Plan, and establishes a directory of projects for carbon sequestration from natural and working lands and DAC.
AB 1757 **Climate Goal: Natural and Working Lands** *R. Rivas & C. Garcia, 2022*	Requires the California Natural Resource Agency (CNRA) to establish targets for natural carbon sequestration and nature-based climate solutions. These targets[140] were published in April 2024.
SB 643 (Vetoed) **Carbon Dioxide Removal Purchase Program** *Caballero, 2025*	Vetoed. Would have required the CARB to establish and administer the Carbon Dioxide Removal Purchase Program. The program would have allocated $50 million through a competitive grant process for eligible carbon dioxide removal projects by 2035.
SB 614 **Transportation of Carbon Dioxide** *Stern, 2025*	Lifts the moratorium on the utilization of carbon dioxide pipelines in the state of California.

[140] https://resources.ca.gov/-/media/CNRA-Website/Files/Initiatives

In addition to these state efforts, the Federal Bipartisan Infrastructure Law (BIL, 2021)[141] and Inflation Reduction Act (IRA, 2022)[142] provided over $14.4 billion to scale up both industrial and land-based CDR. Within this funding package for CDR, there is $3.5 billion to build four DAC hubs across the country. Each DAC hub is projected to provide at least 1 million metric ton of carbon dioxide removal per year. One of the companies awarded funding through this program is Heirloom, which is working in partnership with Climeworks to establish a DAC hub in Louisiana. Heirloom also operates a DAC facility in Tracy, California.[143]

Scientists and academics around the world have also called for setting separate targets for carbon emissions reductions, land-based sequestration, and permanent CDR efforts.[144] Setting separate targets between these efforts, with the appropriate oversight, can help maximize benefits of all strategies, support effective governance, diversify the risks, and provide clear targets to hold governments and companies accountable for projects.[145] Incentivizing a portfolio of strategies that adhere to high standards and regulations, rather than preemptively choosing winners and losers, will also allow this nascent industry to scale-up effectively.

While California set CDR targets in the 2022 CARB Scoping Plan, there is no established roadmap on how to achieve them. Since the level of CDR needed is contingent on how quickly society reduces emissions, it is imperative to create intentional policy that incorporates a variety of CDR pathways in the context of various overshoot scenarios to effectively scale-up these efforts. Building off the momentum of already introduced legislation and the Scoping Plan, California can now act to establish a roadmap for CDR in California.

This roadmap could create a framework that:

- Outlines feasible CDR solutions for California;
- Further clarifies separate targets for emissions reductions and carbon removal;
- Creates stringent regulations on CDR projects, carbon dioxide pipelines, and geologic storage;
- Outlines requirements for community engagement; and

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141 https://www.congress.gov/bill/117th-congress/house-bill/3684
142 https://www.congress.gov/bill/117th-congress/house-bill/5376/text
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145 https://www.wri.org/technical-perspectives/separate-climate-targets-carbon-dioxide-removal

- Creates innovative financing mechanisms to support the research and deployment of CDR strategies.

The Climate Center Policy Recommendations

Policy Recommendation 1

Ensure that CDR projects are exclusively counted toward the state's carbon dioxide removal targets of 7 million metric tons (MMT) by 2030 and 75 MMT by 2045 as outlined in the Scoping Plan. CDR projects should not be counted toward the emission reduction goal of 85 percent by 2045 as outlined in AB 1279 (Muratsuchi, 2022).[146]

Policy Recommendation 2

All industrial CDR projects, whether state or privately owned, should be subject to a set of comprehensive principles for Community Benefits Agreements. The state should incorporate the following into Community Benefit Agreements:

a. Codify a *right of first refusal* and a right to restitution for communities impacted by projects.
b. Codify a requirement that the impact of the project should not adversely affect frontline communities.
c. Codify a requirement to ensure the community has timely notice and opportunity for input about upcoming projects that are posted in the most common languages of the community.
d. Outline best practices for community engagement and ownership, as referenced in the Community Protections and Guardrails section of the paper.

Policy Recommendation 3

Establish stringent regulations around the transportation and storage of carbon dioxide in all of its various states. Regulations should also include:

a. Establishing a meaningful and science-based setback distance between a CDR project — including the injection and storage sites — carbon dioxide pipelines, and the surrounding community;
b. Adding odorants to carbon dioxide to alert CDR project employees and surrounding community members of possible leaks;

[146] https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=202120220AB1279

c. Requiring that CDR operations are powered with clean energy and uphold existing laws to ensure carbon dioxide is not used for Enhanced Oil Recovery, in California or elsewhere;
d. Requiring investment in efficient emergency response practices to equip first responders and communities with the resources they need if and when a carbon dioxide leak occurs;
a. Requiring corrective action plans that sufficiently characterize and develop remediation plans for carbon dioxide leakage pathways;
b. Establishing a maximum transportation distance between a project and the storage site to minimize transportation risks; and
c. Including an analysis of the environmental and public health impacts of proposed projects, with attention to cumulative impacts on already overburdened communities. This analysis should be conducted through the CEQA process and ensure robust consideration of affordability impacts and access to water and energy.

Policy Recommendation 4

Support continued funding for the research and development of CDR technologies to better understand the impacts and trade-offs of these projects to eventually scale effective solutions

Policy Recommendation 5

Support the continued funding and implementation for NBS across the state of California, per the AB 1757 targets, to ensure timely action on scaling CDR to avoid peak temperatures and the necessary co-benefits for climate resilience.

Policy Recommendation 6

Refine Monitoring, Reporting, and Verification (MRV) protocols for relevant CDR strategies[147] to ensure real and additional carbon removal benefits.

Policy Recommendation 7

Develop a policy mechanism to effectively and continually fund CDR that does not facilitate the continued reliance on fossil fuels (i.e. no offsets or carbon credits), and ensures polluters are accountable for addressing their pollution. These financing mechanisms can include compliance markets, extended producer responsibility programs, public procurement, and tax incentives.

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[147] https://co2re.org/wp-content/uploads/2023/11/CO2RE_Report_CDR_Permanence-FINAL-v7.pdf

Policy Recommendation 8
Support continued funding for partnership with local environmental justice and/or community organizations throughout the lifecycle of a project to ensure industrial CDR projects are as beneficial to a community as possible and that there is incentive for community members to engage in the outreach process.

Conclusion

The world is nowhere close to reaching established net-zero emissions goals. For the first time in 2024, global average temperatures exceeded the Paris Agreement targets of 1.5 degrees Celsius.[148] This trend has continued into 2025 and demonstrates the extraordinary measures needed to mitigate the climate crisis.

First, the production and consumption of fossil fuels and other carbon emitting sources must be phased out as quickly as possible. Second, CDR must be scaled up and deployed efficiently and equitably to reach established net-zero targets, mitigate residual emissions, and restore the climate. CDR policy and methods must encompass both nature-based solutions and nascent industrial approaches that have robust measurability, durability, scalability, and additionality. Critically, safeguards must be developed to ensure communities and ecosystems are not harmed by these projects.

Governments and communities will need to use every tool available to secure a safe climate. A portfolio approach to CDR will help scale up drawdown efforts and support an array of benefits. Healthy soils, restoration, conservation, urban greening and forest management will create resilient communities, ecosystems, and food systems. DAC, ERW, and other nascent CDR approaches support innovation and job growth, offset hard-to-decarbonize industry, and provide longer-term carbon dioxide storage.

Now is the time to invest in education and community engagement on CDR, research and develop innovative CDR approaches, and scale nature-based solutions across California. CDR is critical to achieve established climate goals, however these strategies must be deployed responsibly, equitably, and with close community collaboration.

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[148] https://www.pbs.org/newshour/politics/watch-live-nasa-and-noaa

Citations for CDR Approaches

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2. Soil Carbon Sequestration
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Glossary

45Q Tax Credit (45Q)	A federal tax credit intended to incentivize investment in carbon capture and sequestration, calculated per metric ton of qualified carbon dioxide removed and sequestered
Additionality	The additional value or benefit generated by an action, beyond what would have happened if no action had been taken. If you plant trees on an acre of land that would have otherwise sat empty, then there is an additional benefit to your action
Advanced Market Commitment	A binding contract from a government or financial entity that guarantees a viable initial market for a product once it is developed
Anthropogenic Emissions	Human activity that results in an overall increase in greenhouse gas emissions. Includes fossil fuel use and land use change *Fossil fuel use, like cars* *Land use change, as in clear cutting or development*

Aquifer	A body of porous rock or sediment saturated with groundwater
Asphyxiant	A vapor or gas that can cause unconsciousness or death by suffocation (lack of oxygen)
Avoided Emissions	An action that helps an operation avoid emitting carbon dioxide in the atmosphere. *Using solar to power a building versus relying on electricity sourced from fossil fuels*
Biomass	Plant or animal material used as fuel *Wood and agricultural byproduct*
Bipartisan Infrastructure Law (BIL)	Bill passed into law in 2021 to provide new funding for infrastructure projects, including resiliency projects
Carbon Credits	Also known as carbon allowances, carbon credits are permission to emit a certain amount of carbon dioxide. These credits are generally purchased from a government entity
Carbon Cycle	The flow of carbon through land, water, living things or air via photosynthesis, fire, burning fossil fuels, weathering and volcanic activity
Carbon Dioxide Equivalent (CO2e)	Shorthand used to describe the impact of another greenhouse gas by converting its mass to the same mass as carbon dioxide that would have the same global warming effect *For every 1 kilogram of methane (CH_4), it is the same as emitting 25 kilograms of carbon dioxide*
Carbon Offsets	Programs or policies that allow companies and individuals to pay for activities that will result in emissions reductions or CDR to offset their surplus emissions. This can be through a voluntary or compliance market. *An oil company pays for a forest stewardship project to ‘offset’ their emissions at a refinery*

Carbon Sink	When more carbon is drawn down from the atmosphere than is released *Trees and oceans*
Carbon Source	When carbon is released into the atmosphere *Fossil fuel use, land use change, degraded ecosystems*
CCS	Carbon Capture and Sequestration, which purports to capture carbon dioxide emissions at a point source of emissions. *Filter on a smokestack*
CDR	Carbon Dioxide Removal, which draws down legacy emissions from the atmosphere *DAC, BiCRS, nature-based solutions*
Climate Stabilization	Refers to the goal of a stable climate, avoiding the worst effects of climate change
Community Benefit Agreement	CBAs are legally binding contracts between community-based organizations and developers that outline how a project will improve the quality of life for residents *Aggie Square CBPA in Sacramento, California invests in affordable housing, job development, and a fund for neighborhood priorities*
Community Benefit Plans	Outlines how a project will benefit the local residents and how it will address their concerns
Compliance Carbon Market	A market mandated and regulated through a government entity. In this context, it requires companies to adhere to predetermined emissions targets by purchasing and using credits *California's Cap and Invest Program*
Contract for Difference	Locks in a specific price for carbon removal

Corrective Action Plan	A strategy to identify, resolve, and prevent issues in operations
Decarbonization	The process of stopping and reducing carbon gases being released into the atmosphere *Using clean energy to power a building instead of electricity created by fossil fuels*
Direct Emissions	Also known as Scope 1 emissions. These are emissions that come from a source owned by an organization. *The emissions from your car while you are driving it*
Enhanced Oil Recovery	Injection of supercritical carbon dioxide into oil reservoirs to increase the amount of oil production beyond initial extraction
Extended Producer Responsibility	A policy that holds producers responsible for product management through the product's lifecycle *The California Responsible Battery Recycling Program establishes a program to collect and recycle batteries*
Feedstock	Material used to produce something else in an industrial process *Wood to create biochar through the process of pyrolysis*
Fossil Fuels	Hydrocarbons formed from deeply buried, dead organic material subject to high temperature and pressure for hundreds of millions of years *Oil* *Natural gas* *coal*
Frontline Communities	Communities that experience the 'first and worst' consequences of climate change *Communities that live near active oil wells, shipping ports, etc.*
Geological Carbon Sequestration	The process of storing carbon dioxide in underground geologic formations

Gigatonne of carbon dioxide ($GtCO_2$)	A billion metric tons *NASA: A billion metric tons - 10,000 fully loaded US aircraft carriers*
Greenhouse gases (GHG)	Various gaseous compounds that trap heat in the atmosphere and contribute to the greenhouse effect *Carbon Dioxide (CO_2), Methane (CH_4), and Nitrous Oxide (N_2O)*
Greenhouse Gas Reduction Fund (GGRF)	Proceeds from the California Cap and Invest Program are appropriated through the Greenhouse Gas Reduction Fund to support programs and projects that reduce greenhouse gas emissions while delivering economic and environmental benefits to all Californians
Governance	Process of governing or overseeing the control and direction of a country, project, or organization
Hard-to-Avoid Emissions	Emissions that are extremely difficult to eliminate within a certain timeframe or which would impact the well-being of people *Aviation and construction industries*
Intergovernmental Panel on Climate Change (IPPC)	The United Nations body for assessing the science related to climate change
Kilowatt-Hour (kWh)	A measure of energy per hour
Leakage	carbon dioxide that has left its storage and returned to the atmosphere *carbon dioxide leaking from underground storage wells*
Legacy Emissions	Emissions, namely carbon dioxide, that were released into the atmosphere in the past
Lifecycle Analysis	The systematic analysis of environmental impact over the course of the entire lifecycle of a product, material, or process

Measurement, Reporting, and Verification (MRV)	A multi step process that measures the amount of greenhouse gas emissions reduced by a mitigation strategy, and reports these findings to a third party. The third party verifies the report
Methane (CH_4)	A colorless, odorless gas that occurs abundantly in nature and from human activities. It is the most potent greenhouse gas
Mine Tailings	Unwanted rock material leftover from a mining operation, usually stored in ponds or in piles
Moral Hazard	Ethical concerns that CDR will slow down and delay emissions reductions efforts
Natural and Working Lands	A variety of land types that cover natural lands (forests) and working lands (farms) *Farms, wetlands, forests, urban areas, rangelands*
Nitrous Oxide (N_2O)	A long-lived, potent greenhouse gas that is emitted from nitrogen fertilizers and animal waste
Nature-Based Solutions	Actions to protect, restore, and steward natural and working lands to address societal challenges and climate change *Improving soil quality to sequester more carbon and increase food production*
Net-Zero Emissions	This refers to a scenario where all emissions released by humans are counterbalanced by removing carbon from the atmosphere
Net-Negative Emissions	Where the deliberate removal of greenhouse gases from the atmosphere exceeds the amount of gases emitted.
No-Till Farming	When soil is left undisturbed
Ocean Stratification	The layering of ocean water based on density differences, which impacts marine life and climate

Odorants	Chemical additives that create a distinct smell to help early detection of gas leaks
Organic Carbon	Measure of the carbon content in soils derived from plant and animal matter
Overshoot	Climate scenarios where emissions trajectories exceed their concentration or temperature targets, and then use large scale CDR to achieve their goals
Paris Agreement	A legally binding international treaty on climate change to limit the global average temperature to below 2 degrees Celsius
Parts per Millions (PPM)	The number of units of mass of a contaminant per million units of total mass *There is currently around 420 PPM of carbon dioxide in the atmosphere, but it should be below 350 PPM*
Permanence (aka Durability)	The duration for which carbon dioxide can be stored in a stable or safe manner *A tree can store carbon dioxide for decades, depending on its lifespan* *carbon dioxide can be stored in concrete for centuries*
Point Source	A local, stationary and concentrated source of pollution *Smoke stack, exhaust pipe*
Procurement	For CDR, this refers to a government purchasing carbon removal credits to bring about projects *Carbon Dioxide Removal Purchase Pilot Prize from the U.S. Department of Energy*
Pyrolysis	Heating of an organic material in the absence of oxygen *Conversion of biomass into biochar and bio-oil*
Reservoir	Wherever greenhouse gases are stored *Forests, oceans, wells, soil, rocks*

Right of Refusal	The right of a community to refuse a proposed industrial CDR project that is within their locality
Right to Restitution	Right to financial compensation if a community is harmed by an industrial CDR project
Setback Distance	The required minimum distance between a building and a carbon dioxide removal project, sequestration site, and/or pipeline
Soil Organic Carbon (SOC)	The measure of carbon contained within soil organic matter
Supercritical State	A state of carbon dioxide when it is held above its critical temperature and pressure. At this point, carbon dioxide exhibits properties midway between a gas and liquid
Voluntary Carbon Market	Avoided or removed carbon emissions exchanged through a marketplace not created through policy *Frontier carbon market*
Volatile Organic Compounds (VOCs)	Compounds that have a high vapor pressure and low water solubility. Often components of petroleum fuels, paint thinners, and dry cleaning agents.

Further Resources

1. Understanding Carbon Dioxide Removal
    a. The Climate Center webinar series
    b. AirMiners BootUp
    c. CDR Primer
    d. Visualizing Jobs in a Carbon Dioxide Economy
    e. RMI CDR Taxonomy
    f. Co-benefits of nature-based solutions exceed cost of implementation
    g. Groundbreaking Technology in CDR
    h. IPCC Reports
    i. Marine CDR Code of Conduct

j. DIY DAC Unit
k. Video: How Big is 1 Ton of CO2?
l. Scale of CDR needed to remove 1 GT C

2. Understanding the Carbon Dioxide Removal Market
    a. Scaling Carbon Removal
    b. MRV and Carbon Removal
    c. Standards, Methodologies, and Protocols of Durable Carbon Removal
    d. High Quality Carbon Removal Credits
    e. Carbon and Land Use Model (CALM)
3. Carbon Dioxide Removal in California
    a. Bills
        i. SB 1314 (Ban on Enhanced Oil Recovery)
        ii. AB 32 Low Carbon Fuel Standard
        iii. SB 905
        iv. AB 1757
        v. SB 27
        vi. AB 2447 - Disadvantaged community members must receive adequate notice to provide input on CEQA related projects.
    b. Lessons Learned from California's Carbon Dioxide Removal Policies
    c. CalEnviroscreen
    d. Overshoot and CDR
    e. The Role of Cities and Carbon Dioxide Removal
    f. The City CDR Initiative
4. Carbon Dioxide Removal and Environmental Justice
    a. California Environmental Justice Advisory Committee Resolution
    b. Environmental Justice Opposition to DAC
    c. Indigenous Perspectives on Climate Engineering
    d. Community Alliance for Direct Air Capture (CALDAC)
    e. Pipeline Safety Trust: Carbon Dioxide Pipeline Risks
    f. Charting a Path to Just Direct Air Capture Hubs
    g. Regulatory and Knowledge Gaps in Carbon Dioxide Pipeline Transportation
    h. World Resources Institute: How to Scale CDR Responsibly
    i. Rethinking Local Control: Placing Environmental Justice and Civil Rights at the Heart of Land Use Decision-Making
    j. A first step in defining equitable and just carbon removal
    k. Ocean CDR Social Considerations