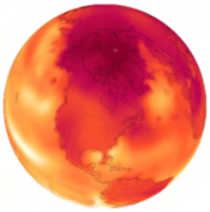
Carbon Dioxide Removal: Balancing Urgency with Scientific Unknowns



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MIT Alumni for Climate Action

Credits

The MIT Alumni for Climate Action is a non-partisan group of Massachusetts Institute of Technology alumni. The following MIT Alumni wrote this document: Margaux Filippi, Martyn Roetter, Jeremy Grace, Shiladitya DasSarma.

VERSION 1.0

Executive Summary

Active removal of atmospheric carbon dioxide (CO_2) through carbon dioxide capture (CDR) and sequestration, along with the aggressive reduction of greenhouse gas (GHG) emissions, is necessary to achieve Net Zero carbon emissions. Achieving meaningful CDR faces two major challenges: (i) Reducing the cost of CDR, which remains high for novel technologies even compared to the increasing cost of climate change, and (ii) Scaling up a portfolio of CDR technologies to a cumulative capacity of 10-100 times current levels to achieve Net Zero. It is therefore paramount that careful planning be applied in the interest of the public good to achieve Net Zero by 2050. MACA's public policies recommendations are as follows:

1. Proven emission reduction strategies, i.e. the rapid and drastic (>80%) elimination of GHG emissions by replacement of fossil fuels as the source of energy throughout our economy by clean electricity, is imperative to limit global warming and concomitant development. The subsequent scaling of CDR must complement, not substitute, the decarbonization of the power sector and is needed to ultimately achieve Net Zero.

2. Given the low capacity of CDR, significant support for technological R&D is critical to scale up CDR to gigatonne levels. We support the development of a portfolio of CDR solutions through government support of nascent potential approaches, as no one or few CDR technologies have emerged as a panacea comparable to wind or solar power in clean energy.

3. Policymakers must consider the opportunity cost of CDR and the Social Cost of Carbon (SCC) when evaluating the scaling of technologies and/or other climate mitigation strategies to ensure that public funds are directed toward effective solutions equitably. For instance, given the vast and known sequestration capacity of natural sinks, the protection of such biodiversity should be prioritized.

4. We need a shift in governance, policy and the financial environment for CDR to scale up legitimate CDR technologies. Establishing favorable policies, well-regulated marketplaces and rigorous Measurement, Reporting and Verification (MRV) standards are vital for ensuring the credibility and effectiveness of CDR technologies, especially given the scientific uncertainties around some approaches.

5. Reallocation of fossil fuel subsidies towards CDR and renewable energy R&D is needed to accelerate the transition and create a more equitable climate policy. Currently, the financial burden primarily lies on startups that are incurring risk to scale critical climate technologies and, in turn, rely on marketplaces that provide insufficient incentive for effective and proven carbon removal.

6. When CDR technologies have matured in the longer-term, CDR will have to be scaled up by one (ten times greater) or more orders of magnitude to contribute significantly to the global goal of reaching Net Zero, and then Net Negative to restore the atmosphere.

A phased approach is needed for the development and large-scale deployment of CDR. The immediate needs in the current and following decades are to eliminate all possible emissions through a transition to clean energy, as well as to protect and expand natural carbon sinks, while developing the technological and economic tools for additional carbon removal strategies. When R&D of novel technologies have produced reliable solutions for CDR, then their scaleup and deployment should be prioritized for achieving Net Zero and ultimately Net Negative emissions and restoring Earth's atmosphere to an agreed safe level of greenhouse gas concentrations.

Introduction

Since 1751, anthropogenic activities have emitted ~1,500 metric gigatonnes of carbon dioxide or equivalent greenhouse gasses ($GtCO_2eq$, see Glossary), making up nearly 50% of all CO_2 in the atmosphere today, with CO_2 levels increasing from under 300 ppm in the preindustrial era to ~420 ppm today (Carbon Majors, 2024; NOAA, 2024). These emissions are disrupting a delicate balance in the Earth's carbon cycle, which includes cycling ~100 Gt naturally (Moseman & Rothman, 2024). In 2023, emissions from burning fossil fuels resulted in the release of 37 Gt of carbon with another 4 Gt from deforestation and wildfires (Cassidy, 2024). About 44% of anthropogenic emissions remain in the atmosphere, with the remainder absorbed by the ocean and land. The effectiveness of these natural carbon sinks has been declining recently - a trend likely to continue into the future (Friedlingstein et al., 2020). Without drastically reducing emissions from the current levels, the world will continue to experience rapid increases in CO_2 and in global warming, unless robust climate action is deployed at a large scale (DasSarma et al., 2021). Every degree increase in global warming expands the breadth and intensity of negative climate impacts, including the number of affected people. The targets of limiting global warming to 1.5°C[1] or 2.0°C above pre-industrial levels were established in 2015 by the Paris Climate Agreement as crucial thresholds to avoid catastrophic impacts on the environment, including extreme weather events and rapid sea level rise (IPCC, 2022a, Lamb et al., 2024)

Carbon Dioxide Removal (CDR) is the process of artificially removing CO_2 from the atmosphere with the intent to sequester the carbon long-term. In this paper, we apply three principles to qualify an activity as CDR as adopted in Smith et al. (2024): (1) the CO_2 captured must come from the atmosphere, not from fossil sources (2) The subsequent storage must be durable (i.e. no reintroduction to the atmosphere) (3) the removal must be a result of human intervention, additional to the Earth's natural processes. We refer the reader to Smith et al. (2024) for additional examples and definitions. CDR can be used to reduce the impact of carbon emissions and to purchase carbon offsets, which are typically measured in tCO_2eq. Examples of proposed CDR approaches include pulling carbon out of air mechanically processed through powerful fans or pumping carbon from photosynthesizing plants deep underground. The idea of artificially removing atmospheric carbon goes back several decades. For example, marine CDR field trials to fertilize the ocean with iron to create large blooms of photosynthesizing algae first took place about 30 years ago (Coale et al., 1998; Tollefson, 2017) . It has remained a very controversial topic, with its economic viability long contested and its environmental impacts unclear, whether in terms of effectiveness or of adverse side effects on biodiversity (Dooley et al., 2021).

There is a growing consensus among the scientific community that CDR is necessary to achieve the 2015 Paris targets. In other words, anthropogenic activities have released and accumulated so much carbon that solely cutting emissions will not be enough. In the remainder of the 21st century, it is clear that natural carbon sinks will be insufficient to maintain atmospheric carbon dioxide levels at a steady-state (NASA, n.d.). Not only do we need to curtail emissions, but we also need various technologies to remove carbon from the atmosphere, and we need the

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[1] For the first time, we have passed the 1.5°C warming in the last year (Copernicus, 2024).

deployment of these technologies to scale rapidly, i.e. by mid-century. Figure 1 illustrates different timelines for the implementation of CDR and its impact on climate over the 21st century, projections based on the latest Intergovernmental Panel on Climate Change (IPCC) report. In short, current scientific consensus states that we have released GHGs into our atmosphere and ocean to such an extent that we now urgently need to engineer ways to remove them, specifically carbon dioxide.

Despite the climate urgency, confusion persists in the political discourse, even at the highest levels of policy making. This includes lack of clarity and rigor in the definitions of and distinctions between CDR, Carbon Capture, Utilization and Storage (CCUS, see Inset 1), Direct Air Capture (DAC), etc. In addition, CDR as an umbrella term includes a broad range of approaches, technologies and scientific disciplines. It is imperative that investment of public funds in CDR technologies is guided by effective implementation strategies. The current confusion should not be exploited or magnified by financial and industrial interests to divert attention from Net Zero goals. To dispel confusion, genuine CDR must follow the principles outlined above.

The purpose of this paper is to summarize our positions on CDR and, specifically, the use of public funds to finance R&D and scale the deployment of CDR. A comprehensive technical review of CDR lies outside the scope of this paper and we instead refer the interested reader to Smith et al. (2024), which examines the state of CDR; GESAMP (2019), which focuses on marine geoengineering; and the IPCC's technical factsheet (IPCC, 2022b), which provides an overview of CDR technologies. Here, we aim to provide guidance for balancing various factors and tradeoffs that need to be considered carefully to achieve the desired goals of emissions reduction and carbon removal. We outline our recommendations for public policymakers.

CDR and Its Imperative

To meet the Paris Agreement targets and limit global warming to 1.5 to 2°C, all pathways rely on the deployment of CDR technologies to remove on the order of 10 $GtCO_2eq$ annually (IPCC, 2023; also see Figure 1). It is paramount to remember that CDR must happen concurrently with drastic emission reductions. A $GtCO_2eq$ never emitted because it is replaced with clean electricity has more impact than removal of an existing $GtCO_2eq$ from the atmosphere. The latter, if technology-based, requires the consumption of considerable energy (and other limited resources), which will generate additional GHGs so long as the power sector remains significantly dependent on fossil fuels. Moreover, claims that climate targets can still be achieved with continued use of fossil fuels, rather than their aggressive replacement by clean electricity, are false; see Inset 2. Emissions must be reduced substantially over the next 25 years and then the additional drawdown of carbon from the atmosphere must occur within relevant timescales to achieve Net Zero.

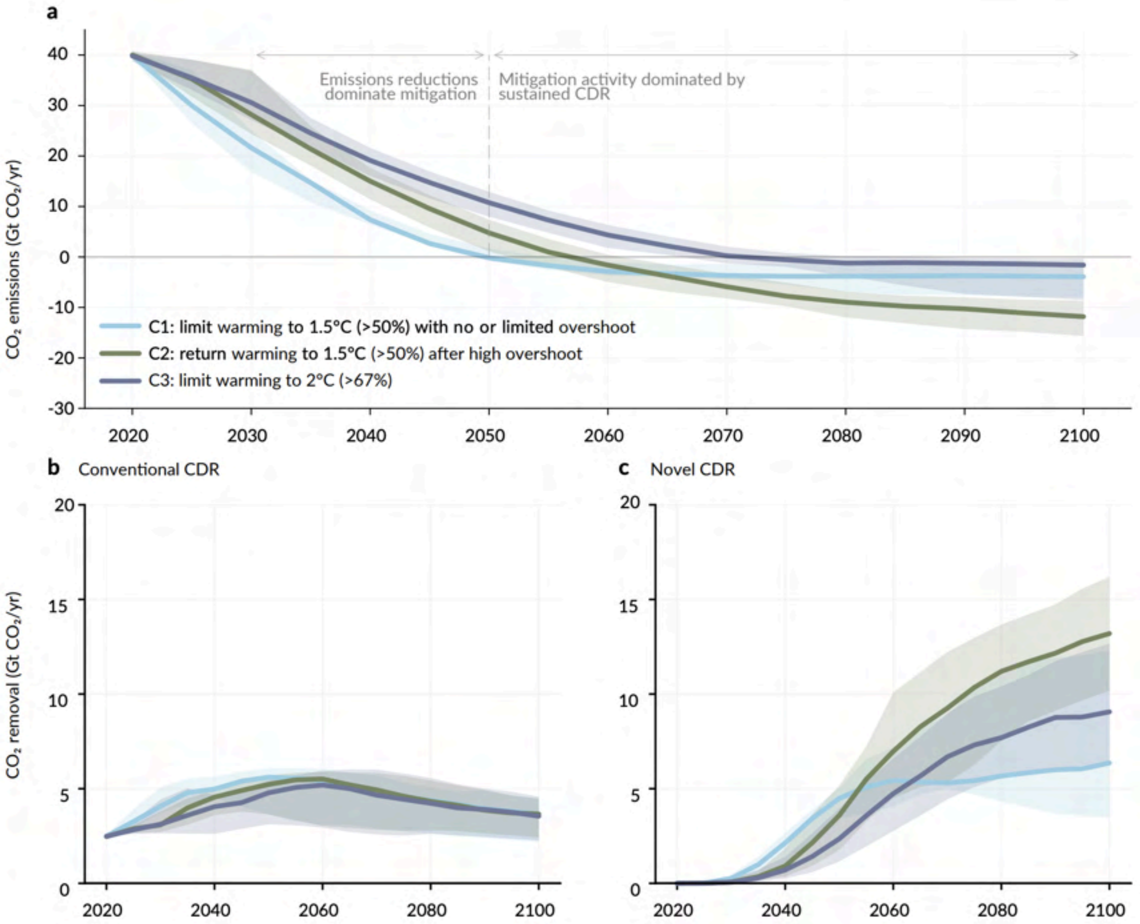

Figure 1. Adapted from Figure 8.1 in Smith et al. (2024) under the CC BY 4.0 license. (a) CO_2 emissions and (b, c) CDR tonnage projections under the C1, C2 and C3 scenarios from IPCC (2023). Thick lines refer to the median values and shaded ranges refer to the interquartile ranges. In C1, warming is limited to 1.5°C with no or limited overshoot. In C2, warming returns to 1.5°C after a high overshoot. In C3, warming is limited to 2.0°C. Here, "conventional" CDR refers to established and currently-deployed methods while "novel" CDR refers to technologies still in development (see Glossary).

Inset 1: CCS vs CDR

Carbon capture and storage (CCS) of CO_2 from fossil fuel emissions does not meet all three criteria for CDR [it fails criterion (i) nor does the use of captured CO_2 from the atmosphere to produce short-lived products such as fuels (it fails criterion (ii)]. Resources (money, engineers, electricity, water etc.) applied to the implementation of non-genuine or bogus (despite technological similarities) CDR will be diverted from their much more important and effective application to permanently eliminate anthropogenic emissions wherever feasible. By delaying or slowing emissions eliminations, bogus CDR will be creating an ever widening carbon gap for humanity to try to fill in eventually. Two conditions must be met to justify the support of CDR projects: (a) The CO_2 captured must be generated by applications where it is not feasible to replace the combustion of fossil or other polluting, including lower carbon fuels with clean electricity, and the use of bogus CDR is not being presented as a reason for delaying decarbonization where feasible through electrification, and (b) The resources consumed by the bogus CDR could not otherwise be applied to the decarbonization i.e. elimination of emissions from other applications by replacing fossil fuels. Satisfaction of this second criterion (b) will become more likely as we make progress towards maximum decarbonization of the economy, which will probably not be achieved for at least two or more decades. Efforts to support projects that fail to meet these criteria are deceptive or worse deceitful.

While “Net Zero” describes a state where anthropogenic emissions are balanced by the amount of GHGs it can remove from the atmosphere, “Net Negative” describes a state where the rate of removals exceeds these emissions. Net Negative targets are important in the long-term since global temperatures will continue to increase beyond their value when Net Zero is achieved and sustained. This is because of the Transient Climate Response (TCR), which at the time of Net Zero results from the accumulated emissions up to that point and will lead eventually to a higher Equilibrium Climate Sensitivity (ECS) value than the current situation (Hausfather, 2018). In contrast, by reducing atmospheric concentrations of GHGs, “Net Negative” removals will inhibit further increases in temperature over the long term, beyond the short-term TCR and will ultimately enable temperature decreases below TCR. Without Net Negative emissions, the ocean will respond over time to establish a new, warmer steady-state at the GHG concentration of the Net Zero point. Current levels of atmospheric CO_2 will likely result in sea level rise of 5-25 meters, among other impacts (NOAA, 2022). In other words, Net Negative is needed to restore the atmosphere to a state with a lower concentration of GHGs and to reestablish climatic conditions on Earth that are more favorable for humans and most other living creatures.

Inset 2: The scales of removal

To reduce the atmospheric concentration of CO_2 by 1 ppm (parts per millions) about 7.8 $GtCO_2$ must be removed. Therefore, to lower this concentration to 300 ppm, the highest level during the last 800,000 years (in the mid-1700s before the First Industrial Revolution it was 280 ppm) we would have to remove around 936 $GtCO_2$ if we start from today’s still increasing level of 420 ppm. One estimate of the remaining carbon budget for a 50% likelihood to limit global warming to 1.5, 1.7, and 2ºC is 75 Gt C (275 $GtCO_2$), 175 Gt C (625 $GtCO_2$) and 315 Gt C (1150 $GtCO_2$), respectively, from the beginning of 2024, equivalent to around 7, 15, and 28 years, assuming 2023 emission levels. These estimates suggest that we will have to remove just over 1,000 $GtCO_2$ if global warming is limited to 1.5°C and over 1,800 $GtCO_2$ if it is limited to 2°C to bring the CO_2 concentration down to 300 ppm.
It has also been estimated that, in the few decades after Net Zero is achieved, CO_2 concentration will have to be reduced by 40-55 ppm (or 312-429 $GtCO_2$ removed) to avoid a temperature overshoot during this period. See the Glossary for definitions of TCR (short-term temperature increase when Net Zero is reached) and ECS (long term temperature increase at a higher sustained level of atmospheric concentration of greenhouse gasses).

Given the urgency of the climate crisis, it is paramount to implement high-impact solutions. Substantial technological R&D and a favorable financial environment are crucial to achieve large-scale CDR deployment. Innovation is happening in various areas, from DAC to marine CDR (mCDR) (Lieber et al., 2023; Zhang et al., 2024). Recognizing that no single technology (“silver bullet”) currently exists that can provide a silver bullet solution on a global scale, we support a diverse portfolio of CDR approaches (DasSarma et al., 2021). Table 1 shows the scale of the current capacity of various CDR approaches in comparison to other climate mitigation factors, such as natural sinks. It becomes evident that there is a huge gap between the capacity of the current CDR approaches and the aim to remove $GtCO_2$. Table 1 also highlights the small scale of “technological” CDR, which currently totals less than 0.04 $MtCO_2$ / year, compared to natural carbon sinks and other approaches to natural carbon management. For instance, Smith et al. (2024) estimate that averaged over the period 2013- 2022, the conservation and restoration of forest, peatland or coastal wetland sequestered about 2 $GtCO_2$ / year. Even if the existing CDR technologies were scaled, they would very likely still be insufficient to reach such a scale and new technologies are needed to reach the Paris targets. For example, the maximum scalable capacity of DAC may be limited by the sheer volume of air that has to be processed to capture or extract 1GtCO_2, given the low concentration of CO_2 - currently in the range of 420 ppm (2024), and perhaps rising to 500 ppm (Stauffer, 2024; also see Inset 3).

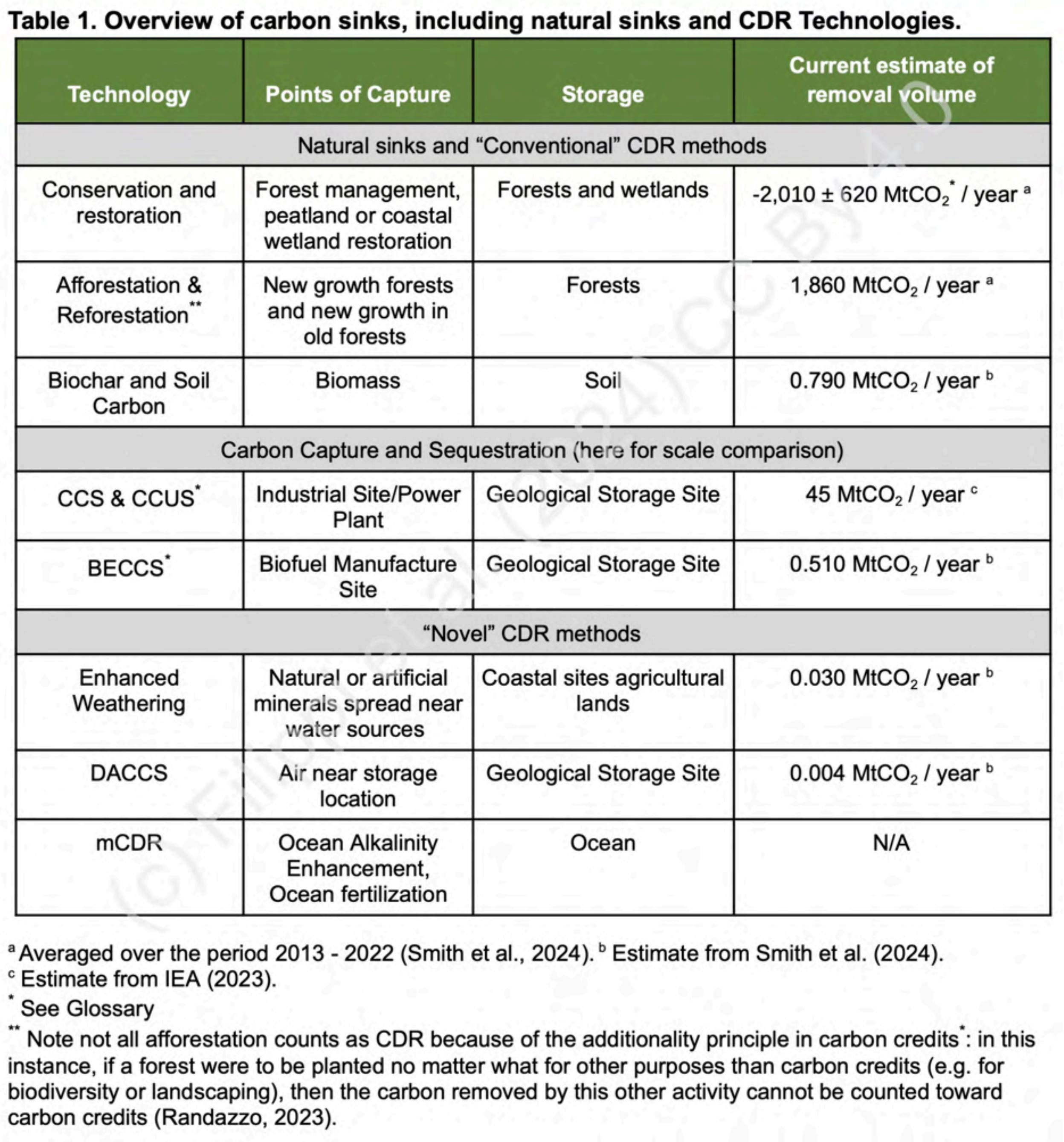

Table 1. Overview of carbon sinks, including natural sinks and CDR Technologies.

Technology	Points of Capture	Storage	Current estimate of removal volume
Natural sinks and "Conventional" CDR methods			
Conservation and restoration	Forest management, peatland or coastal wetland restoration	Forests and wetlands	-2,010 ± 620 MtCO_2* / year [a]
Afforestation & Reforestation**	New growth forests and new growth in old forests	Forests	1,860 MtCO_2 / year [a]
Biochar and Soil Carbon	Biomass	Soil	0.790 MtCO_2 / year [b]
Carbon Capture and Sequestration (here for scale comparison)			
CCS & CCUS*	Industrial Site/Power Plant	Geological Storage Site	45 MtCO_2 / year [c]
BECCS*	Biofuel Manufacture Site	Geological Storage Site	0.510 MtCO_2 / year [b]
"Novel" CDR methods			
Enhanced Weathering	Natural or artificial minerals spread near water sources	Coastal sites agricultural lands	0.030 MtCO_2 / year [b]
DACCS	Air near storage location	Geological Storage Site	0.004 MtCO_2 / year [b]
mCDR	Ocean Alkalinity Enhancement, Ocean fertilization	Ocean	N/A

[a] Averaged over the period 2013 - 2022 (Smith et al., 2024). [b] Estimate from Smith et al. (2024).

[c] Estimate from IEA (2023).

* See Glossary

** Note not all afforestation counts as CDR because of the additionality principle in carbon credits*: in this instance, if a forest were to be planted no matter what for other purposes than carbon credits (e.g. for biodiversity or landscaping), then the carbon removed by this other activity cannot be counted toward carbon credits (Randazzo, 2023).

Inset 3: The scalability of DAC

DAC involves processing the atmosphere to remove CO_2, a gas present in concentrations of only several hundred ppm. Other GHG are present in much lower concentrations. DAC systems consequently require using active mechanical or chemical equipment and vast quantities of energy, which must be clean and renewable so they do not contribute to further GHG emissions, in a battle against entropy. Regardless of how the air is processed to remove CO_2, how much air needs to be processed to remove $GtCO_2$ quantities per year?

According to our calculations:

i. A 420 ppm CO_2 concentration means we have 420 mol CO_2 / 10^6 mol air*.

ii. Given a molar mass of CO_2 of 44.01 g/mol, a mass of 1 $GtCO_2$ corresponds to:
10^{15} g CO_2 / 44.01 g/mol = $2.272 \cdot 10^{13}$ mol CO_2.
That is the number of atmospheric moles of CO_2 to remove to capture 1$GtCO_2$.

iii. The corresponding number of moles of air to capture is thus:
($2.272 \cdot 10^{13}$ mol of CO_2) • (10^6 mol air / 420 mol CO_2) = $5.41 \cdot 10^{16}$ mol

iv. Based on the ideal gas law ($V = nRT/p$), at p = 1 atm and T = 25°C, this corresponds to: $V = (5.41 \cdot 10^{16}$ mol$) \cdot (8.3145$ m^3 Pa/mol/K$) \cdot (298$ K$) / (101{,}325$ Pa$) = 1.32 \cdot 10^{15}$ m^3 The corresponding volume is V = 1.32 million cubic kilometers per $GtCO_2$.

v. According to *iv*, the volume of air that must be processed to remove a total of 1 $GtCO_2$ during a year is $1.32 \cdot 10^6$ km^3. Since there are 31.536 million seconds in a year (ignoring leap years) this annual volume translates into a requirement to continuously process 1.32/31.536 km^3/sec or 41.9 km^3 /sec throughout the year.

vi. The capacity of the mechanical equipment needed to move this volume of air for processing to remove 1 $GtCO_2yr^{-1}$ through DAC** can be put into perspective by considering the capacity of jet engines. The air mass flow rate of a Rolls-Royce Trent 900 jet engine (one of the world's largest jet engines used to power the Airbus A380) that is sucked in by its fan blades is 1,245 kgs^{-1}, or ca. 1,100 m^3s^{-1} at sea level.

vii. Hence to process $41.9 \cdot 10^6$ km^3/s of air to remove 1 $GtCO_2yr^{-1}$ with DAC assuming a 100% capture rate, a total of 38,000 fans or fan systems with the capacity of one of these engines would be needed (41,000 fans / $GtCO_2$), or about 380,000 of them to remove 10 $GtCO_2yr^{-1}$. The actual number needed would be significantly higher given that it is unrealistic to expect such mechanical systems to operate continuously. For reference the cumulative numbers of jet engines produced globally with air mass flow rates comparable to that used in this calculation amount to at most thousands.

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* By convention, ppm is in mass in water but in moles in air.

**Adapted from Cebon (2022)

CDR has historically fallen under the field of geoengineering, i.e. the deliberate planet-scale engineering of the climate to counteract anthropogenic global warming. The other main subfield of geoengineering is Solar Radiation Management (SRM), which consists of modifying the way sunlight enters the atmosphere (UCS, 2020). Unlike CDR, SRM does not remove CO_2 from the atmosphere but focuses solely on climate without directly addressing excess CO_2. An example SRM project is modifying how the sun reflects off the Arctic ice to prevent massive melting. Many SRM projects are however much wider in scope and less reversible than protecting sea ice in the Arctic. These commonly involve altering clouds or spraying aerosols in the stratosphere, which will have side effects on the global scales that are far from being understood (Trisos et al., 2018; GESAMP, 2019; Haywood & Tilmes, 2022). Other schools of thought consider CDR to be a type of waste management rather than geoengineering. Although the end goal of CDR is to restore the climate on a planetary scale, the process involves removing excess atmospheric CO_2 through point sinks, i.e. very localized sources of carbon capture, as opposed to deliberately impacting weather patterns. Removing atmospheric CO_2 focuses on removing pollutants from the atmosphere rather than attempting to alter how Earth - including its atmosphere, oceans, land mass and ice mass - responds to incoming solar energy. Compared to such climate change mitigation strategies, CDR can offer significant advantages and fewer risks or unknowns.

In addition to SRM and CDR, other proposed climate mitigation strategies include the use of hydrogen and “renewable natural gas” to replace methane for heating buildings (Energy and Policy Institute, n.d.), the production of “Net Zero Oil” (Liekens et al., 2024), or investments in carbon capture facilities that reduce but do not eliminate emissions (Foley, 2023). All these schemes consume clean electricity required for emissions reduction, delaying and impeding already overdue targets needed for the Paris Agreement. Further delays increase the already large gap in current CDR capacity which must be filled if our goal of Net Zero (and ultimately Net Negative) emissions are to be achievable within a human lifetime. Investment in carbon capture facilities at sites for applications that cannot be electrified will however be valuable later by reducing the CDR capacity needed to achieve Net Zero.

The delay in implementation of emissions reduction over the past decades has already made the need for developing effective CDR increasingly urgent. The longer is our time frame for substantially reducing growth in atmospheric GHGs (and thus achieving the temperature targets of the Paris Agreement, and, ultimately Net Zero), the more urgent will CDR become in future (Gore, 2007). The timing of the at-scale deployment of CDR technologies is also critical. Whether introduced too early - the technology is not yet ready or other conditions for market development are not in place - or too late for some if other participants have established dominant positions in a market that satisfy all needs are both recipes for business failure. The investment of public resources must take into account factors such as the timing and timescales of atmospheric carbon removal. A specific example is Bach et al. (2021), which found that certain mCDR efforts can remove oceanic carbon without achieving net atmospheric drawdown for centuries due to global oceanic patterns; in other words, 1 kg of CO_2 removed from the ocean does not always equate to 1 kg of CO_2 removed from the atmosphere; see Long et al. (2024) for additional examples. The allocation of resources needs to be balanced against those devoted to proven, effective climate action. Most importantly, the protection and enhancement of existing carbon sinks that have been proven to remove carbon within relevant timescales must be prioritized especially in the short term, when novel CDR technologies are not yet mature.

In summary, the obstacles to reaching Net Zero while staying within the goals of the Paris Agreement are political, economic, social and institutional, often reinforced by resistance to change and opposition from influential special interest groups (see the “Fog of Enactment” in Stokes, 2020). In contrast, there are major barriers and unknowns about how to achieve CDR at the $GtCO_2$ scale on timelines that are relevant and can influence the climate trajectory within a human lifetime. The novel CDR technologies required are not yet ready for deployment at scale and it is unclear when one or more orders of magnitude improvements in their performance and costs can be achieved. It is therefore paramount to boost R&D efforts to even have a chance at meeting the Paris targets.

Opportunity Cost of CDR

The opportunity cost of CDR relates to both other methods of emissions reductions and the social cost of carbon. When it comes to public funding for CDR, expending resources on activities that do not drive down emissions prevents use of those resources for current emissions reductions. Fortunately, we already understand how to decarbonize the power sector, which requires major transformations on both the supply and demand sides. They include wind and solar generators of electricity, heat pumps and battery technologies (Rosenow et al., 2022; Lempriere, 2024). When evaluating the public funding of CDR deployment, we advocate for a thorough assessment of the societal benefits of the various approaches, mindful of opportunity cost compared to direct decarbonization, mitigation, adaptation and other climate strategies. In addition, we highlight the need for a coherent approach when evaluating the price of CDR technologies, typically expressed in \$/tCO_2eq, against the estimated Social Cost of Carbon (SCC or SC-CO_2). SCC is used to estimate the economic damages associated with the emission of an additional tCO_2eq, which is especially relevant considering that we are relying on the voluntary carbon markets to develop and scale CDR.

Similar to other emissions reduction approaches, such as transitioning to renewable energy and electrification, a relevant basis of cost comparison for CDR technologies is the opportunity cost of not practicing CDR, i.e. the price of climate change. Given the recent trends with the average annual costs of weather-related large disasters exceeding well over \$100 billion on average over the last 5 years and \$600 billion in 2023 (Smith, 2024) and the cost to human health estimated to be over \$820 billion annually (Duncombe, 2021), the opportunities are substantial (nearly \$ 1 trillion or about 4% of US GDP). These damages include the costs of the destruction caused by more frequent and more intense extreme climate-related events (floods, fires etc.), as well as the additional costs of health care resulting from pollution caused by our use of fossil fuels and other losses in human productivity.

One crucial factor when estimating the SCC is the discount rate. This rate affects the perceived cost of future climate harms in today's dollars and is a key variable in decision-making regarding climate action. A higher discount rate diminishes the value attributed to the wellbeing of future generations, making it a critical ethical choice. When evaluating CDR investments, a lower discount rate provides a stronger justification for immediate action, as it gives greater weight to the long-term benefits of removing carbon today. Similarly, discount rates can influence the costs and risks associated with CDR technologies, emphasizing the importance of careful consideration in policy frameworks. Rennert et al. (2022) produced a mean estimate of \$185 / tCO_2 using a 2% discount rate. If a 3% rate is applied, this drops to \$80 per tonne, while lowering the rate to 1.5% increases it to \$308 per tonne. These estimates underscore how discount rates shape the economic case for CDR and other climate actions. In light of the accelerating impacts of climate change, lower discount rates are increasingly seen as appropriate, as they reflect the greater urgency of reducing carbon emissions now to prevent future damages. By assigning greater value to future generations, lower discount rates make a compelling case for investing in CDR technologies today.

In comparison to the SCC of \$185/tCO_2, the cost of CDR is estimated to vary between \$10 to \$500 / tCO_2eq (IPCC, 2022b). Industrial CDR is expensive because it typically requires alternative or new facilities and equipment that can be powered by electricity. There are also concerns about scalability given the volumes of air that need to be processed annually through DAC facilities (see Inset 3). However, its results and benefits are easy to track and validate. Every other CDR approach confronts still unresolved obstacles to achieving orders of magnitude improvements in removal capacity. For example, biomass is cheaper but faces challenges in terms of uncertain and potentially damaging side effects, such as on biodiversity, and concerns regarding scalability and the validity or potential for fraud of associated carbon offsets (Pörtner et al., 2021). This is also true for marine CDR, as operating in the ocean is very expensive and many mCDR methods have a tractability issue. These examples alone provide reason to first, pursue a portfolio of CDR approaches, especially for the goal to achieve a cumulative annual capacity of $GtCO_2$, and second to remain skeptical that it will be possible to find one or two silver CDR bullets to meet Net Zero and Net Negative targets (Herzog et al., 2024). The various CDR technologies all exhibit very different value-based characteristics and these must also be considered when evaluating the opportunity cost.

In summary, we urge that the public discourse surrounding CDR incorporate the economic principle of opportunity cost. This cost variance is influenced by the diverse CDR technologies, the discount rate, as well as by considerable remaining uncertainties in the costs of some individual CDR modalities. Thus, when evaluating CDR options, a value-based decision-making approach is indispensable. It must incorporate an analysis of not only the direct monetary expenses but also the broader implications and trade-offs involved in deploying various CDR technologies. Additionally, confidence in the integrity and efficacy of CDR deployments is contingent on rigorous Measurement, Reporting and Verification (MRV). MRV standards, along with comprehensive life-cycle analysis and environmental impact assessments, are however currently in their infancy (CarbonPlan, 2023). While we envision immense potential in CDR technologies, establishing their costs, scalability and effectiveness remain critical challenges that necessitate rigorous scientific inquiry and innovation. As briefly explained in Illustrative Inset 4, the history of the semiconductor industry offers some insights into the importance of public policies and investments in building and scaling up new technological capabilities.

Inset 4: Comparison to the semiconductor industry

The history of the semiconductor industry in the US [22] provides some lessons for public policies and funding designed to stimulate the development of CDR technologies and approaches. The technological, historical and other circumstances and market and political conditions affecting the development of semiconductors are very different from those of CDR removal today so we must be careful in drawing parallels or identifying lessons that are transferable from one to the other. Nevertheless, CDR policies must include a mix of R&D support ranging from scientific research for those at low TRL levels to the support of pilot and increasingly large applications, along with procurement policies that provide opportunities for CDR companies to build revenue streams as early as possible and attract private sector investments. In the case of semiconductors, procurements by the military and NASA played a significant role for the latter purpose. For CDR the development of national and state plans setting CDR objectives and making public funding available for genuine CDR projects is the equivalent and supported by the substantial social cost of carbon and the relative costs of emissions reduction and carbon dioxide removal.

Political and Legal Landscape

The current urgency of climate action results from decades of political inaction and slow political and industrial response to academic and scientific consensus. Even a decade after the Paris Agreement, we have not yet succeeded in materially reducing emissions (UNEP, 2023). Recent milestones in the climate crisis indicate that forecasts of the impact of climate warming may even prove to be too conservative (Lauro & Khanna, 2024). Moreover, despite the imperative of decarbonizing the electric power sector, fossil fuels have continued to generate more electricity worldwide. Although fossil fuel power plants account for a smaller share of total electricity generation, they are generating more of it because the demand for electricity has been increasing in both developing and developed economies. Current plans do not directly address the increasing demand for electricity resulting from new technologies and applications, nor the vulnerability of the transmission network (Do et al., 2023). Examples of new applications include the power consumption of data centers, especially those handling AI workloads, and the share of electricity consumption of data centers in the US is forecast to increase from 4% in 2023 to over 9% by 2030 (EPRI, 2024; Bryce, 2024). The slow phaseout of fossil fuels, transition to renewables and increased electricity demands all underscore the need for scalable CDR for avoiding global warming beyond 2ºC, even while these technologies are fully developed or market-ready.

Policies that support CDR must prioritize sustained R&D efforts, enabling innovators to bring working solutions to market within well-regulated (including, among others, added transparency and long-term accountability) carbon marketplaces. The 2021 bipartisan Infrastructure Law (BIL) included investments of $3.1 billion in natural CDR, including reforestation, and conservation and management, and $8.6 billion in technological CDR investments, including 4 regional DAC hubs for 0.1 Gt/year capacity, expanded CCS, and transport of captured CO_2 (Beugels, 2022). In addition, the 2022 Inflation Reduction Act (IRA) included several billion dollars more for both natural CDR and tax credits for technological CDR investments. While the combined $12 billion investment through the BIL and IRA is significant, this corresponds to 63 $MtCO_2$ at a carbon credit price of $100/$tCO_2$ and 117 $MtCO_2$ at the SCC price of $185/$tCO_2$, falling short of the $GtCO_2$ scale by an order of magnitude. Additionally, public investments also rely on creating tax credits for carbon, which have rewarded dubious carbon capture claims on many occasions (Greenfield, 2023a, 2024; Euronews Green, 2024; Kim, 2024). To scale up CDR meaningfully, future investments must focus on technologies with genuine large-scale carbon removal potential, without undermining renewable energy investments, which have been proven to effectively reduce emissions.

Globally, direct fossil fuel subsidies totaled $1 trillion in 2022; when accounting for indirect subsidies, this number rises to $7 trillion, which corresponds to 7.1% of global gross domestic product (GDP), reflecting a $2 trillion increase since 2020 due to government support from surging energy prices (IMF, n.d.). In the United States fossil fuel subsidies totaled $757 billion in 2022 (Black et al., 2023). While an in-depth economic analysis is beyond the scope of this paper, these staggering figures raise two questions: first, why are we continuing these enormous subsidies of an economic sector we must reduce our dependence on? Second, can we redirect a fraction of these subsidies towards climate R&D, including CDR R&D? This seems to be a key opportunity as even diverting 0.5% of these direct fossil fuel subsidies toward CDR would be ~$1.5 billion. This figure should grow with the transition and would help emerging startups grow and signal a decisive shift in climate policy priorities. This reallocation would create a more equitable market for CDR while also addressing inefficiencies in current tax credit schemes. Public investments should be channeled into R&D and the deployment of verified CDR projects rather than allowing ineffective subsidies to perpetuate fossil fuel reliance. Ultimately, policy must foster collaboration between CDR and renewable energy sectors, avoiding unnecessary competition for resources and ensuring that the focus remains on achieving Net Zero.

To increase CDR innovation and achieve scale-up, additional policies are needed to meet unmet demand (at reasonable prices) for carbon removal by stimulating effective removal. The viability of startups is at risk if there are no pathways to sustain them until they become profitable. If they will not be able to sell quality credits for 5-10 years, then government financing is necessary to support R&D, innovation and startups and market development. Otherwise all the burden falls on these companies to “sell” quality CDR, which can be especially problematic for a few reasons. First, while some companies refuse money from oil (Axios, 2023), not all startups are in the position to negotiate with much larger organizations that are potential customers where there is an enormous asymmetry of power, and whose agendas, priorities and motivations are very different and even antithetical to theirs. Second, there currently remains scientific uncertainty around the efficacy of multiple CDR approaches. While we advocate against large-scale deployments without understanding the effects of these technologies, startups should not bear alone the price for this uncertainty about the eventual potential size of the markets for their technology. The required level of confidence or confirming evidence as a CDR technology progresses successfully along the TRL scale justifies further and inevitably rising investments to reach the next level, and ultimately successful large-scale deployments.

Recent events underscore the need for effective and transparent governance. Concerns about MRV and CDR are supported by evidence of bogus verification and certification of carbon offsets, as well as conflicts of interest arising from the financial ties between DAC firms and fossil fuel companies (Greenfield, 2023b; Valle & Bose, 2023). The market forces that can stimulate and support the supply of CDR removal to meet demand, as well as other elements of climate action, are not yet in place in sufficient breadth and depth. Today’s market forces together with existing subsidies are loaded against adequate timely climate action and in favor of the interests of the incumbent fossil fuel and other industries with vested interests. Along with the establishment of market incentives that prioritize robust MRV processes and effective CDR, political and economic leadership is indispensable. Such leadership should support legitimate CDR efforts in the context of a broader collective response to the increasingly tangible threats to humanity from climate change.

In summary, strategic advances in the political and legal landscape for CDR are needed. Our position that governments should financially support R&D and adopt policies to help the transition is a policy recommendation that is not revolutionary. Reports from the World Economic Forum (Pour, 2024) and Carbon Futures (Manhart, 2024) recommend regulation of markets, direct purchases of technology or credits and adopting policies that provide clarity and stability for industries on the scale of decades. In addition to subsidies and tax credits, Manhart (2024) also emphasizes the guidance role that the government can play as an effective multiplier for real climate solutions, prompting the development of the CDR market to the scale needed.

Conclusions

The increasing urgency of tackling climate change and the growing intensity and frequency of damaging climate-related events is the result of our collective failure over multiple decades to listen to the warnings of the scientific community and to exercise caution. Consequently, the needs for effective climate actions are becoming increasingly urgent. We must first substantially reduce the continuing growth of the concentrations of atmospheric GHGs and within a generation achieve Net Zero to stabilize these concentrations at the lowest possible level. Since this will most likely be higher than that which is desirable for the long term, and may not meet the temperature targets of the Paris Agreement, we must strive to achieve Net Negative emissions to restore the atmosphere by bringing GHG concentrations down to a safer level. The timing and mix of actions, specifically emissions reductions and carbon dioxide removal, will require careful scientific, economic, and policy considerations to achieve these critical goals. Moreover, since no single CDR approach in existence thus far seems to have the potential to scale to net (i.e. effective) $GtCO_2$ potential, a portfolio of approaches is to be privileged, to avoid every fraction of a degree of global warming possible.

The preceding discussions reveal the considerable uncertainties both scientists and policymakers face, given the current inadequacies of necessary novel CDR technologies. In the absence of any obvious one or few silver bullets, developing policy to achieve the targets of the Paris Agreement must ultimately rely primarily on emissions reduction. Thus it is imperative to eliminate fossil fuel emissions by replacing fossil-fuel powered electricity with renewable clean electricity as extensively and rapidly as possible, which is both technologically possible and economically favorable (Jacobson et al., 2019). Analysis has shown the considerable benefit to human health from reduction in pollution that will result (De Alwis & Limaye, 2021). Diverting resources to false or demonstrably inadequate solutions is unacceptable and will prolong fossil fuel usage and further increase atmospheric CO_2 levels significantly beyond what could otherwise be achieved. This paper also underscores the need for creative financing measures and support of R&D to build and sustain a portfolio of capable CDR systems with a combined capacity one or more orders of magnitude higher by mid-century. Development and innovation must be encouraged and sustained across a portfolio of CDR modalities to meet foreseeable substantial demands for carbon removal. Additionally, natural sinks for carbon are critical for reducing atmospheric CO_2, and they must be protected and enhanced for future generations of human society.

In summary, our policy recommendations are:

- Prioritize the timeline of substantial decarbonization by minimizing our dependence on fossil fuels - the slower the rate of decarbonization, the greater the amount of CO_2eq that will have to be removed by CDR technologies -, as well as by other proven climate mitigation strategies such as the protection of existing natural sinks
- Heavily invest and support CDR R&D to ensure the world will have the technology to reach Net Zero and Net Negative. This support includes financial as well as political, legal and regulatory initiatives
- Prioritize approaches for any R&D, deployment and scaling of CDR, with lower opportunity cost of CDR based on progress in R&D and scaleup and rigorous MRV
- Transition fossil fuel subsidies to development and implementation of renewables and CDR technologies

Beyond technological innovation, climate change mitigation and adaptation require coordinated and effective efforts on a global scale. This necessitates proactive, targeted policies and investments that are consistently maintained and adapted over several decades as we learn more. Our messages to the global public stakeholders stress the need for coherent policy frameworks, transparent evaluation metrics and value-based decision making. We urge world economies to align their investments with societal values recognizing the urgency and gravity of the threats to human life and wellbeing caused by changes in the Earth's climate. These changes and their consequences on extreme weather events are being exacerbated by our own actions. We can control, and then stop and reverse, these changes if we reject the mis- and dis-information that is commonplace, and find the collective will to implement policies and transform market forces.

Glossary

Term	Brief Definition
BECCS	Bioenergy with Carbon Capture and Storage.
Carbon Credits	Credits generated by projects that have avoided or removed GHG emissions. Each credit represents one less tCO_2eq in the atmosphere as a result of the project.
Carbon Capture and Storage	Carbon Capture and Storage. Refers to technologies that capture CO_2 emissions from industrial processes and transport them to be stored durably underground to prevent them from entering the atmosphere.
CDR	Carbon Dioxide Removal.
CDR (Conventional)	CDR methods that are well established, already deployed at scale and widely reported by countries, typically as part of land use, land-use change and forestry activities. Included in this group are the following methods: afforestation, reforestation; agroforestry; forest management; soil carbon sequestration; peatland and coastal wetland restoration; and durable wood products.
CDR (Novel)	All other CDR methods. The captured carbon is typically stored in geological formations, the ocean or products. Generally, these methods have lower TRLs and are deployed at smaller scales. Examples of such methods include bioenergy with carbon capture and storage, DAC, enhanced rock weathering, biochar, mineral products and ocean alkalinity enhancement.
CO_2eq or CO_2e	Carbon Dioxide equivalent. A metric measure used to compare the emissions from various greenhouse gasses on the basis of their global-warming potential (GWP), by converting amounts of other gasses to the equivalent amount of carbon dioxide with the same global warming potential (E.U. definition)
DAC or DACCS	Direct Air Capture or Direct Air Carbon Capture and Storage.
ECS	Equilibrium climate sensitivity. The temperature change once the system has reached a new equilibrium after CO_2 doubling. A further increase in temperature, over and above the increase already experienced, will occur thanks to the delayed ocean response to CO_2 changes before the system reaches a new equilibrium with a stable CO_2 concentration (i.e. sustained Net Zero).
$GtCO_2eq$	Billions of tCO_2eq.
mCDR	marine CDR.
MRV	Measurement, Reporting and Verification.
$MtCO_2eq$	Millions of tCO_2eq.
$SC\text{-}CO_2$ or SCC	Social Cost of Carbon ($SC\text{-}CO_2$). Measures the monetized value of the damages to society caused by an incremental tCO_2eq emissions.
tCO_2eq	Metric tonnes of GHG emissions expressed in metric tonnes of CO_2eq.

TCR	Transient Climate Response. The estimated level of global warming at the time of CO_2 doubling, following a rise of 1% per year, or the near or medium-term warming. The Paris Agreement targets are TCR values.
TRL	Technology Readiness Level. System to assess a technology's maturity, ranging from level 1, at which "initial scientific research has been conducted", to level 9, at which a system is "ready for full commercial deployment" (Manning, 2023). Conventional CDR Methods are at levels 8-9, while novel methods are currently assessed at the levels 1-6 or even down to 1 Smith et al. (2024).

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