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Primer

Carbon accounting for carbon dioxide removal

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SUMMARY

Carbon dioxide removal (CDR) technologies are essential to address climate change and serve to compensate for legacy and hard-to-abate greenhouse gas emissions. Although near-term emissions reductions should be the priority, development and deployment of CDR must proceed now to ensure that relevant technologies are ready at scale in the future. Despite a rapid growth in CDR purchases, no single standardized methodology for evaluating project-level net CO_2 removal exists. Life cycle assessment (LCA) frequently produces net-negative emissions footprints, but only a small subset of those systems achieves a net flux of CO_2 out of the atmosphere. In contrast to LCA, CDR accounting uses expansive system boundaries and excludes avoidance credits to distinguish between systems that achieve net removal from those that only contribute to emissions mitigation. This primer discusses a framework and set of metrics for CDR accounting.

The current state of quantifying and valuing CDR

A common mantra in climate change mitigation is “do our best, remove the rest.” Decarbonizing the global economy is crucial for avoiding the most catastrophic impacts of climate change. The Intergovernmental Panel on Climate Change (IPCC) projects that humans must cut net carbon emissions to zero by mid-century and achieve net-negative emissions thereafter to compensate for the warming effects from legacy emissions. Most integrated assessment models suggest that carbon dioxide removal (CDR; Box 1) will be needed to achieve both of these goals. Although the mantra implies that removal should be the *last* climate change mitigation strategy, employed only after all cheaper options for mitigation and decarbonization have been exploited, the reality of technology development and scale up necessitates that CDR be pursued now so that it is poised to operate at the scales needed in several decades. In response, a CDR ecosystem of suppliers, verifiers, and buyers is emerging.

As of August 2024, more than 10 million tons of nominal CDR have been sold at a weighted-average price of approximately \$270/ton CO_2, according to CDR.fyi, of which 3.4% has been delivered. The greenhouse gas (GHG) emissions footprints of most CDR buyers are far from zero and typically include sources that could have technically viable mitigation options (e.g., grid electricity, low-temperature heat, and material selection). Purchases span a diverse range of technologies, from biochar production and land application to direct air capture with storage (DACS) (Figure 1). In part, the interest and investment in the CDR industry exist because the broader carbon offsets market has failed to reliably and verifiably deliver on its promises of both mitigation and removal and because companies may have limited options to directly decarbonize their own supply chains without broader system-wide shifts in how we use energy and manufacture goods. With the increasing focus on carbon removal, it is essential to develop consensus around what CDR is and how project-level accounting should be done to avoid pitfalls of the past.

CDR’s attractiveness is tied to the fact that, in theory, it involves simple-to-track flows of carbon out of the atmosphere. A DACS facility can pull CO_2 out of the air, compress it, and inject it underground. A biomass with carbon removal and storage (BiCRS) facility can process plant material containing carbon that was absorbed from the atmosphere and convert it to a more stable and/or storable form. A mineralization technology can expose otherwise occluded reactive rocks to the atmosphere to convert ambient CO_2 into thermodynamically stable minerals. However, not all technologies that remove CO_2 from the atmosphere, nor all projects that achieve net negative life cycle emissions according to conventional life cycle assessment (LCA; Box 1), actually result in net removal of CO_2 from the atmosphere. This primer outlines the basics of a carbon accounting methodology, applied to a range of CDR technologies, to evaluate their effectiveness in achieving a net flux of CO_2 from the atmosphere. We share illustrative examples for applying this framework to DACS, BiCRS, and land-based mineralization systems.

The need for uniform standards to evaluate CDR

At the most fundamental level, CDR projects should deliver a net flux of CO_2 from the atmosphere to stable storage after accounting for the actual energy, materials, and environment used for a project. A standardized process for quantifying net CO_2 removal is important for the development of a trusted

Box 1. Key terms and definitions

Carbon dioxide removal (CDR): activities that remove CO_2 from the atmosphere and transform it for durable storage. CDR includes enhancement of natural carbon sinks and direct air capture and storage (DACS). It excludes natural CO_2 uptake not directly caused by human intervention.
CDR project: a human intervention that results in a net flux of $CO_{2eq.}$ from the atmosphere.
CDR technology: a component of a CDR project that is required to remove CO_2 from the atmosphere.
Greenhouse gas (GHG) mitigation: a human intervention to reduce GHG emissions and/or to remove GHGs from the atmosphere.
CDR accounting: a summation of all GHG fluxes due to a CDR project that quantifies the net flux of CO_{2eq}.
Life cycle assessment (LCA): a standardized methodology for assessing the system-wide environmental impacts from a particular product, service, or system over its life cycle (e.g., production, use, and disposal).
System boundary: the set of technological, spatial, temporal, and other criteria that determines which activities and environmental impacts are included in LCA or CDR accounting.
Counterfactual: A description of the activities and impacts that would have occurred if a particular activity or project had not been implemented.

CDR industry. Two important aspects of this process are the system boundaries and counterfactuals. The system boundaries define what is in the analysis and what is not. Boundaries are spatial (e.g., considering only impacts within a specific country), temporal (for a defined time span), and technological (only certain infrastructure systems are included). The importance of system boundaries is well illustrated by the case of carbon capture and storage (CCS) applied to corn ethanol facilities. When a system boundary is narrowly defined to include only the capture and storage of the CO_2, these facilities achieve net CDR on paper: they take biogenic CO_2 generated at fermenters and inject it underground. However, a broader system boundary that accounts for the emissions from cultivation, delivery, and conversion would suggest that no net removal occurs. Instead, CCS serves to reduce the GHG emissions of net-emitting facilities, a prime example of emissions mitigation. Counterfactuals describe the activities and impacts that would have occurred in the absence of a proposed intervention. For example, consider a BiCRS facility that collects and uses manure as a feedstock. The counterfactual for the manure may be no collection (leave on land as a soil amendment) or storage in an emissions-producing lagoon.

Most peer-reviewed studies rely on LCA, a method for quantifying the total environmental impacts from an industrial process, to calculate net GHG footprints. However, LCA system boundaries vary, and counterfactuals are inconsistently applied. Using standard LCA approaches can result in a system achieving net-negative life cycle GHG emissions relative to the defined counterfactual. This does not necessarily equate to achieving net removal of CO_2 but, rather, indicates a reduction in system-wide GHG emissions.

There is already a rapidly expanding number of methodologies and protocols developed by nearly 20 different developers, registries, and other entities, according to CDR.fyi. They draw on, and build upon, elements of LCA, and they are already in use for policies such as state-level low carbon fuel standards, the Carbon Offsetting and Reduction Scheme for International Aviation, and the European Union's Renewable Energy Directive. Establishing and applying system boundaries and counterfactuals so that the accounting calculations consistently reflect a net flux of CO_2 from the atmosphere to stable storage is key to assigning value to CDR projects.

A carbon dioxide removal accounting framework

CDR accounting draws on, but differs from, conventional LCA. Best practices in LCA are established in two widely used standards: International Organization for Standardization (ISO) 14040 and 14044. These standards are based on an overall goal of quantifying the net system-wide environmental impacts of a product or service. They depend on clearly defined counterfactuals and recommend applying credits for avoided emissions or other impacts elsewhere in the system. For example, avoided methane emissions when manure is diverted from high-emitting storage lagoons would be reported as emissions removed from the system. LCA best practices are not structured to distinguish between emissions mitigation and removal. A product can have a net-negative GHG footprint simply by avoiding more emissions than it causes. In contrast, CDR that can compensate for hard-to-abate sectors and legacy emissions must achieve a net removal of CO_2 from the atmosphere. Therefore, appropriate CDR accounting uses expansive system boundaries and excludes carbon credits for avoided emissions.

CDR accounting addresses a more focused question than LCA: does a given process or project result in a net flux of $CO_{2eq.}$ from the atmosphere when all of the relevant activities are accounted for? Two basic metrics for CDR accounting shown in Table 1 answer this question. Net $CO_{2eq.}$ removal (*R*) indicates the net removal and storage for a defined operational time frame (e.g., annual basis or project lifetime). The net $CO_{2eq.}$ removal efficiency (*RE*) compares the net and gross $CO_{2eq.}$ removals. If *R* is positive and *RE* is between 0 and 1, then the system removes carbon. A small positive *RE* means the project removes carbon but also must emit substantial GHGs in the process. Unlike *R* and *RE*, the net carbon mitigation (*C*) includes credits for avoided emissions, aligning with conventional LCA best practices.

As shown in Table 1, time frames are key to calculating final metrics for CDR projects. The removal time frame (*T*) refers to the number of years over which carbon storage is being valued, and there is currently no consensus on what the value for *T* should be. Expected durability of carbon storage can vary from decades, (e.g., carbon storage in biochar), to millennia (e.g., CO_2 storage in geologic reservoirs). In the absence of broad consensus, evaluating *R* or *RE* for multiple removal time frames (e.g., until 2100, 100 years, or 1,000 years) and transparently

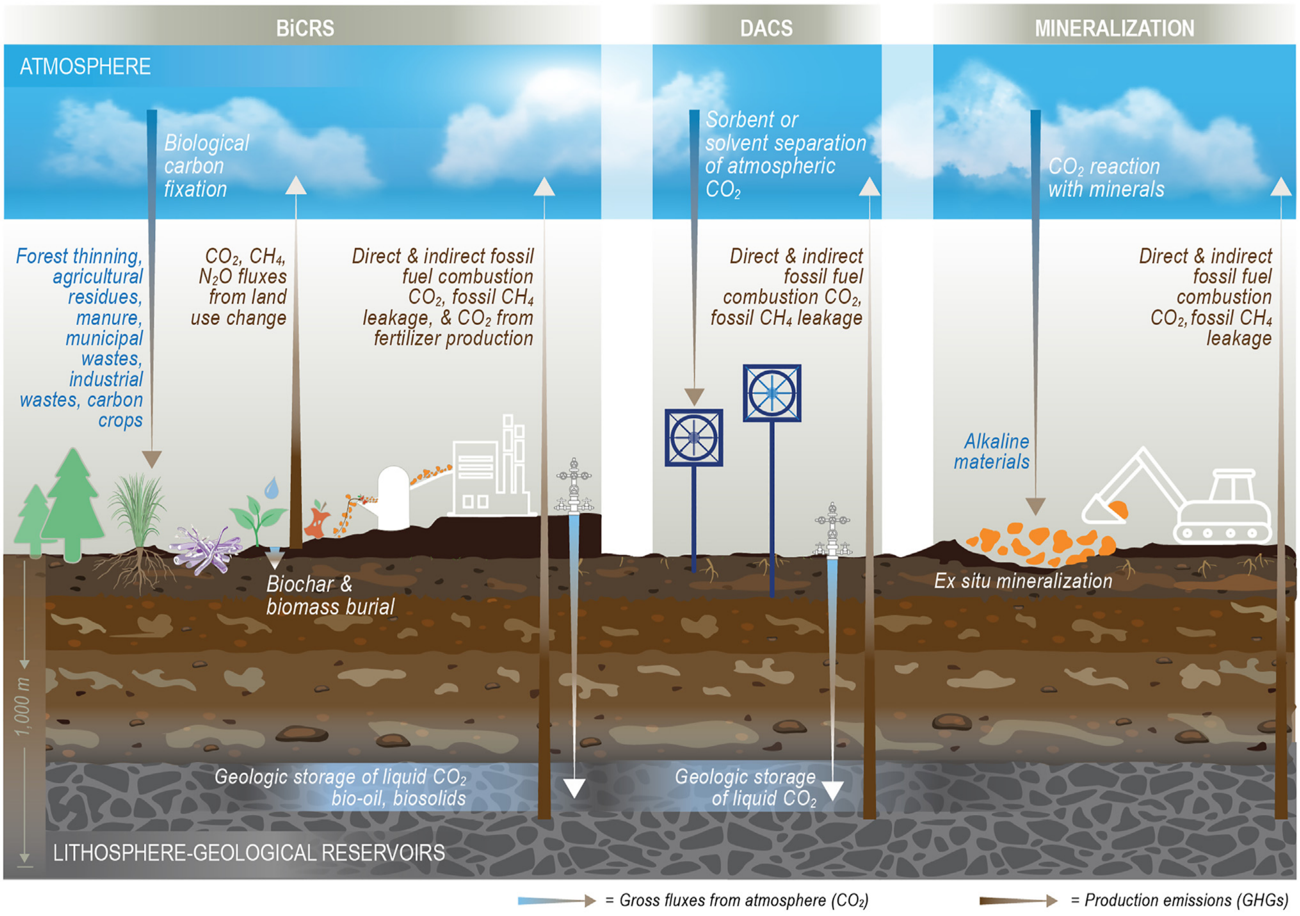

Figure 1. Engineered, closed-system carbon dioxide removal technologies and removal mechanisms

We illustrate the primary greenhouse gas (GHG) fluxes that must be accounted for when determining whether a biomass with carbon removal and storage (BiCRS), direct air capture and storage (DACS), or closed-system mineralization project is achieving a net removal of CO_2 from the atmosphere. Specific projects may have additional fluxes not listed here.

disclosing the time frame on which removal is evaluated will be important.

GHG flows relevant to CDR accounting and LCA can be divided into three basic categories: atmospheric CO_2 stored, direct and indirect emissions, and avoided emissions (Table 1). Atmospheric CO_2 stored refers to CO_2 removed from the atmosphere as a direct result of human intervention (where the counterfactual is no intervention), which is then stored for at least *T* years. For example, the counterfactual for CO_2 mineralization using natural rocks is the extant weathering rate of those minerals in their undisturbed setting. In this case, atmospheric CO_2 stored only includes the additional removals due to the mineralization intervention. Atmospheric CO_2 stored does not include the capture and storage of carbon that did not originate from the atmosphere prior to entering the CDR system (e.g., fossil CO_2 captured directly from a power plant).

The terms "direct" and "indirect" have been used inconsistently in the LCA community. For our purposes, "direct emissions" refers to emissions that occur on site at a given CDR facility as well as direct physical leakage of GHGs. Indirect emissions are often modeled rather than measured. Upstream indirect emissions are those generated by upstream activities, including, but not limited to, feedstock production/collection, materials inputs, and energy consumption. Downstream indirect emissions are emissions generated by activities such as waste treatment and disposal, including off-site physical leakage of GHGs. Avoided emissions refers to a reduction in emissions relative to a counterfactual, achieved by preventing or offsetting a more emissions-intensive activity (e.g., offsetting a production process or diverting waste from emissions-intensive management).

Properly assessing the direct and indirect emissions associated with CDR inputs is key. Primary inputs (feedstocks) that CDR facilities take in can be purpose grown/produced, naturally occurring, or a waste from another human activity. For example, a BiCRS process may take in biosolids from wastewater treatment or crops that were grown and harvested for their use. If the feedstock is not a waste product or co-product, the full burden of producing the feedstock is included in both CDR accounting and LCA methods. CDR accounting and LCA are more likely to diverge when accounting for wastes as inputs. It is common practice in LCA to assign no environmental burden to wastes, except the additional emissions/impacts of collecting and using it relative to the counterfactual management

Table 1. Metrics and equations for quantifying net carbon removal and net life cycle carbon mitigation

Metric	Metric	Associated measurements or calculations	Units
Removal time frame	T	T = time frame on which carbon storage is required	years
Operational time frame	T	t = time frame of operation being observed or assessed	years
Atmospheric CO_2 stored	S_t	S = CO_2 removed and stored from t years of operation	kg $CO_{2eq.}$
Direct and indirect emissions	$E_{t,T}$	E = direct process emissions during t years + indirect emissions from energy and material consumption during t years + reversal emissions (environmental leakage) during T years	kg $CO_{2eq.}$
Avoided emissions	A_t	A = avoided emissions from waste diversion or coproduct generation during t years	kg $CO_{2eq.}$
Net carbon impact metrics (conventional LCA)			
Net carbon mitigation	$C_{t,T}$	$C_t = S_t - (E_{t,T} - A_t)$	kg $CO_{2eq.}$
Net carbon removal metrics (carbon accounting for CDR)			
Net $CO_{2eq.}$ removal	$R_{t,T}$	$R_t = S_t - E_{t,T}$	kg $CO_{2eq.}$
Net $CO_{2eq.}$ removal efficiency	RE_T	$RE_T = 1 - (E_{t,\ T}/S_t)$	%

$CO_{2eq.}$ in the units refers to the combined climate impacts of all GHGs normalized to a CO_2 basis.

practices. However, CDR accounting, which has the purpose of calculating net carbon flux from the atmosphere, potentially requires a different approach. For example, if a livestock producer collects a portion of their manure for use in a BiCRS process, but the entire operation (livestock production and BiCRS facility combined) is net emitting, this suggests that the BiCRS facility is mitigating emissions from livestock production but not achieving net CDR. In short, this waste takes on the full burden of the livestock operations for the purposes of CDR accounting.

There are wastes for which assigning the full burden of their production system is impractical or illogical. Wastes that cannot easily be traced back to a specific production system (e.g., municipal wastewater, septage, or municipal solid waste) could be such examples. Particularly in the case of inorganic materials such as mine tailings, materials that go unutilized for years could also be considered "legacy wastes," where the emissions associated with producing them are effectively sunk environmental costs. However, there is no consensus cutoff point to differentiate between legacy wastes and newly generated wastes. This is primarily an issue for mineralization strategies, as organic materials used in BiCRS decompose rapidly if left in the environment. In some cases, a CDR project may induce additional demand for products or services by diverting a waste feedstock that was already beneficially used (economic leakage). For instance, some BiCRS pathways use agricultural residues that would otherwise be used to enhance soil health or serve as fertilizer supplements. CDR accounting would need to incorporate any induced demand for fertilizers, as is already common practice in LCA for such products as corn stover.

Indirect emissions from energy and material use can be evaluated by tracking their consumption and leveraging existing datasets or source-specific measured data to quantify GHG emissions associated with the production and transportation of these inputs. Emissions accounting for grid electricity is particularly contentious. An electricity-consuming process may be assigned the marginal grid emissions impacts (i.e., emissions from power plants that are needed to meet the new additional load due to the CDR project) or average emissions impacts (i.e., a proportional share of the total grid emissions). Defining grid regions within which to calculate the carbon intensity of electricity is a subjective choice and impacts the results. Electricity is often a major, if not the primary, source of emissions for many grid-connected CDR systems. While some early-stage developments of CDR technologies may not achieve net carbon removal based on current grid mixes, they may have greater potential in the context of a decarbonized future energy system.

Examples for applying CDR accounting

Direct air capture

Direct air capture (DAC) systems capture atmospheric CO_2, which can then be stored in geologic reservoirs (DACS) or used to produce a product. DAC is relatively simple for carbon accounting because the feedstock is ambient air, and the counterfactual is no DAC. In the instance of geologic sequestration, DAC can achieve net removal as long as the quantity of stored atmospheric CO_2 exceeds the direct and indirect GHG emissions associated with the construction and operation of the system. In this case, the system is not multifunctional, so quantifying R and C, as defined in Table 1, is essentially the same because there are no avoided emissions ($A = 0$). However, in the case where CO_2 is utilized rather than stored, a DAC system may not result in net CO_2 removal but instead serve as GHG mitigation, depending on the durability of carbon storage in products. For example, converting CO_2 to liquid fuels or solvents can mitigate emissions but will almost certainly not result in net removal because those products tend to have short lifetimes and are oxidized back to CO_2 at their end of life. If CO_2 is used to make long-lived products like carbonate aggregates, then this

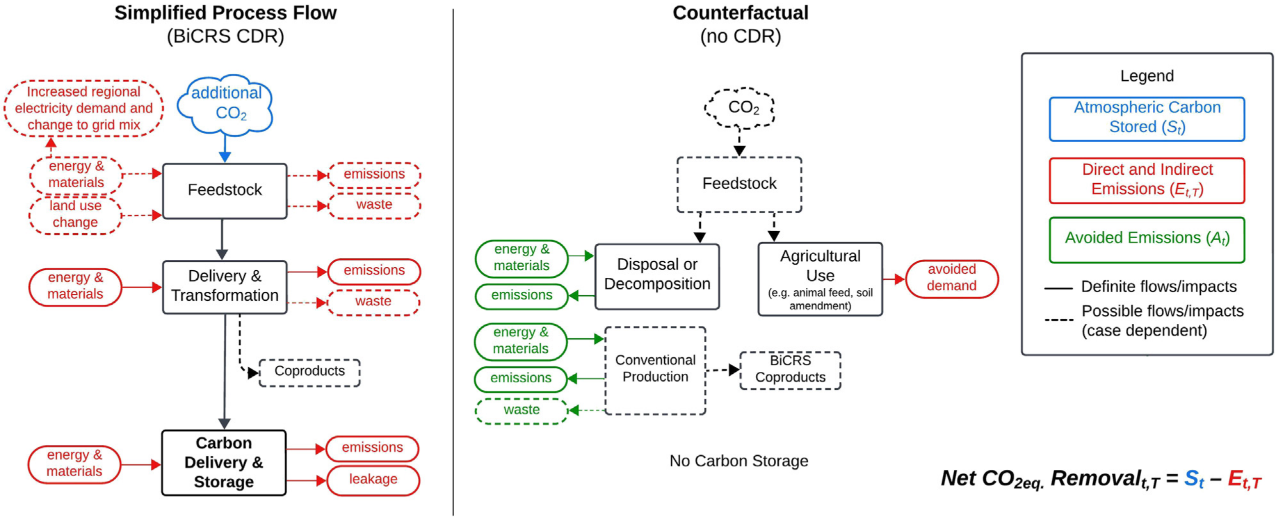

Figure 2. Process flow diagrams depicting emissions that must be accounted for when evaluating BiCRS projects

is long-term carbon storage and the system has the potential to achieve net carbon removal. In these cases, *C* will likely credit avoided emissions from conventional production of such products ($A > 0$), whereas *R* will not.

BiCRS

BiCRS systems, unlike DAC systems, can involve waste or purpose-grown feedstocks, multiple functions/co-products, and less clearly defined counterfactuals. BiCRS technologies leverage biological carbon fixation processes to convert atmospheric CO$_2$ into organic material that can be transformed for long-term carbon storage. Some BiCRS facilities can play a critically important role in GHG mitigation by diverting organic waste from high-emitting management practices, such as landfilling or lagoon storage. Figure 2 visualizes a generalized process flow and counterfactual for BiCRS systems, including emissions categories outlined in Table 1. Examples of BiCRS feedstocks include purpose-grown crops (e.g., switchgrass or farmed trees), agricultural residues (e.g., corn stover or wheat straw), manure, forest thinnings, and municipal or industrial organic wastes. Accounting for emissions from purpose-grown crops is straightforward: they carry the full burden of crop cultivation and collection in both LCA and CDR accounting.

Estimating emissions impacts from wastes or co-products is far more challenging and contentious. Both agricultural residues and manure are fundamentally tied to crop and livestock production systems, respectively, but are not the primary products. A typical LCA approach would treat them as wastes, allocating only the additional impacts of their collection and removal (e.g., fuel use for collection and supplemental fertilizer requirements) while crediting any avoided impacts from their disposal. Given that some manure is conventionally stored in methane-emitting lagoons and pits, these emissions offset credits for diverting manure to lower-emitting applications can be substantial. However, manure management emissions are, at least partially, tractable to mitigate in a decarbonized future. The offset credits applied in LCA do not apply in CDR accounting. Whether agricultural residues and manure should carry some or all of the GHG emissions burden of their respective crop and livestock production system remains a subject of debate. The same argument could be made for industrial wastes, such as residual solids from food processing operations. If these wastes carry the full burden of their production systems, their use in BiCRS would only achieve net removal if the carbon stored exceeds the full GHG footprint of those systems.

Unlike crop residues, forest thinnings are not part of a dedicated production system. Instead, they are a by-product of sustainable forest management interventions. The alternative uses of forest thinnings in the absence of demand for BiCRS could vary from controlled burning to use in other industries, such as wood pellets. Whether forest thinnings should be assigned some or all of the GHG emissions from the forest management operations, such as fuel combustion in trucks and logging equipment, is an open question. If, however, forest biomass is harvested beyond what is required for sustainable forest management, it ceases to be a waste product. In this case, the full burden of harvesting and the net loss of carbon would be included in a net flux framework.

Municipal solid wastes and biosolids from wastewater treatment that have a near-zero or negative monetary value are arguably on the opposite side of the spectrum from purpose-grown feedstocks. Assigning, for example, the burden of all human activity that leads to organic municipal wastes to that material would be impractical. For these wastes, the most logical carbon accounting approach is to assign only the additional GHG emissions associated with their diversion and use for BiCRS. Their disposal can lead to GHG emissions, as is the case for landfills and incinerators, and these would typically be incorporated in an LCA as emissions offset credits. In a net flux framework for carbon accounting in CDR, such offset credits would not be included.

In addition to the wide range of potential feedstocks, BiCRS technologies include multiple forms of carbon storage, and each is managed differently. Examples include biochar, bio-oil injection, biosolids injection, CO$_2$ injection, and biomass burial. Biochar in particular has uncertain durability when used as a soil amendment, where the carbon is subject to oxidation via chemical and biological processes, but its use can also improve soil texture and crop yields, thus indirectly contributing to soil carbon accumulation. The durability and overall impact on soil carbon fluxes is so dependent on site-specific factors that there is no simple, widely accepted approach for estimating carbon stored (nor the net impacts on N_2O fluxes). Other forms of carbon storage that are injected underground, buried, or enclosed in above-ground storage structures require monitoring to ensure no appreciable leakage but do not come with the same complexities of soil amendments. One final mechanism sometimes claimed as carbon storage is the landfilling of stable bio-based materials, such as bioplastics. This case is less straightforward than other dedicated burial strategies. Plastic contamination in waste streams is one of the biggest economic and engineering challenges facing composters, anaerobic digesters, and other organic waste diversion facilities. This leads to continued landfilling of mixed wastes that emit fugitive methane. From this perspective, introducing bio-based plastic into waste streams destined for landfills can only serve to partially mitigate the net-positive GHG emissions from landfilling mixed waste.

Land-based mineralization

Similar to some BiCRS technologies, carbon accounting for land-based mineralization requires clearly defined counterfactuals because it can rely on purposefully mined minerals or streams traditionally defined as wastes (e.g., mine tailings). These minerals often provide CO_2 removal even without intervention via natural weathering, though at a substantially lower rate and extent over a defined time period. The storage (S) achieved through human intervention can be calculated as the difference between the CO_2 mineralization for a project and the background CO_2 removal rate. The GHG emissions (E) from transporting and processing minerals to remove and durably store CO_2 can be subtracted from S to calculate the net removal (R). If the mineralized products are used as a replacement for existing products (e.g., magnesium carbonate replacing gypsum in drywall), then R and C diverge because $A > 0$. Co-products from a mineralization process are subject to the same counterfactual considerations as discussed for BiCRS. The systems that produce the minerals used to remove CO_2 often have primary or co-product streams that do not have an inherent physical risk of GHG generation or release (e.g., nickel-bearing ore) but whose further processing (e.g., into metallic nickel) does result in GHG emissions. These scenarios are analogous to many BiCRS systems, and emissions allocation remains a point of open debate.

Some land-based mineralization systems can be implemented over a limited footprint with controls to prevent liquid and solid mass transfer out of the system boundary. However, even these systems must include the loss of biological carbon and net primary productivity from the land disturbed to access minerals. Although modern mineral extraction activities in most jurisdictions require active intervention to restore a landscape to its original condition, these activities occur in the far future, and their efficacy in terms of restoring the original carbon stocks is highly case dependent. Therefore, site restoration should only be included in CDR accounting after the restoration activity has occurred. Mineralization systems that involve the dispersal of minerals into the environment (e.g., enhanced rock weathering and ocean alkalinity enhancement) are not covered in this example, as they create novel questions of how these minerals and their reaction products might alter existing GHG stocks and fluxes.

The way forward

There is an urgent need to proactively identify and develop CDR projects that will serve its two key purposes in the coming decades: (1) compensating for difficult-to-abate anthropogenic emissions (e.g., N_2O emissions from agriculture) and (2) removing CO_2 from the atmosphere to counteract warming from legacy GHG emissions. This moment is pivotal, as growth in CDR purchases have accelerated from 4.2 million tons in August 2023 to over 10 million tons in August 2024. Choices made in defining and investing in CDR now will shape the industry for decades. Conventional wisdom in policy design dictates that loosening standards is far easier than attempting to tighten them later, as entities who benefit from the current system are motivated to entrench the elements that benefit them.

This primer describes the fundamentals of CDR accounting and illustrates how different system boundaries and counterfactuals lead to divergent conclusions in the calculation of project-level CDR and net GHG emissions mitigation. The goal is not to question the merits of projects that achieve GHG mitigation but, rather, to highlight the need for separate mechanisms to purchase removal versus mitigation, where high-integrity CDR capable of achieving net CO_2 removal in the long term is expected to be more costly than mitigation. Adequate support for both mitigation and CDR while clearly distinguishing between the two is essential for meeting global decarbonization goals.

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DECLARATION OF INTERESTS

The authors declare no competing interests.

RECOMMENDED READING

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