Examining the Viability of Net-Negative Carbon Removal Techniques in Limiting Global Warming to 1.5 Degrees Celsius: An Economic and Environmental Evaluation

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15.06.2023
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Background

1.1 The necessity of Carbon Dioxide Removal

Bergman and Rinberg (2021) estimate that human activities have caused 2500 Gt[1] of carbon emissions into the atmosphere since 1850. This has caused the atmospheric concentration of CO_2 to rise from 278 ppm before the beginning of the industrial era to over 410 ppm in 2021 (Friedlingstein et al., 2022, p. 5). Anthropogenic global warming already reached 1 degree Celsius in 2017 (IPCC, 2018, p. 6), and the UNEP (2022, p. 30) estimates that even in the most optimistic scenarios, peak warming will likely exceed the 1.5-degree goals.[2] Similarly, a report by the National Academies of Sciences and Medicine (2018, p. 9) concludes that to meet the goals of the Paris Agreement, negative emissions of 10 Gt/y CO_2 by 2050 and 20 Gt/y CO_2 by 2100 are required.

Additionally, while for most sectors and industries the cost of CO_2 abatement through either emission avoidance or capture is significantly lower than the projected cost of most CDR strategies, there are some hard-to-avoid emissions, e.g. from agriculture and air transportation. This means that even after an atmospheric concentration of CO_2 in accordance with the goals of the Paris Agreement is reached, some carbon removal will be required to offset the remaining emissions and ensure the concentration of CO_2 remains stable (National Research Council, 2015).[3]

1.2 Definition of Carbon Dioxide Removal

There is a number of different definitions of Carbon Dioxide Removal (CDR), all of which are broadly equal, but slightly differ in the scope of strategies and technologies they include. For example, the IPCC (2018, p. 544) defines CDR as "anthropogenic activities removing CO_2 from the atmosphere and durably storing it in geological, terrestrial or ocean reservoirs, or in products", which suggests that any kind of

[1] 1 Gt = 1 billion (metric) tons

[2] The Mercator Institute estimates that as of May 8, 2023, the remaining carbon budget to stay below the 1.5-degree goal is roughly 262Gt CO_2, which at the current pace will be exceeded within the next seven yerars. The current numbers can be found at: https://www.mcc-berlin.net/en/research/co2-budget.html

[3] The amount of CDR required depends on the definition of *hard-to-avoid emissions*. While many definitions include any emissions for which their high financial cost makes CO_2 abatement non-viable, Bergman and Rinberg only include emissions that cannot be avoided for physical reasons or whose avoidance would cause unacceptable social injustice, and warn against using proposed future CDR strategies as an argument to avoid emission reduction in the present.

carbon capture or storage constitutes CDR, given that the carbon was taken from the atmosphere and not a single point source. The National Academies of Sciences and Medicine (2018, p. 1) use the term Negative Emissions Technologies (NETs) instead, which they define as strategies "which remove carbon from the atmosphere and sequester it." More recently, Smith et al. (2023, p. 11) argued that CDR must follow the three principles of (1) removing carbon from the atmosphere, (2) using durable[4] storage, and (3) being the result of active human intervention. All of these definitions imply that CDR can be divided into approaches that capture CO_2 from the atmosphere, such as Direct Air Capture, approaches that store CO_2, such as geological storage or in-situ mineralization, and approaches that capture and store CO_2, such as land management or afforestation and reforestation. This thesis uses the more narrow definition, focusing only on strategies and technologies that either capture or capture and store carbon, excluding storage-only strategies.

1.3 Natural and technological CDR strategies

CDR strategies can be grouped into biological capture, geochemical capture, both of which mostly rely on using or enhancing natural (i.e. biological or chemical) processes, and chemical approaches, which uses technological processes involving chemical solvents (Smith et al., 2023).

Biological capture processes include land-management strategies that aim to increase the amount of CO_2 stored in e.g. agriculturally-used soil, afforestation and reforestation, which are based on the natural ability of trees to capture and sequester CO_2 during their growth phase and beyond, as well as sea-based approaches that rely on fertilizing oceans to increase the growth of phytoplankton or seaweed.

Geochemical capture processes are mostly based on enhancing the natural weathering and mineralization process, which binds carbon in solid rock material, as well as increasing the alkalinity of oceans, which increases their ability to absorb CO_2.

Chemical processes use novel, typically two-stage technological processes that involve solid or liquid solvents, which initially absorb CO_2 from the atmosphere and later release it in concentrated form for storage or sequestration.

The various approaches differ greatly in their CO_2 removal potential, their feasibility on a larger scale, their energy requirements, the durability of the storage they use, and their cost, measured in dollars per ton of CO_2 removed (National Academies of Sciences & Medicine, 2018, Chapter 8).

The approaches discussed in this thesis are largely those that were considered by

[4]Smith et. al define durable storage as storage that "has a characteristic timescale on the order of decades or more".

the National Academies in their 2018 research agenda.

1.4 Current State of CDR research and development

In the past years, the investment into CDR research and development of CDR projects has increased substantially (Smith et al., 2023, p. 11). However, research and development of the various CDR strategies are currently at very different stages. Biological processes have a long history of literature and are more well-understood, and they are also cheaper to deploy at the present time, but less durable and face greater limitations in their total carbon removal potential due to natural constraints (Fuss et al., 2018). In comparison, chemical processes are still in their infancy and limited to few, small-scale experiments (Smith et al., 2023, p. 24). For example, while direct air capture is believed to have a carbon removal potential in the Gt/y range, it presently faces issues of high costs and lack of experience apart from relatively small-scale experiments. The largest currently operational direct air capture plant captures 4 kt of CO_2 annually, and even the largest project currently under development will only capture 1 Mt of CO_2 per year (Pernot & Jaruzel, 2022).
Uncertainty also exists about the contribution CDR can make to climate change mitigation efforts in general. While some reports (e.g. National Academies of Sciences and Medicine (2018)) include the usage of large amounts of CDR in the future as a necessity to reach the goals of the Paris Agreement, Fuss et al. (2018) argue that CDR is no alternative to rapid and sustainable reductions in carbon emissions and warn against over-reliance on CDR, citing the uncertainty and risks involved in its large-scale deployment.
In summary, while the efforts to develop and deploy strategies for anthropogenic carbon removal are increasing and many different approaches are being trialed, there is still a lot of research to be done before CDR can be used on a scale large enough to make a significant impact on climate change. Until then, efforts to reduce carbon emissions and reach a net zero should not only be continued but increased.

1.5 Economic viability of CDR

Since carbon removal is generally (with some exceptions) costly, and comes with no immediate benefit to its producer, the economic viability of CDR depends on a carbon price instituted by systems such as the European Emissions Trading System (EU-ETS), which requires companies in some industries to buy carbon certificates and allows trading between companies, or a government-enforced carbon tax. Currently (May 2023), the price for one ton of carbon dioxide produced in the EU-ETS stands at 88 € (97 US$), after exceeding 100 € for the first time in February of this year. Other definitions of carbon costs include the total cost of the social damage caused by carbon emissions, with different models proposing prices in a wide range between 50 US$ and 5000 US$ (Kikstra et al., 2021, pp. 1, 7). This thesis uses the definition instituted by Griscom et al. (2017, p. 3), who define a price of 100 US$/t CO_2 as cost-effective based on the costs to society avoided if global warming is kept to a level below two degrees Celsius.

Biological Strategies

2.1 Afforestation and Reforestation

Trees store CO_2 by converting it into plant biomass using photosynthesis. Crowther et al. (2015) estimate that there are approximately three trillion trees worldwide, and forests make up 38% of all habitable land area (Ritchie & Roser, n.d.). Despite significant deforestation in the past, 7.6 Gt of CO_2 are sequestered by forests annually, removing nearly 20% of anthropogenic carbon emissions from the atmosphere (Harris et al., 2021).

Potential

Afforestation refers to the cultivation of forests in areas that were recently deforested, whereas reforestation occurs on lands that did not grow forests in the recent past.[5] The total potential for carbon sequestration through afforestation and reforestation (AFRF) depends on three factors: (1) the amount of land available, (2) the amount of carbon that trees can sequester, and (3) the environmental climatic conditions. The IPCC's 2000 report estimates that trees in boreal regions sequester up to 1.2t CO_2/ha/y, while trees in temperate regions can store 4.5t CO_2/ha/y, and trees in tropical rainforests can store up to 8t CO_2/ha/y. These differences are explained mostly through the different lengths of the growing season, which only lasts a few months in boreal climates, but spans nearly the entire year in tropical regions (Watson et al., 2000). Other reports assume higher storage potential, with the National Academies of Sciences and Medicine (2018) claiming an upper bound of 30t CO_2/ha/y. Overall, the IPCC report estimated that an additional 87Gt could be sequestered using AFRF between 1995 and 2050, resulting in an annual uptake of 1.58Gt CO_2, 75% of which would be stored in tropical rainforests. More recent reports, such as Fuss et al. (2018) and Griscom et al. (2017) use higher theoretical estimates of up to 10Gt/y.

In addition to carbon removal, AFRF can bring benefits such as increased biodiversity, a reduction of land erosion and desertification in dry areas, and the protection of watersheds. (Watson et al., 2000)

[5]'Recent past' is typically defined as the last 30 - 50 years.

Limitations

Carbon removal through AFRF comes with vast land requirements. At a storage rate of 10t CO_2/ha/y, sequestering 1Gt CO_2/y would require 100 million hectares of additional forests.[6] Cultivating ecologically sustainable forests can also prove to be difficult. Creating vast mono-cultures of a single species of trees or turning previous grasslands into forests can harbor unforeseen dangers and negatively impact ecosystem diversity. This also raises the question of durability. Compared to other, more durable carbon removal strategies, forests are vulnerable to wildfires, pests, and other disturbances that can cause the rapid loss of stored carbon. Using forests as carbon storage, therefore, requires ongoing fire management, e.g. through the removal of deadwood and limited-scale intentional fires, and pest management (Watson et al., 2000). Depending on the region, other factors such as surface albedo and evapotranspiration can also play a role and significantly reduce the effectiveness of carbon storage. Forests generally have lower albedo rates than grasslands, meaning that they reflect a lower portion of the incoming sunlight and therefore trap a larger amount of heat. This effect is especially strong in high-latitude forests. In comparison, evapotranspiration occurs mainly in tropical rainforests, where large amounts of water evaporate and, while cooling the surface, can act as a potent greenhouse gas and cause atmospheric warming. (National Research Council, 2015). Finally, the net additionally of AFRF also depends on what the land was previously used for. If farmland is converted to forest, then it is likely that, considering the increasing food demand worldwide, somewhere else, forests will be cut down to ensure sufficient supply. This would significantly reduce or fully eliminate the net effect of AFRF. The same is true if forests are planted on lands that would naturally have re-grown forests anyways (Gates, 2021, p. 128).

Carbon storage by trees is also limited by their growth rate and natural lifecycle. Carbon uptake is generally the highest during the growth phase, which can be between 20 and 200 years long depending on the species, but slows down afterward (Watson et al., 2000). The highest uptake rate is typically reached after 30 - 40 years, depending on environmental factors (National Research Council, 2015). Watson et al. (2000) propose using non-organic nitrogen fertilizers to increase growth rates and carbon uptake. However, a study by Crutzen et al. (2008) has shown that nitrogen fertilizer is partially converted to nitrous oxide, whose greenhouse potential is 300 times stronger than that of CO_2. The assumed amount of nitrogen fertilizer required ranges from 24kt/y (Rau et al., 2013) to 500kt/y (Dipple et al., 2021) for 1Gt CO_2/y stored and in a worst-case scenario could create more CO_2e than the

[6] For comparison, Germany has a total surface area of about 36 million hectares.

tree growth removed (National Research Council, 2015).
Finally, climate change itself is heavily affecting forest ecosystems. While increased levels of atmospheric CO_2 and warmer temperatures can increase tree growth, an increased frequency of droughts, wildfires, and other extreme weather events disturb forest growth and negatively impact plant and animal life (EPA, 2015), making AFRF efforts more difficult. Verification of the effects of AFRF is also an issue. While it is possible to measure forest growth by using a land-based approach, the accuracy of such measurements can be limited and the measuring capabilities can vary by country. (Watson et al., 2000).

Cost

The cost of AFRF largely depends on the cost of land, the terrain, and the type of trees being planted. According to Gorte (2009), the cost of reforestation after severe wildfires in the United States in 2002 ranged between 200 and 2000 US$/acre[7], and the average cost was 523 US$/acre in 2007. At a storage rate of 10t CO_2/ha/y, this suggests costs between 49 US$/ton CO_2 and 494 US$/ton CO_2, and an average of 129 US$/ton CO_2.
Other studies resulted in slightly lower cost estimates, with a lower limit of 1 US$/ton CO_2, a cost of 7.5 - 22 US$/ton CO_2 for sequestration of 1Gt CO_2/y, and half of the total sequestration potential being available below 55 US$/ton CO_2. However, it remains questionable whether these estimates properly account for the potential risks of fires, pests or other disturbances that could lead to the release of sequestered carbon (National Research Council, 2015, pp. 41–42).
Additional cost reductions might be realized by using and systematizing agroforestry, an approach which integrates trees into crop pastures and comes with numerous co-benefits that can offset the cost of tree cultivation, and is useful especially in economically disadvantaged regions and dry climates (Reij, 2014).

2.2 Soil Sequestration

According to the 2000 IPCC report, the cultivation of soil can result in the release of over half the carbon initially stored in it into the atmosphere. The National Research Council (2015) estimates that in the last ten thousand years, agricultural activities have caused a net release of up to 840 Gt of CO2. Despite this loss, soils are still a major carbon storage, containing up to 10% of the global carbon stocks.

[7] 1 acre = 0.405 hectares

Potential

Using a number of improved land management techniques, such as conservation tillage practices, planting cover crops, and optimizing crop types and fertilization practices, the loss from agricultural use can be partially reversed and the amount of organic matter in soils, more than half of which is typically stored not above ground, but in roots, dead leaves and wood litter, can be increased (Ontl & Schulte, 2012; Watson et al., 2000, p. 192). This increased sequestration serves both economic and environmental purposes, as it increases the amount of carbon stored while potentially increasing crop yields and promoting soil health. (Dipple et al., 2021)
Improved-land management practices are well-understood techniques and have been in use in the United States since the 1950s, and since then saw an increasing adoption in Asia and parts of South America (Watson et al., 2000, p. 202). Compared to forest-based carbon removal approaches, carbon sequestered in soils is less vulnerable to fires and other diseases, making soil sequestration a more reliable form of carbon storage (Dipple et al., 2021). The theoretical potential of soil sequestration for carbon storage is determined by the historic stock before the beginning of agricultural use, which caused much of the ecosystem degradation and resulting loss of soil carbon (National Academies of Sciences & Medicine, 2018). Dipple et al. (2021) estimate that soils are currently a net sink of CO_2, with an annual uptake of 1 - 2Gt CO_2, caused mostly by the increased CO_2 concentration in the atmosphere itself.[8] However, the use of optimized land management practices can significantly increase carbon uptake. Conservation tillage is one of the most effective techniques. It involves a reduction or complete elimination of tilling to prevent soil disturbance, while also leaving at least 30% of the residual crop biomass from agricultural use on the field. Originally developed to reduce soil erosion, studies found that by minimizing soil disturbance and maintaining crop residues, the aeration and decomposition of organic matter are reduced, leading to increased soil organic carbon (SOC) and prolonged carbon storage. Studies estimate that an average of 1.2t of CO_2 could be stored per hectare of farmland annually through conservation tillage on about 60% of the total arable land. With a total cropland area of approximately 1.5 billion hectares worldwide, conservation tillage has the potential to sequester a total of 0.33 to 4.3Gt CO_2/y[9] (National Research Council, 2015; Watson et al., 2000). Another promising method for soil carbon sequestration is the use of cover crops, which are planted between cash crop seasons to protect and enhance soil quality. These crops provide continuous soil cover, thus reducing erosion, promote biological

[8] This effect is also referred to as "CO_2 fertilization".

[9] The 2000 IPCC report (p. 202) estimates carbon storage of 0.1 - 1.3t C/ha. Based on molecular mass, this equals 0.37 - 4.9t CO_2/ha; applying that to 60% of 1.5Gha worldwide yields these results.

activity in the soil and supply organic matter to the soil through roots and biomass, while increasing nitrogen content and serving as natural fertilizers (Dipple et al., 2021; Ontl & Schulte, 2012). In total, studies estimate that in feasible scenarios soils could sequester between 3.3Gt and 5.2Gt CO_2/y globally (Bossio et al., 2020; Dipple et al., 2021; National Research Council, 2015).

Limitations

The two biggest limitations soil sequestration through improved land management faces are the limited potential for carbon absorption per hectare of agricultural land, and the requirement of permanent upkeep.
Naturally, the amount of carbon soil can absorb is limited. P. Smith (2016) estimates that soil saturation will occur after 10 to 100 years, depending on the soil type and environmental conditions, being slower in colder climates. The 2000 IPCC report estimates that on average, sequestration reaches its highest annual potential within the first 5 to 20 years after adopting conservation tillage approaches, and then declines to near-zero after 50 years. Accordingly, if started globally today, soil sequestration would not be available as a sink for the second half of the 21st century. This problem is increased by the fact that while uptake is limited, it is also easily reversible, meaning that a return to previous, standard land use and management techniques would release the carbon stored previously. This means that the improved land management techniques will have to be used indefinitely, and the costs potentially associated with it will have to be paid continuously. (P. Smith, 2016, p. 9). Thus, the use of optimized land management techniques faces not just technical, but also socio-economic issues (Dipple et al., 2021). Zelikova et al. (2020) argue that to increase the incentive for farmers to implement improved land management, demonstration projects should be conducted and the support for farmers increased.

Cost

Due to the wide range of different agricultural processes involved and the difficulty in measuring their exact costs, the economic feasibility of soil carbon sequestration techniques such as conservation tillage and cover cropping is hard to quantify. Bossio et al. (2020) expects that half of the total soil sequestration potential is available below 100\$/t CO_2, while one-fourth is available below 10\$/t CO_2, based on available marginal abatement cost curves. A study by McKinsey (2009) reaches a similar conclusion. However, these estimates include sequestration not only on agricultural land but also in forests. Bossio et al. (2020) also note that based on the co-benefits of enhanced soil health and reduced inputs, some soil sequestration can be cost-effective, i.e. have negative costs. Yet, Zoebisch et al. (2022) remark that these co-benefits can take some years to become effective, while the initial costs of implementing new practices can be high. Chambers et al. (2016) used the subsidies paid to farmers in the US for the adoption of such practices as a reference point and found costs to be between 3.44 - 11.34 US$/t CO_2 sequestered. However, this estimate is based on a small-scale study, only includes the sum paid to the farmers by the government, and may not be representative of the costs associated with the broader implementation of these measures.

2.3 Summary of Biological Strategies

Overall, since biological carbon removal technologies are based on the usage and enhancement of natural processes that have occurred for millions of years, they are comparably well understood, with large amounts of research available, and a theoretically large carbon removal potential in the range of 5 - 10 Gt CO_2/y. Their implementation is very straightforward, and mostly an issue of deploying them on a large-enough scale. The biggest advantage of biological carbon removal is that most of the costs are incurred during the initial implementation, i.e. for planting trees and adapting to new land management processes, while the operating costs, under ideal circumstances, could be relatively low. However, there is relatively little experience with the dedicated application of these methods for carbon removal purposes. While studies generally point to the costs being below 100 US$/t CO_2, which would make biological strategies economically viable, the vast land requirements, the limited amount of carbon that biomass and soil can sequester, and the risk of natural disasters such as wildfires and pests impacting the permanence of carbon storage cast doubt on whether these strategies can be used for long-term, large-scale carbon removal operations.

Additionally, it should be noted that with an ever-increasing world population, the demand for food will continue to rise, thus potentially creating competition for land or forcing farmers to choose between using long-term, sustainable farming techniques (i.e. those that also allow enhanced carbon sequestration) and maximizing shorter-term yields.

Geochemical Strategies

3.1 Enhanced Mineralization

Carbon mineralization is a chemical process in which alkaline materials such as magnesium and calcium silicates react with water and carbon dioxide to produce stable, solid carbonates. Similarly to the aforementioned biological processes, it has occurred naturally for millennia, albeit at a very slow rate.

Potential

Mineralization strategies include enhanced weathering (EW), which involves the spreading of finely-ground alkaline minerals over large land surfaces to naturally react with atmospheric CO_2, in-situ processes, for which concentrated CO_2 streams are injected into geological formations containing appropriate minerals, and ex-situ processes, which involve the extraction and processing of alkaline materials to enhance their reactivity with CO_2. All of these processes fixate carbon dioxide in stable carbonate minerals, which can then be stored for hundreds or thousands of years and avoid the risk of leakage.
Sources of alkalinity are typically minerals such as peridotites and serpentinites, which are abundandly available (Lackner et al., 1997), and mineral-heavy industrial byproducts such as waste materials produced during resource extraction, construction, and manufacturing, which are highly reactive and available at little cost (National Research Council, 2015). Since 38% of all global land area are cropland or pastures, which are ideal for spreading rock dust (Almaraz et al., 2022), EW theoretically has a huge potential for carbon sequestration. Beerling et al. (2018) estimate that if two-thirds of the most productive cropland worldwide (a total area of 900 million hectares) were treated with rock dust at a rate of 20-30 t/ha/y, a sequestration potential of 0.5 - 4Gt CO_2/y could be achieved. They also argue that treating cropland with basalt has been shown to have significant co-benefits, including increased soil fertility and crop yields, and an increased amount of organic material in soils. Combined with the previously mentioned improved soil management techniques, this could make EW an attractive strategy from both a carbon removal and agricultural productivity perspective. Another study by Goll et al. (2021) proposes spreading a single dose of 5t of basalt dust per hectare on 5500 million hectares of unpopulated land, and based on a land-surface model that uses experimental weathering data, estimates a sequestration potential of 2.5Gt CO_2/y

over the next 50 years.
For ex-situ approaches, Lackner et al. (1997) propose an exothermic chemical process that uses a reactor vessel and concentrated CO_2 atmosphere to carbonize alkaline minerals under pressure without requiring large additional energy inputs. For in-situ processes, proof-of-concepts that inject carbon-rich liquid in underground basalt formations are currently underway, with one experimental plant in Iceland sequestering about 12Kt CO_2/y. In optimistic estimates, both of these processes could also sequester multiple gigatons of CO_2 per year if deployed on a large scale (Dipple et al., 2021).

Limitations

The primary issue of enhanced mineralization is that it requires a constant supply of fresh rock and large amounts of energy to mine, grind and transport the rock dust. For EW, Schuiling and Krijgsman (2006) estimate that about 2t of olivine rock dust are required per tonne of CO_2 removed, based on a calculation of the amount of rock required per square meter to absorb the entire atmospheric CO_2, which was estimated at 5kg/m^2 of surface area.[10] If basalt is used, the amount of rock dust required is even greater, with Beerling et al. (2018) estimating that up 6.75t of basalt per tonne of CO_2 could be needed. On a global scale, this would require between 9 and up to 27 Gt of basalt to remove a maximum of 4Gt of CO_2 annually. The study by Goll et al. (2021) arrived at a more optimistic estimate of 5.5Gt of rock dust needed to remove 2.5Gt CO_2/y, albeit on unpopulated land.[11] Extracting, processing and transporting such large amounts of rock dust would require significant energy and resource inputs, which would not only be costly but also offset between 10 - 30% of the carbon sequestered. Large-scale mining operations also necessarily disrupt ecosystems and have negative ecological impacts (Beerling et al., 2018). Almaraz et al. (2022) note that there is little experience with the ecological impact of rock dust application, and warn that heavy metal contents in the rock material could accumulate in the soil and then be introduced into the food chain.
The second issue is the land requirement: Due to the relatively slow weathering, it could take years to decades to fully mineralize the rock dust. Weathering speed also heavily depends on environmental circumstances. While acidic rain with pH values around 4, which occurs e.g. in Europe and North America, can mineralize

[10] The full calculation is as follows: Schuiling et al. estimate that a rock dust layer of 0.4cm would be required on all global land area to remove the entire CO_2 content from the atmosphere. This equals 0.004m^3 of rock dust per m^2 of surface area, which at a density of about 2500kg/m^3 results in a requirement of 10kg of olivine dust.

[11] For comparison, about 8Gt of coal and 2.5Gt of iron ore are mined globally per year.

the proposed rock dust layer within 30 years, an pH increase of just 0.3 units could double the required time (Schuiling & Krijgsman, 2006). This means that a large percentage of the total land area would have to be treated, and while rock dust application does usually not compete with other land usages such as agriculture and forestry, it would still be a significant logistical challenge (Dipple et al., 2021).
Another issue is the question of how the mineral dust would be spread. For farmland application, small-scale experiments in Germany by the Carbon Drawdown Initiative (2022) have shown that using existing agricultural spreaders, such as manure spreaders or fertilizer spreaders, is the only method that can effectively and efficiently distribute rock dust, with the spreading of 40t on one hectare of farmland taking a little more than 30 minutes. However, this process requires the use of larger-grained rock coarse instead of super-fine dust, which results in a less homogenous rock layer and makes monitoring results more difficult. The Goll proposal on the other hand includes the usage of spreader aircraft for distribution, which would require significant resources and infrastructure to operate, further adding to the costs of implementation.
Lastly, it should be considered that for ex-situ processes, the study by Lackner et al. (1997) admits that to speed up the mineralization to complete within hours instead of days, high-pressure and high-temperature reactors are required, which could result in significant energy requirements. Also, both in-situ and ex-situ reaction processes (excluding EW) are strictly speaking not carbon-removal but carbon-storage processes, since they require the usage of pre-concentrated CO_2, e.g. from DAC or point sources in industrial plants.

Cost

The costs associated with the implementation of enhanced mineralization are somewhat difficult to calculate, considering the number of steps involved in the process, from mining to spreading (or mineralizing) the rock dust. While Almaraz et al. (2022) argue that EW can be economically viable for farmers due to the previously mentioned co-benefits, they don't provide specific numbers. These benefits also don't apply to other in-situ or ex-situ mineralization processes.
Overall, the biggest share of the costs would come from the extraction, processing, and transportation of large amounts of rock dust. Studies by Beerling et al. (2018) and Fuss et al. (2018) provide wide-range estimates for EW, with a minimum of 50 US$/t and a maximum of 578 US$/t of CO_2 removed, mostly based on the cost for grinding the basalt rock and transporting the dust to its destination. The study by Goll et al. (2021) comes to a similar conclusion, stating that 0.2Gt CO_2/y should be available below 100 US$/t CO_2, and up to 2.5Gt/y below 500 US$/t CO_2, based

on the logistics cost for application in uninhabited areas. The Lackner et al. (1997) study estimates costs for raw materials to be between 40 and 100 US$/t CO_2 removed for ex-situ mineralization, and argue that they could be reduced further once large-scale production begins. However, this estimate does not include the costs for energy required, nor the cost of building and maintaining the required infrastructure and industrial-scale processing plants. If energy requirements were included, Lawler and Knops (2021) argue that costs could be as high as 600 US$/t CO_2 removed for ex-situ mineralization, but do not provide a detailed basis for this calculation. They also argue that ex-situ mineralization could be cost-effective, albeit at a limited scale, if the mineralization byproducts were sold to e.g. the paper industry as a replacement for lime. For in-situ mineralization, even less data is available. CarbFix, the company currently running one of the largest in-situ mineralization projects, estimated their costs to be around 25 US$/t CO_2 sequestered (Lawler & Knops, 2021). While this relatively low estimate is promising, it is important to note that it only accounts for the costs of carbon sequestration, while the costs for capturing it using e.g. DAC technology are not included.

3.2 Ocean Fertilization

During its growth, phytoplankton absorbs solved carbon dioxide from the surface ocean through photosynthesis. When it dies, it falls to the ocean floor, taking the CO_2 it absorbed with it. There, it is consumed by fish and other animals, which respire and convert the organic carbon back into CO_2. This cycle is called the biological carbon pump (BCP). The idea of ocean fertilization is to stimulate phytoplankton growth and strengthen the BCP to sequester more carbon in the oceans.

Potential

In most oceans, the growth of phytoplankton is limited by the availability of nutrients such as iron, nitrogen, and phosphorus. The first step of ocean fertilization (OF) is to supply these nutrients, either by adding the micronutrient iron (Ocean Iron Fertilization, OIF) or the macronutrients nitrate and phosphate (Ocean Macronutrient Fertilization, OMF) (National Academies of Sciences & Medicine, 2022, p. 77). OIF was first popularized by John Martin ("Give me half a tanker of iron, and I will give you the next ice age.") and is proposed for regions where macronutrients are high, but phytoplankton content is low (i.e. iron where iron is the limiting factor). These high-nutrient, low-chlorophyll (HNLC) regions are mainly in the Southern Ocean, the Equatorial Pacific, and parts of the North Atlantic. OMF on the other hand would be applied to low-nutrient, low-chlorophyll (LNLC) regions (Chisholm et al., 2001). In the second step, the stimulated phytoplankton growth takes up CO_2 from the surface ocean, converting it into organic matter through photosynthesis. Once this organic matter falls to the ocean floor, its carbon content are incorporated into sediment and sequestered for hundreds of years or even millennia. (Fuss et al., 2018; S.F. Jones, 2014)

OIF has shown promising results in increasing phytoplankton growth and the uptake of CO_2 in HNLC. It is also favored due to the low ratio of iron required to the carbon sequestered of approximately 1:1000 (National Academies of Sciences & Medicine, 2022, p. 99). The study by Hauck et al. (2016) found the global sequestration potential of OIF to be 113Gt CO_2 per century based on an ecosystem model that includes nitrate, silicic acid, and iron, but does not account for potential sea-air backflow of carbon. At an average rate of 1.1Gt CO_2/y, they require an input of 2.3Mt Fe/y into the oceans. They also propose coupling OIF with EW, since the olivine minerals used in EW release iron that can be used for OIF. Keller et al. (2014) give a more optimistic estimate of up to 15Gt CO_2/y, based on a scenario in which the entire southern ocean would be fertilized continuously, but admit that this number would quickly decrease to a maximum 5Gt CO_2/y as the large reservoir of available macronutrients is used up. Overall, the National Academies of Sciences and Medicine (2022, p. 87) found a realistic potential for OIF in HNLC regions of 1Gt CO_2/y.

For OMF, Harrison (2017) estimates a one-off potential of 3.6Gt CO_2, with about 0.7Gt CO_2/y afterwards if only nitrate is added. Their estimate is based on the quantity of phosphate (which would be the limiting factor) available in the oceans, and the amount of nitrogen needed to "use up" that phosphate, combined with the expected efficiency in boosting phytoplankton growth. In a second scenario, they consider the addition of both nitrate and phosphate, which increases the annual potential to 1.5Gt CO_2, with only the amount of mined phosphate added being the limiting factor.

Limitations

OF is limited to specific regions of the oceans which present ideal conditions for fertilization (i.e. HNLC for OIF and LNLC for OMF). This largely limits OIF to the Southern Ocean encircling Antarctica. For OMF, the viable oceanic regions are easier to access since large parts of the global oceans are LNLC, however, the amount of material (nitrate and phosphate) required is huge in comparison, based on the Redfield ratio[12] and calculations by S.F. Jones (2014) and Harrison (2017), and in addition to the required logistics would make up a significant share of the total phosphate produced worldwide.

The biggest concern however is that only a small fraction of the organic carbon is transferred to the deep ocean and buried. When phytoplankton dies and starts sinking to the ground, most of it is consumed by zooplankton, microbes, and other animals within 100 meters of the photic zone. Their respiration releases the carbon, which quickly returns to the surface ocean and eventually the atmosphere (National Academies of Sciences & Medicine, 2022, pp. 82, 84). Zeebe (2005) estimates a sedimentation rate of only 10 - 25% based on ocean carbon cycle models. This means that of 1Gt CO_2 absorbed by phytoplankton, only 0.1 - 0.25Gt are incorporated into the bottom sediment while the rest is returned to the surface quickly. Furthermore, Harrison (2013) estimates that even under optimal conditions, only 8.3% are sequestered and stored for over 100 years, with the average being a mere 0.4%.

Other issues include (1) the fact that OF is a geoengineering technique with global implications, and as such, can negatively impact ocean food webs and alter biochemical cycles (Chisholm et al., 2001; Zeebe, 2005), (2) the potential for OIF to cause "nutrient robbing", which means that macronutrients are drawn from other areas of the ocean, reducing the amount of biomass growth there, and leading to limited additionality (Zeebe, 2005), and (3) the emission of N_2O (which is a potent greenhouse gas) caused by the usage of nitrate fertilizer. All of these issues have the potential to severely limit the net carbon removal effect of OF and cause unintended consequences for the ocean ecosystem. Finally, measuring the effect of OF is difficult (National Academies of Sciences & Medicine, 2022, p. 87). While surface waters can be sampled for nutrients and phytoplankton growth and monitored using satellite imaging, measuring sequestration rates in the deep ocean is more challenging and requires highly advanced sensors and instruments (Chisholm et al., 2001; National Academies of Sciences & Medicine, 2022).

Cost

Optimistic estimates for OIF claim costs as low as 2 US$/t CO_2 removed (Fuentes-George, 2017), however, these estimates are at least partially influenced by the commercial and marketing interests of the companies involved. A more realistic estimate by Harrison (2013), based on OIF experiements conducted in the past, includes the losses mentioned above and puts the cost of OIF at 18 US$/t CO_2 in the best case, but admits that at the average long-term storage rate, they could be

[12] The Redfield ratio of 106:16:1 describes the ratio of carbon to nitrogen to phosphorus (C:N:P) found in phytoplankton.

as high as 457 US$/t CO_2. For OMF, a detailed economic analysis by S.F. Jones (2014) concluded that if only nitrogen fertilization is required, costs could be as low as 20 US$/t CO_2 removed, including the cost for producing and transporting the nitrate. However, this study does not take into account the low rate of long-term sequestration. All things considered, Gattuso et al. (2021) expects the average cost per ton of CO_2 sequestered to be 230 US$ across both approaches.

3.3 Summary of Geochemical Strategies

Geochemical CDR (gcCDR) strategies are based on enhancing natural geological carbon sinks on land and in the oceans on a global scale. Proponents of these strategies promise cheap, large-scale carbon removal. Their biggest advantage is the safety and durability of storage as either solid rock or sequestered in the ocean floor, which makes them less prone to leakage and requires less long-term care than the biological approaches discussed in Chapter 2. In combination, their sequestration potential could be between 5 and 10Gt CO2/y at proposed costs as low as 50US$/t CO_2 for EW and 20US$/t CO_2 for OF.

However, gcCDR strategies suffer from the global scale of deployment required to realize a significant impact, which presents logistical and environmental challenges. Enhanced weathering requires large-scale mining operations and large amounts of energy for processing and transportation, which is counter-intuitive to climate protection and would probably face opposition due to the impact on local ecosystems and communities. Also, as Goll et al. (2021) conclude, it would only be viable if sufficient renewable energy was available to keep the supply chain carbon-neutral. Ocean fertilization is highly dependent on uncontrollable factors such as ocean currents and ecosystem response and suffers from uncertain effectiveness for long-term sequestration and potential nutrient robbing. Therefore, more research into the real durability and additionality depending on the specific conditions of the ocean is needed. From an economic perspective, the existing estimates for both approaches are highly uncertain and vary widely. They are mostly based on small-scale experiments and ecosystem models, making it difficult to accurately predict the cost and efficacy of large-scale implementation. The necessary mining and transportation also mean that the ongoing operating costs would be significantly higher compared to biological approaches. In a worst-case situation, if required investments and potential negative impacts are included, the cost per ton of CO_2 could exceed 400US$. Lastly, the global scale of these approaches, especially OF, requires international cooperation and a framework that governs who can deploy them in which locations and ensures proper accountability for the potential long-term consequences.

Chemical Strategies

4.1 Direct Air Capture

4.2 Bioenergy with Carbon Capture and Storage

4.3 Summary of Chemical Strategies

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