German Environment Agency

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Short Typology of Carbon Dioxide Removals

How to best differentiate methods and technologies for establishing and enhancing carbon sinks?

1 What is the aim of the paper?[1]

This fact sheet presents a suggested typology of Carbon Dioxide Removals (CDR) that serves as a basis for:

- introducing and defining key terminology around CDR,
- differentiating general methods of CDR regarding their effectiveness to remove CO_2, and
- characterising concrete CDR technologies for assessing the environmental impacts of their implementation.

The paper aims to stimulate the public debate by highlighting key aspects and implications of CDR activities that should be taken into account in implementing the framework and future policy-making promoting CDR. This is particularly relevant with regards to the current policy process of developing an EU Carbon Removal Certification Framework (CRCF) that will define a process for certifying CDR activities at EU level and set quality criteria which such activities will need to fulfil (EC 2022b).[2]

The paper first presents and compares different definitions of CDR that are available in the literature (section 2). Secondly, it briefly outlines activities for removing CO_2 from the atmosphere (section 3). In a third step, it discusses characteristics that distinguish different CDR activities (section 4). Lastly, it proposes a schematic overview on the basis of the evaluation of existing literature and summarises implications implied in the typology proposed by the European Commission in its proposal on a CRCF (section 5).

2 What is Carbon Dioxide Removal?

2.1 A wide range of definitions

The IPCC defines CDR as **human activities "removing CO_2 from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products. It includes existing and potential anthropogenic enhancement of biological or geochemical sinks and direct air capture and storage, but excludes natural CO_2 uptake not directly caused by human activities**" (IPCC 2022, p. 807). The mechanisms to achieve carbon dioxide removals are sometimes also referred to as "negative emission technologies"[3] in the literature (IPCC 2018).

[1] This paper was prepared as part of the research project "Wissenschaftliche Begleitung zur Ausgestaltung des Zertifizierungsrahmens für Kohlenstoffbindungen in der EU" (FKZ 3722 42 515 0) funded by the German Enviroment Agency (UBA).

[2] The authors have published comments and assessments of this draft, see McDonald et al. (2023) and Meyer-Ohlendorf et al. (2023).

[3] The term "negative emission technologies" must not be misunderstood to only refer to sinks that involve human technology, but it covers all types of activities to remove CO_2 from the atmosphere discussed in this paper.

Smith et al. (2023) define three principles that CDR must fulfil, namely (1) the captured CO_2 must be **taken from the atmosphere** and not from fossil sources, (2) the subsequent storage must be **durable** ("timescale in the order of decades or more") and (3) the removal must be **related to human action** and not occur as a result of natural processes. While the IPCC definition also talks about "durable storage", it does not further define what would be considered as "durable". Another study by Fuss et al. talks about a time period that is longer than a reporting year for the preparation of GHG inventories; considering CDR options into different types of activities according to the time period for which they store CO_2 (short-term 2-29 years; mid-term 30-99 years; long-term more than 100 years) (Fuss et al. 2021).

It is questionable which timeframe should be considered as a minimum period for storage of CO_2 considering that the extent to which permanence can be guaranteed for different types of removals varies significantly (see section 4.3). Particularly for some carbon farming activities it can be challenging to ensure storage of CO_2 for several decades. At the same time, such activities often entail positive environmental impacts as well as co-benefits and are available at much lower cost than CDR approaches like DACCS which have not reached sufficient technological maturity yet in order to be scalable.

The CRCF proposal by the European Commission defines carbon removal as "either the storage of atmospheric or biogenic carbon within geological carbon pools, biogenic carbon pools, long-lasting products and materials, and the marine environment or the reduction of carbon release from a biogenic carbon pool to the atmosphere" (Art. 2.1(b)). The definition proposed for the CRCF deviates from the IPCC definition of CDR by mixing carbon removals with emission reductions ("the reduction of carbon release from a biogenic pool to the atmosphere") aiming to include carbon farming activities avoiding emissions. However, this is misleading. Activities to avoid or reduce emissions, including e.g. the rewetting of peatlands, should not be subsumed under the term "removals".[4]

2.2 Types of activities included

The CRCF proposal covers three types of CDR activities, namely carbon farming, geological sequestration and carbon stored in products (CCU, see below). Even though storing carbon in products is discussed as one form of CDR, products are an option for storing carbon, but the actual removal occurs earlier, during biomass production or chemical capturing. Additionally, several studies highlight the importance to distinguish between CDR and Carbon Capture and Utilisation (CCU), which does not necessarily involve a durable storage of CO_2 (Smith et al. 2023). While the CRCF proposal talks about storage of carbon in "long-lasting products or materials" (Art. 2.1.(i)), a time frame is not further defined and short-term storage is not explicitly excluded. This entails that products which do not constitute a removal per se and additionally may store carbon for short time periods could be considered CDR activities under the CRCF.

Smith et al. (2023) use the term "conventional CDR" for CDR on land that is nature-based, including afforestation, reforestation and management of existing forests. "Novel" CDR activities relate to those that rely on the use of technology for creating a carbon sink, including BECCS, DACCS and enhanced rock weathering (Smith et al. 2023). Differentiating between 'natural' and 'technological' removal options is not always evident but rather subject to human choice and perception (Bellamy und Osaka 2020). Minx et al. (2018) define "technology" in a broad sense as a means to achieve a mitigation effect, thus also including e.g. afforestation and reforestation as well as soil carbon sequestration. This terminology is not used in the CRCF proposal though.

[4] For a more detailed discussion of the implications of this definition see Meyer-Ohlendorf et al. (2023).

2.3 What CDR is for

According to Smith et al. (2023), CDR can fulfil three major functions: it can reduce net emissions in the near future, compensate for residual emissions to achieve net zero targets and help to achieve net-negative emissions in the longer run.

The potential option to remove large amounts of CO_2 from the atmosphere must not be misunderstood as a way out of ambitious action to reduce emissions. Firstly, the amount of cumulative CO_2 emissions determines the level of temperature increase. Additionally, high GHG concentrations in the atmosphere are more likely to trigger dangerous tipping points of the climate system which can cause additional emissions and exacerbate climate change (Riahi et al. 2022). This means that emissions cannot simply be compensated for by carbon removals but must be reduced as quickly and drastically as possible (Zickfeld et al. 2021; Carton et al. 2021).

Nevertheless, CDR will be crucial for meeting the goals of the Paris Agreement: All scenarios of emissions pathways that are in line with limiting global warming to 1.5°C as prescribed by the Paris Agreement rely on substantial amounts of CDR to balance out residual emissions that will be hard to abate (Smith et al. 2023; Riahi et al. 2022). At EU level, the European Climate Law sets the target to become climate neutral by 2050 and to remove more GHG than the EU emits thereafter so that residual emissions are more than outweighed by removals.[5]

3 What CDR activities exist?

The following activities can be distinguished in the context of CDR, while their status as removals can in some cases however be debated (Smith et al. 2023; IPCC 2022):

- **Direct Air Capture with Carbon Capture and Storage (DACCS):** Carbon is captured from the atmosphere through chemical processes (solid sorbent or liquid solvent) into a concentrated CO2 stream which is then stored in geological formations. Captured CO_2 is utilised in products is referred to as direct air carbon capture and utilisation (DACCU).

  - **Carbon Capture and Use (CCU)**: relates to industrial activities that capture CO_2 chemically and convert it into products, including drinks, fuels, plastics or construction materials. As mentioned above, products can store carbon for a period of time, but do not constitute removals as such. The removal takes place before the product is produced. Examples are direct air capture as a basis for e.g. material use of carbon in the chemical industry or photosynthesis as a basis for e.g. wood-based products. Additionally, it is debated in the literature if CCU activities fall under the concept of CDR if the carbon remains stored in products for long time periods (Smith et al. 2023, p. 12). However, using atmospheric or biogenic carbon as an input for fuels or for the chemical industry means to delay emissions since they will only be kept out of the atmosphere during the lifetime of the product in which they are used. This does not constitute a real mitigation measure. For these reasons, **CCU activities should not be considered as removals.** Additionally, the energy use during a CCU process can be considerable (Purr et al. 2021). The IPCC talks about a "climate-relevant time horizon" for CCU to become CCUS (2022, p. 807) (see also section 4.3). If products originate from biological capture (e.g. wood-based products) and the carbon is transferred to geological storage at the end of life of the product, CCU can become BECCS.

[5] Regulation (EU) 2021/1119, see https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32021R1119.

- **Carbon Capture and Storage (CCS):** Smith et al. (2023) differentiate CDR from CCS which refers to a set of industrial activities which capture CO_2 chemically and store it in geological formations. If the CO_2 originates from fossil fuels or minerals, the related CCS activities are emission reductions rather than removals ("fossil CCS"). **CCS activities comply with the CDR definition only if the used CO_2 originates from biomass (BECCS) or from the air (DACCS)** (p. 12). The CRCF proposal follows the same logic for excluding CCS from those activities that can be certified under the framework.

► **Biomass growth and use for energy with Carbon dioxide Capture and Storage (BECCS)**: CO_2 is removed from the atmosphere through biomass growth. The biomass is then used to produce energy and the CO_2 captured from a bioenergy facility into a concentrated CO_2 stream which is then stored in geological formations. The CO_2 can also be utilised in products (BECCU).

► **Biomass growth and utilisation**: CO_2 is removed from the atmosphere through biomass growth. The biomass is then used for different purposes:

- **Biobased products:** include biomass-based materials that retain the CO_2 captured through biomass growth and temporarily prevent it from being re-emitted as long as the product is in circulation (and not burned or decomposed). Therefore, **biobased products (like also biochar) do not constitute a removal per se**, but a form of storage, as the removal has usually already occurred regardless of the creation of the product. Wood harvested from forests and used for products such as construction wood, furniture, panels, paper and paper-like products are referred to as **Harvested Wood Products (HWP)**.

- **Biochar**: includes the production of charcoal that is incorporated into soils. The biomass can be directly produced by agriculture or forestry or recovered from waste streams. It is produced by heating the biomass in the absence or under low concentrations of oxygen (pyrolysis or gasification). Biochar is sometimes also categorised as a form of BECCU (see above). Similar to biobased products, **biochar does not constitute a removal in itself, but is a form of storage,** as the removal has occurred during biomass growth.

► **Carbon farming/the enhancement of natural carbon sinks**, including:

- **Afforestation/reforestation**: the establishment of tree cover on formerly unforested areas[6] or deforested areas, either through active tree planting or seeding or natural regeneration,

- **Improved forest management**: changes in the intensity and quality of management of existing forests with the aim to increase carbon storage in living and dead biomass and soils,

[6] While afforestation refers to establishing forests on areas that have historically not have been under forest cover, reforestation implies that the areas had forest cover in recent times and had since been converted to another land use (IPCC, 2006). The period without forest cover can vary and is not clearly defined.

- **Soil carbon sequestration**: changes in agricultural practices and pasture management with the aim to increase carbon stocks in mineral soils,
- **Agroforestry**: involves the establishment of single trees or vegetation elements like hedges in an agricultural landscape aiming at co-production systems delivering agricultural and forestry goods.
- **Blue carbon**: includes all biologically-driven carbon fluxes and storage in marine systems that are amenable to conservation, restoration and sustainable management. Coastal blue carbon focuses on rooted vegetation in the coastal zone, such as tidal marshes, mangroves and seagrasses (IPCC 2019).
- **Peatland and wetland restoration**: re-establishes an intact wetland ecosystem with an increasing peat layer. It has to be noted that **peatland rewetting** foremost leads to a reduction of emissions from the degradation of the peat layer[7] and **is thus not to be considered a removal** (in the sense of CDR, but definitely a nature-based solution to mitigation climate change). Such activities would be included in the definition of removal activities under the proposal for the CRCF, though.

► **Enhanced weathering:** removes CO_2 from the atmosphere through the weathering of silicate and carbonate rocks broken into small particles and applied on soils, coasts or oceans. It is also possible to use construction waste and waste materials from mining as resources for enhanced weathering (Babiker et al. 2022).

► **Ocean fertilisation:** increasing macronutrient (nitrogen, phosphorus) or micronutrient availability in ocean to enhance CO_2 uptake through growth of phytoplankton or enhance fish stocks. Iron fertilisation is the best studied option of ocean fertilisation to date.

► **Ocean alkalinisation:** Alkaline materials such as silicate or carbonate rocks are added to the ocean so that carbon is stored in minerals or as biocarbonate.

► **Artificial upwelling:** Nutrient-rich deep ocean waters are pumped up fertilising upper ocean levels and algae so that more CO_2 is stored in biomass (Böttcher et al. 2023).

4 What are important criteria for comparing and categorising CDR activities?

As shown above, many types of CDR activities exist. In the following we briefly assess existing activities in light of a number of criteria by which they can be differentiated. Firstly, CDR activities differ in the process of capturing CO_2, the destination of storage that also implies different likely duration times of storage. Moreover, activities can be complex regarding processes involved and also regarding required energy and resource input and thus potential emissions along the process chain. Another criterion for differentiation is the absolute potential for removing CO_2 that depends on the efficiency of removals but also capacities for removal and storage. Influencing factors of the potential are also technological readiness and scalability as well as costs that differ considerably between CDR activities. Finally, environmental impacts of

[7] Under ideal conditions, when the extraction of peat is completely stopped, the peat layer can grow and entail additional carbon removals from the atmosphere; however the main mitigation effect of rewetting of peatlands results from reduced emissions.

the activities that can be employed are varying. Additionally, it is important to note that different CDR options may compete for resources like available area, biomass or renewable energy.

4.1 Process of capturing CO_2

CDR may occur through different capture processes. In biological capture, CO_2 is taken from the atmosphere and absorbed through the process of **photosynthesis**, i.e. by trees, crops and aquatic biomass (e.g. kelp and seagrasses). **Geochemical** capturing involves the binding of CO_2 by minerals or alkaline waste materials from construction and industry in form of solid carbonate or dissolved biocarbonate. In both cases, this form of capture immediately leads to durable storage. Solid carbonates may be used in products such as construction materials. In **chemical** capture, CO_2 is captured from the air by the use of chemical solvents and sorbents; thereafter it can either be stored or used in construction materials or plastic products (Smith et al. 2023; Hermann et al. 2022). The latter technology is typically applied in installations for direct air capture. Less advanced are **mechanical** capture technologies involving membranes or metals.

A removal only occurs if the absorbed carbon originates from the atmosphere. In the case of biomass, removals occurred during the phase of biomass growth. However, in the process of sourcing CO_2 from biomass, considerable emissions can occur, if carbon stocks in vegetation and soil are depleted to increase productivity of the vegetation, e.g. through drainage of organic soils. This has implications for biomass-based CDR technologies such as BECCS. Net removals occur only when cumulated removals from biomass growth exceed cumulated emissions from such activities and if carbon removals that occurred during biomass growth are included in the calculations.

4.2 Destination of CO_2 storage

Three different types of removals can be distinguished with regard to the location where the removed CO_2 is stored (see e.g. IPCC 2022, p. 807; Smith et al. 2023, p. 13):

- **Storage of CO_2 as a gas through geological storage in the lithosphere**, e.g. in depleted oil or gas fields or saline aquifers. Careful management of these reservoirs is necessary in order to keep the carbon stored.
- **Storage of CO_2 as solid material through:**
  - **Geochemical storage** in the lithosphere in reactive minerals through enhanced weathering.
  - **Biological storage** of CO_2 in terrestrial or ocean reservoirs, including plants which can store carbon for short periods (annual plants) or up to centuries (trees), soils and wetlands and oceans and marine sediments. Careful management of these reservoirs is necessary in order to keep carbon stored.
  - **Storage** of CO_2 **in products**, which can store carbon for short time periods (drinks, fuels, plastics) or longer time horizons (construction materials, biochar or aggregates); carbon can come from the conversion of harvested biomass, concentrated CO_2 streams or from ambient air. As explained above, carbon storage in products is discussed in the context of CDR but does not constitute a removal in itself.

According to Minx et al. (2018), ocean-based removals will require higher levels of international coordination than land-based removals because they can lead to pollution that transgress national borders. Removal options could thus also be differentiated into domestic and trans-boundary removal methods, depending on whether they have effects across national borders (Boucher et al. 2014). This aspect is not considered in the CRCF proposal though.

The Commission's proposal for a CRCF differentiates geological storage, biological storage and storage of CO_2 in products (EC 2022b).

4.3 Permanence of CO_2 storage

Geological storage is considered to be the most permanent way of storing CO_2 with least risks of reversals, i.e. releasing the CO_2 back to the atmosphere. Leakage could occur during transport of CO_2, during injection due to well failure or gradually through undetected faults, fractures or wells. For "well-selected, designed and managed storage sites", the leakage risks are estimated to be negligible (IPCC 2005). Various characteristics of potential storage sites impact the leakage risks associated with geological storage though. Long-term evidence on leakage from pilot-sites is not available yet (Gholami et al. 2021). It is therefore possible, that in practice, leakage from geological storage will occur in the future since risks can only fully be evaluated after long time periods.

For **ocean storage**, models estimate that 0-35% of stored carbon will be released after 100 years. In case of mineral carbonation, no leakage risks exist (IPCC 2005). **Marine sediments** and **biochar** can store carbon for up to millennia. **Wood in construction, soils and trees** can store carbon for decades up to centuries (Smith et al. 2023), depending on human management of these reservoirs and the effects of climate change and natural disturbances, such as floods, storms, droughts, fires or soil erosion (see Anderegg et al. 2020). Biochar is assumed to persist in soils for hundreds or thousands of years under right conditions. However, evidence of long-term impacts remains scarce (Ding et al. 2016) and the mitigation potential and environmental impacts of biochar are contested (see below).

For **products**, the time period during which carbon remains stored depends on the type of product as well as its use (see section 3). In terms of CCU, it is therefore debated in the literature to what extent CCU can be understood as a CDR method if the storage of CO_2 in products is not ensured permanently, but in some cases for days, months, years or decades only (Smith et al. 2023, p. 12).

The Commission's CRCF proposal defines geological storage to be "permanent" carbon storage. Carbon farming activities and carbon stored in products are not considered to be permanent, but for these removal options, long-term storage should be ensured.

Since **fossil CO_2 emissions last in the atmosphere for millennia, carbon ideally needs to be stored for the same time period** (Mackey et al. 2013; Ciais et al. 2013). However, there are practical barriers to design, implement and monitor the storage for different removal options for longer time horizons.[8] Short-term storage is still a contribution to mitigating climate change. Short-term storage of CO_2 might be valuable while long-term storage capacities are being developed because it lowers the cost of mitigation. Moreover, enhancing natural sinks involves also a number of other social and environmental co-benefits (see section 4.5). Non-permanent removal activities would need to be constantly renewed and monitored (Kalkuhl et al. 2022).

[8] For example, short land tenures might counteract long-term changes to sustainable land management practices or farmers might be reluctant to pass on long-term monitoring obligations to future generations Wreford et al. (2017).

Thus, there are different aspects to consider in evaluating the permanence of different removal options.[9]

4.4 Energy consumption and emissions along the process chain

The efficiency of removal activities to generate negative emissions over the entire life cycle depends on the carbon intensity of the energy as well as the resource input (electricity, heat and biomass) as well as other lifecycle considerations (Babiker et al. 2022). Technologies involve higher or lower demands for energy for capturing and storing CO_2. Energy demand is also associated with emissions of CO_2 and other gases along the process chain, especially for early phases of implementation before energy systems have been fully decarbonised. For example, **enhanced weathering** is a relatively expensive option due to the high energy requirements for grinding. Direct air capture involves similar energy demands (Fuss et al. 2018). **Biochar** and **BECCS** technologies can be considered as options that can provide energy as a co-benefit – even though they imply high resource demand for biomass –, while total energy demand also depends on the type of biomass used. Required fertiliser input for sufficiently high production levels of bioenergy to be commercially viable can be high and thus lead to increased energy demand and related emissions (Fuss et al. 2018). Biochar aims to improve productivity of soils offering the potential to reduce energy consumption for fertilisers. However, meta-studies show that with different soil types and environmental conditions, net positive effects cannot always be achieved (Fuss et al. 2018).

Low-energy demand options involve **carbon sequestration in soils and afforestation**. Natural revegetation can even be achieved with practically no energy input. Despite the reduced removal potentials of these technologies, net efficiency can be comparable with high input technologies if not higher, providing opportunities for these removal options especially in the short-term.

4.5 Overall potential to remove CO_2

Based on different scenarios, the IPCC assessed global mitigation potentials for different CDR activities:

Table 1: Estimates for annual CO_2 removal potential for different removal activities

CDR activity	Annual CO_2 removal potential in $GtCO_2e$ by 2050
Afforestation/Reforestation	0.5 - 10.1
Soil carbon sequestration	0.6 - 9.3
Agroforestry	0.3 - 9.4
Biochar	0.2 - 6.6
BECCS	0.5 - 11.0
DACCS	5.0 - 40.0
Enhanced weathering	2.0 - 4.0
Ocean fertilisation	1.0 - 3.0
Ocean alkalinisation	1.0 - 100.0
Blue carbon	0.02 - 0.08 (by 2030)

[9] Ensuring permanence of mitigation results is particularly important if such results are usable in the form of credits to offset CO2 emissions Schneider und La Hoz Theuer (2019); Siemons et al. (2022).

Source: Babiker et al. (2022); Fuss et al. (2018); Macreadie et al. (2021)

The following factors limit the potential of removal options:

- Costs and technological readiness, particularly for DACCS and enhanced weathering (see section 4.7 and 4.8);
- Negative environmental impacts (see section 4.5), including competition for land and biomass as well as water needs and impacts on water quality[10];
- Limits to and competition for renewable energy sources for removal options with high energy needs (see section 4.4);
- Limits to underground storage for DACCS and BECCS (see Fuss et al. 2018).

4.6 Costs and technological re Environmental impacts

Potential negative environmental and social impacts relate to biomass and resource needs as well as broader environmental and sustainability impacts. However, removal activities may also be accompanied by several environmental and social co-benefits (see e.g. Griscom et al. (2017); Seddon et al. (2020); Minx et al. (2018); Babiker et al. (2022); Fuss et al. (2018); Minx et al. (2018)). The specific design and implementation of removal activities play a crucial role in determining the extent to which positive or negative environmental impacts will occur.

For **conventional CDR approaches** the following impacts were reported**:**

- **Soil carbon sequestration** can enhance soil quality, biodiversity as well as water quality, reduce pollution and improve air quality and promote soil resilience by protecting against soil erosion and enhanced capacities to retain nutrients. Additionally, it can have positive impacts on livelihoods by providing new sources of incomes or increased yields to farmers. However, such activities can also lead to indirect land use changes and negative impacts on food security in other places and may restrict the availability of organic matter in other places and imply N-leaching (if large amounts of organic matter are applied).
- **Agroforestry** can have positive impacts on soil quality and biodiversity as well as on livelihoods.
- **Reforestation and afforestation** activities can have varying impacts, depending on how they are implemented. They can reduce flooding and soil erosion and provide habitats for numerous species. At the same time, there is a risk, that these activities could entail biodiversity loss if implemented as monocultures and lead to Albedo changes that can trigger additional warming of the earth. Furthermore, reforestation and afforestation may be linked to competition for land that causes indirect land use changes and negative impacts on food security elsewhere.

[10] For example, the limited availability of excess feedstock biomass constrain the mitigation potential of biochar. Fuss et al. (2018) estimate a “sustainable” global potential of 0.3-2.0 GtCO2e/yr due to competition with other needs for biomass and land. To determine the overall mitigation effect of biochar, a broader lifecycle assessment is necessary, considering where and how offsite biomass is removed, how it is transported and processed, what its alternative end use would be and how it interacts with the soil to which it is applied (Paustian et al. (2016); Minasny et al. (2017); National Academies of Sciences, Engineering, and Medicine (2018)).

- **Conservation, restoration and sustainable management** of blue carbon ecosystems/habitats can contribute to ecosystem-based adaptation and protect coastal ecosystems from degradation (Hilmi et al. 2021).

It is essential to adhere to criteria set for nature-based solutions, including alignment with natural ecosystems (see Reise et al. 2022), in order to ensure positive environmental impacts in the implementation of such activities.

For **novel CDR approaches** the following impacts were reported**:**

- The use of solid sorbents for **DACCS** can have positive impacts on water availability and quality. However, DACCS activities imply high water usage, which can lead to a competition for water, and consume high amounts of energy which might entail additional emissions. If implemented at large scale, DAC plants would also need larger areas of land that could lead to conflicts over land use (even though at much lower scale than land use conflicts resulting from BECCS activities) (Cames et al. 2021).

- **BECCS** supplies energy, e.g. for the industry sector but implies risks for water and soil quality, biodiversity loss (e.g. through monocultures) and Albedo changes that contribute to warming of the earth. The need for biomass for BECCS may be linked to competition for land which causes indirect changes in land use and may threaten food security elsewhere.

- **Biochar** (storage, but not removal of CO_2 in itself) may reduce CH_4 and N_2O emissions from soils and might have positive impacts on livelihoods by enriching the soil. However, the effects on soil quality are uncertain and depend on specific local circumstances as well as the source of the biomass from which it is produced (Smith 2016; Tammeorg et al. 2016). Furthermore, it may lead to Albedo changes that contribute to warming of the earth by darkening the soil (Bozzi et al. 2015). Biochar may also contain pollutants as it can bind polycyclic aromatic hydrocarbons that are produced during incomplete combustion processes and may be carcinogenic, mutagenic and/or toxic to reproduction (Brandt und Einhenkel, Arle, D. 2016). Additionally, the availability of excess biomass like residues to produce biochar is uncertain so that biochar may be linked to competition for land that causes indirect land use changes elsewhere (Paustian et al. 2016; Minasny et al. 2017).

- **Enhanced weathering** can positively impact soil quality and contribute to soil resilience by enhancing capacities to retain nutrients in soils, thereby also positively impacting yields and livelihoods. Yet, enhanced weathering may involve negative impacts on water quality and soil hydraulic properties though. Additionally, the implied high energy needs of enhanced weathering entail a risk for additional emissions and the extraction of minerals used for enhanced weathering may involve negative ecological impacts as well as negative local impacts like dust or emissions from transport that may affect human health.

- **Ocean fertilisation** can positively impact marine habitats by increasing fish biomass, reducing ocean acidification in the short term in the upper ocean. However, it may also increase N_2O and CH_4 emissions from oceans and negatively impact marine biology and food web structures and involve changes to the nutrient balance, anoxia in the ocean surface and subsurface ocean acidification and deoxygenation. As of now, scientific evidence about determining factors of such positive and negative effects is lacking though so that negative effects cannot be prevented with sufficient certainty.

- **Ocean alkalinisation** can contribute to protecting ocean ecosystems, particularly coral reefs against acidification. However, it can negatively impact marine biology and food web structures and involve changes to nutrient balance, anoxia in surface ocean and subsurface ocean acidification and deoxygenation. Like for ocean fertilisation, scientific evidence about determining factors of such positive and negative effects is lacking though so that negative effects cannot be prevented with sufficient certainty.

The CRCF proposal does not make positive environmental and social impacts mandatory. Minimum sustainability requirements to avoid negative impacts will be defined in delegated acts.

4.7 Technological readiness and scalability

Different limiting factors constrain the feasibility to implement a number of removal activities:

- For **DACCS, DACCU** and **enhanced weathering**, technologies have not reached a level of development where these removal activities can be implemented at scale, as they are too costly and require large amounts of energy to be efficient (Babiker et al. 2022). According to an analysis of the literature by Fuss et al. (2018), DACCS will only deliver large amounts of removal towards the end of this century.

- For **BECCS**, the limited availability of biomass, land and competition with other land uses constrains the potential to implement BECCS on a large scale (Fuss et al. 2018). Other removal activities that are land-intensive, such as afforestation, have to deal with the problem of limited availability of land and potential indirect land use effects that cause additional emissions elsewhere, which in return may reduce their sustainable mitigation potentials (Fuss et al. 2021).

- Other CDR activities, especially those that involve the capturing of CO_2 through photosynthesis and **storage in living and dead biomass, coastal ecosystems and soils** are readily available. Their scalability, however, depends on the competition for land designated for other uses and the context-specific setting. Moreover, demand for other ecosystem services might constrain the scalability of these types of CDR activities.

- For **biochar**, large-scale industrial pyrolysis plants do not exist yet (Schmidt und Hagemann 2021) and experience with large-scale production and use of biochar is still missing, so that “feasibility, long-term mitigation potentials, side-effects and trade-offs therefore remain largely unknown” (Fuss et al. 2018, p. 26).

- For **ocean fertilisation and alkalinisation**, the technological readiness is lowest. Regarding fertilisation, there is scientific uncertainty about the amounts of stored organic carbon that is transferred to deep ocean layers and the time for which carbon remains stored there. The scalability of ocean fertilisation with macronutrients is estimated as unrealistic because of the large quantities of nutrients needed (Babiker et al. 2022).

- For **ocean alkalinisation**, limited capabilities to extract, process and react minerals also constrain its mitigation potential (Babiker et al. 2022).
- In addition, only a minority of countries have set transparent, quantified targets for CDR in their long-term mitigation strategies so that there is a gap between CDR levels required for limiting global warming to 1.5°C and CDR activities currently planned by countries (Smith et al. 2023).

4.8 Costs

The following costs further limit the scalability of CDR activities:

- According to the IPCC (Babiker et al. 2022) for **carbon sequestration in agricultural soils** (soil carbon sequestration, agroforestry and biochar application), costs of removals of up to 5.5 billion tCO_2e/year by 2030 are estimated to be below USD 100 per tonne CO_2e removal per year, with smaller potentials (up to 0.6 billion tCO_2e/year by 2030) realisable at low cost below USD 100 per tonne CO_2e .
- For **reforestation, afforestation, peatland restoration and coastal wetland restoration**, the largest share of the estimated mitigation potential (up to 4.0 billion tCO_2e/year by 2030) are also estimated to be available at costs below USD 100 per tCO_2e removal per year, while additional smaller potentials of up to 0.7 billion tCO_2e/year by 2030 can be realised at costs between USD 100 and 200 per tCO_2e removal/emission reduction.
- For **DACCS and enhanced weathering**, the IPCC estimates that only very small mitigation potentials will be available at costs below USD 200 per tCO_2e removal per year by 2030 (Babiker et al. 2022). For DACCS, cost estimates in the literature range from USD 60-1,000 per tCO_2 removed, suggesting that costs could decrease from USD 600-1,000 per tCO_2 for first plants to USD 100-300 per tCO_2 as experience accumulates (Fuss et al. 2018). For enhanced weathering, costs could fall to less than USD 85 under best scenarios (infras; Perspectives 2020).
- Costs for **ocean fertilisation** are highly uncertain, with median cost estimates of USD 230 per tCO_2e removal per year. For **alkalinisation**, cost estimates range between USD 40 and 260 per tCO_2e removal per year.
- For **conservation, restoration and sustainable management of blue carbon ecosystems/habitats**, median costs are estimated as USD 240 per tCO_2e removal per year for mangroves, USD 30,000 per tCO_2e removal per year for salt marsh and 7,800 per tCO_2e removal per year for seagrass habitats (Babiker et al. 2022).

Smith et al. (2023) suggest that novel CDR activities like DACCS are still at an early stage in which no market prices exist yet. While it can be assumed that costs will decrease as technologies for these activities are further developed and supply increases, this phase does not appear to have begun yet.

The following tables, adapted from the impact assessment accompanying the European Commission's proposal on a certification framework for carbon removals, provide an overview about potentials, costs, feasibility and challenges to implementation of carbon removal activities.

Table 2: Potential, costs, feasibility, long-term sequestration and implementation challenges for industrial removal technologies

Name	Potential (low = <10, medium 10-50, high >50 Mt CO_2e/yr; for 2050 2030 for Blue Carbon)	Costs (low = <100, medium = 100-250, high = >250 USD per tonne CO_2e)	Technological Feasibility (Technological Readiness Level, low = 1-5, medium 6-7, high = 8-9)	Long-term sequestration (low = years to decades; medium = decades to centuries; high = several centuries and more)	Main challenge to Implementation
DACCS	Medium	High	Low	Very high	Energy requirements
BECCS	Medium	Medium / High	Medium	Very high	Biomass requirements
Enhanced rock weathering	Low	Medium	Low	Very high	Large mineral requirements
Biochar	Low	Medium	Medium	Medium	Biomass requirements
Biomass in buildings	Low	Medium	Medium	Low / Medium	Biomass requirement
Long-term CCU	Low / Medium	High	Low / Medium	Low / Medium	Energy requirement

Source: Own assessment as well as EC (2022a)

Table 3: Potential, costs, feasibility, long-term sequestration and implementation challenges for carbon farming activities

Name	Potential (low = <10, medium 10-20, high >20 Mt CO_2e/yr; for 2050, 2030 for Blue Carbon)	Costs (low = <100, medium = 100-250, high = >250 USD per tonne CO_2e)	Technological Feasibility (Technological Readiness Level, low = 1-5, medium 6-7, high = 8-9)	Long-term sequestration (low = years to decades; medium = decades to centuries; high = several centuries and more)	Main challenge to Implementation
Afforestation	Low / Medium	Low	High	Low / Medium	Land competition
Agroforestry	Low	Low	High	Low / Medium	Potential impact on production
Blue Carbon	Low	Medium / High	Medium	Low / Medium	Competition for coastal waters
Soil carbon on mineral soils	Low	Low	High	Low	Short-term impact on production
Peatland rewetting *(emission reductions, not removals)*	Medium	Low	High	Medium	Impact production
Improved forest management	Low / Medium	Low	High	Low / Medium	Reduced near-term yields

Source: Own assessment as well as EC (2022a)

5 Summary

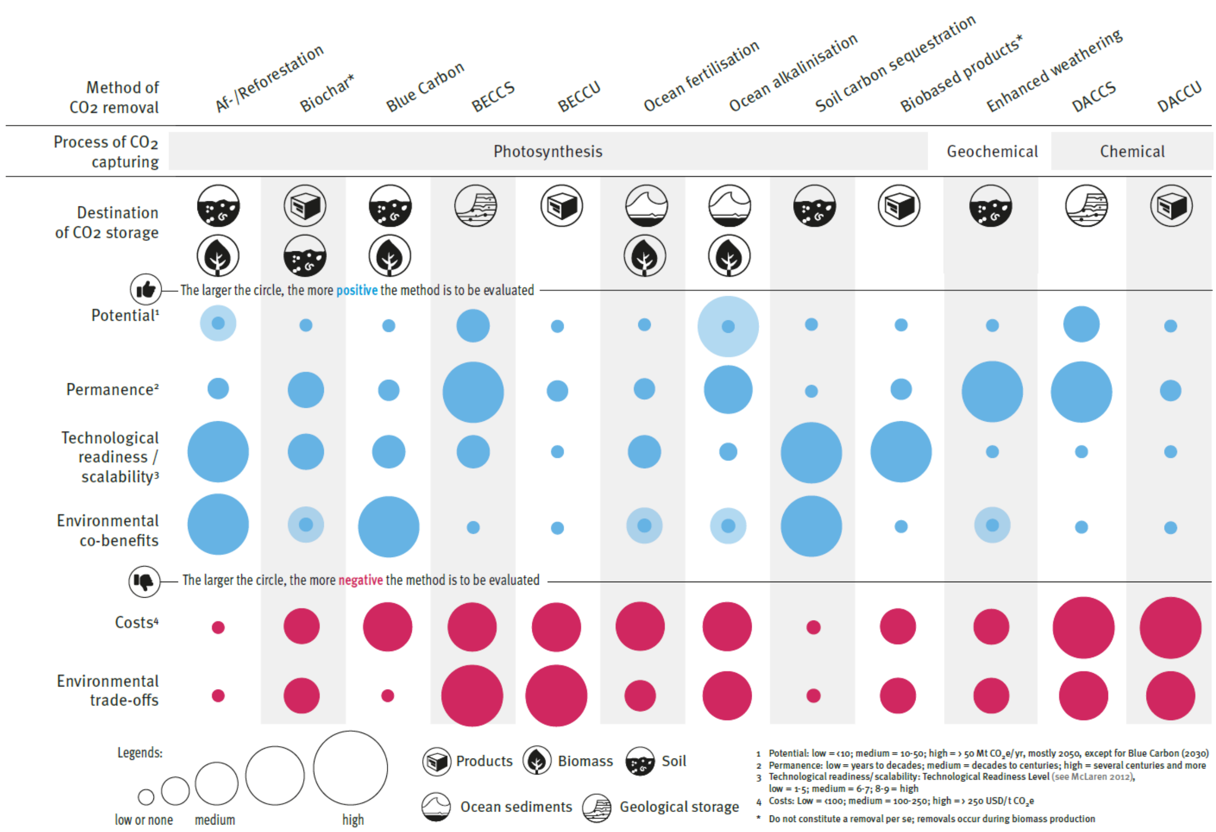
5.1 What is a suitable typology for CDR?

CDRs have already been categorised and assessed by a number of scientific studies. We have extracted the most important aspects of CDR that are useful for developing a typology for CDR that helps identifying crunch issues regarding deployment of CDR activities.

CDR activities differ in the process of capturing CO_2 as well as the storage destinations, resulting in different estimated storage durations. Moreover, activities can be complex regarding both the processes involved and the required energy and resource input and thus potential emissions along the process chain. Another criterion for differentiation is the absolute potential for removing CO_2 that depends on the efficiency of removals but also capacities for removal and storage. Influencing factors of the potential are also technological readiness and scalability as well as costs that differ considerably between CDR activities. Finally, environmental impacts of the employable activities vary. Next, we are briefly assessing existing activities in light of these criteria.

Figure 1 summarises the key characteristic of the selected CDR activities that were reviewed. We propose this typology to ensure that CDR activities are adequately assessed and differentiated according to aspects which are important to consider for the further testing, upscaling and implementation of effective and sufficient CO_2 removal methods.

Figure 1: **Overview of main CDR activities and their key characteristics**



Source: own compilation, Design Erik Tuckow, sichtagitation.de, see McLaren (2012) for a definition of Technological Readiness Levels.

5.2 What are the implications of the typology applied in the CRCF proposal?

Comparing the conceptualisation of CDR in the CRCF proposal with the discussion on CDR in the literature reveals the following major issues:

- **Differentiation between different types of removal activities**: The criteria for categorising different types of removals outlined above show that it is possible to group removal activities according to different aspects. The differentiation in the CRCF proposal in 'permanent storage', 'carbon farming' and long-lasting products' is only one possible way of categorising CDR activities that can be questioned. For some activities like biochar, it is not precisely clear, into which of the three categories they would fall though.
- **Process of capturing CO_2 and definition of removal**: The Commission's proposal for the CRCF subsumes emission reduction activities under the heading "removals". This contradicts the definition proposed by the IPCC and could create confusion about the nature of removal units certified under the framework. Consequently, the proposal also covers the rewetting of peatlands. While rewetting activities should be promoted, they are not removals in the sense of the IPCC definition. This deviation is also unique within the existing scientific literature in the field of CDR.
- **Destination of storage and definition of permanence**: The CRCF proposal applies a definition of permanence that is supposed to help identifying different types of storage. Geological storage is assumed to be quasi-permanent (referring to the EU CCS Directive

2009/31/EC, however, the definition in the proposal remains vague, see Meyer-Ohlendorf et al. 2023). Other types of storage are considered non-permanent. For such activities, reversals must be monitored for a certain period of time. A minimum storage period and a corresponding monitoring period yet remain to be specified, which adds to the ambiguity of the CRCF proposal. The proposal could potentially cover BECCU or DACCU activities, as it includes storage in products, does not clearly define what is meant by "long-term storage" in products and does not explicitly exclude short term storage in general. This is problematic as these activities do not necessarily qualify as long-term removal options and underlines the necessity to more precisely define criteria for 'permanent'/'long-term storage' in the CRCF proposal (see section 3 and 4.3 above).

- **Overall potential to remove CO_2, costs and technological readiness:** In the CRCF proposal the overall potential to remove CO_2, technological readiness or costs do not play a role in the sense that specific activities are prioritised. The impact assessment includes estimates of potential amounts of removals. For a fast deployment of activities and for directing technologies towards where in the long-term the highest potentials can be expected, these activities could be prioritised in a framework. However, due to the high uncertainties regarding potentials as well as potential negative environmental impacts, there is a risk of narrowing the choice of options too early or incentivising options that have not reached technological and economic readiness yet. Therefore, a thorough analysis of potentials and possible risks is necessary.
- **Energy consumption and environmental impacts**: The proposal does not exclude activities with high energy or resource needs (e.g. electricity or biomass). Moreover, it does not require removal activities to entail positive environmental impacts such as biodiversity benefits. Additionally, the proposal does not mention impacts of removal activities on social issues such as human health, or livelihoods. This is problematic as it fails to ensure that removal activities deliver environmental and social co-benefits. These need to be considered when evaluating different removal options.

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