REMOVING CARBON NOW

How can companies and individuals fund negative emissions technologies in a safe and effective way to help solve the climate crisis?

Carbon removals are an important part of the solution of the climate crisis, hundreds of gigatons of CO2 will likely need to be removed from the atmosphere this century with the help of a wide range of negative emission technologies. This paper sets out to answer which negative emissions techniques are available on the market today and how they potentially could be used by companies or individuals who wish to help solve the climate crisis by removing carbon in an effective way without creating risks for people or the environment.

Oxfam Discussion Papers

Oxfam Discussion Papers are written to contribute to public debate and to invite feedback on development and humanitarian policy issues. They are 'work in progress' documents, and do not necessarily constitute final publications or reflect Oxfam policy positions. The views and recommendations expressed are those of the author and not necessarily those of Oxfam.

For more information, or to comment on this paper, email Robert.hoglund@oxfam.se

www.oxfam.org

OXFAM

SUMMARY

Carbon removals are an important part of the solution of the climate crisis. Hundreds of gigatons of CO2 will likely need to be removed from the atmosphere this century with the help of a wide range of negative emission technologies. This paper is aimed at individuals or organizations that want to fund carbon removal and sets out to answer which negative emissions techniques are available to buy carbon removal with today, looking at how effective they are at mitigating climate change and their social and environmental risks.

The available methods for carbon removal assessed are biochar, soil carbon sequestration, storage in the built environment, direct air capture with storage (DACCS), forestation (afforestation and reforestation) and enhanced weathering. Other removal methods are excluded since they are not available to buy carbon removal certificates from today. Each method is evaluated on social and environmental risk and effectiveness meaning additionality, permanence, and speed of capturing carbon. Obstacles, co-benefits, the cost per tCO2 removed, total potential, and an overall assessment of using the technique as a part of a carbon removal strategy are also included.

To summarize, there are possibilities to fund carbon removals in a way that effectively mitigates global heating without creating large social or environmental risks. By doing so organizations and individuals can contribute to solving the climate crisis.

However, what one tonne of carbon removed means varies greatly between the methods used. Carbon removals can be sold without the transaction leading to more carbon being removed due to low additionality. Methods can have high or low permanence, storing the carbon for a short or very long time. Some methods capture carbon quickly, leading to increased mitigation now, but others can take decades or centuries.

Carbon removals can also create social and environmental harm, for example, by driving people in low-income countries off their land or by negatively affecting biodiversity. On the other hand, some methods can create social and environmental co-benefits.

Effectiveness and risk vary between, but also within methods. All methods can be used in non-effective and harmful ways. Therefore, risks and disadvantages for each carbon removal project must carefully be assessed before funding it.

Companies and individuals should strive to do as much good as possible with their carbon removals rather than doing it as cheaply as possible.

Additionally, organizations and individuals should not conflate commitments to remove emissions with commitments to reduce their emissions, as these reflect two different concepts and needs.

1 INTRODUCTION

To avoid catastrophic global heating, greenhouse gas emissions must be drastically reduced. Even if it is still theoretically possible to only *reduce* emissions to limit warming to 1.5°C, [1] carbon in practice also needs to be *removed* from the atmosphere. For example, the vast majority of IPCC pathways limiting warming to 1.5°C include the use of carbon removal techniques, assuming hundreds of gigatons of CO_2 removals this century, even in some of the best-case scenarios. Worst-case scenarios assume that up to 1000 gigatons need to be removed before 2100. [2]

Many companies have started funding carbon removals as part of their sustainability and net-zero strategies, for example by buying carbon removal certificates from forestation in low-income countries. Several countries are including carbon removals in their climate mitigation plans.

This paper investigates negative emissions techniques from which carbon removal certificates are sold on the market today and looks at how effective they are at mitigating climate change and what risks for humans or the environment they might pose.

The paper aims to advise a company or individual wanting to remove carbon, it does not analyse what sustainable carbon removal strategies are for government or multilateral organizations designing policy. The paper does not assess how carbon removal methods can be scaled up other than being funded by individuals or companies. The paper does not assess the positive or negative impacts that new carbon markets could create. For example, that the cost and hurdles of certification could lead to harmful consolidation of small farms, pushing vulnerable people off their land. This is a factor that would need to be assessed before creating large new carbon removal projects, especially in low-income countries.

What are carbon removals?

Carbon removal, carbon dioxide removal, negative emissions, or greenhouse gas removal are all vocabularies that have been used to describe the same thing; to remove carbon dioxide or other greenhouse gases from the atmosphere and store it over a long time. The methods range from naturally occurring ones such as forestation to high-tech ones like direct air capture. Carbon removal certificates from several different negative emission techniques are now available on the market for companies and individuals to buy. Besides buying certificates some companies and individuals advance carbon removals by investing in negative emission companies or funding research projects.

Carbon removal is a different concept to avoiding emissions. The carbon credit market that companies and countries trade on to ‘offset’ their emissions is mainly about avoiding emissions that otherwise would have happened. For example, by buying carbon credits sold by a renewable energy project or a project to increase energy efficiency. Removals are about taking existing carbon out of the atmosphere and storing it, not reducing the rate of new emissions going into the atmosphere.

Removing carbon in an effective and non-harmful way

Advancement of carbon removals must be done in a way that is both effective at mitigating global heating and non-harmful. In this paper we use ‘effective’ to mean that carbon actually is being removed from the atmosphere and stored away in a lasting/permanent manner, and that it happens now and not far in the future. We also look at if the methods create harm or risks to people or the environment.

Note that effectiveness and harm can vary for the same method depending on how it is performed. No technique is always safe and effective, in this paper the *risk* of low effectiveness and the *possibility* of high effectiveness is assessed as well as the risk for harm, and the possibility of no-harm. Even if all methods can be used in non-effective and harmful ways, some have lower risk and higher potential to be done effectively and safely than others.

In this paper the following indicators are used to evaluate each carbon removal technique:

Effective mitigation includes:

Additionality: When purchasing carbon removal through a method, to what degree does the purchase make the carbon removal happen? Is there a chance the removal would have happened even if no one paid for removal certificates?

Additionality can be anything between zero where the purchase of removal certificates did not lead to more carbon being removed to 100% where the removal certainly would not have happened without someone buying the certificate. It can be difficult to assess, especially in cases where a method is already being used commercially but for non-carbon removal purposes, such as storage of carbon in wooden houses. Price is also an important part of additionality. If the cost of removing a tonne of carbon is paid in full by the actor buying the carbon certificate, the chance of additionality is high. If the income from carbon certificates is a small part of the cost of removing carbon, there is a risk of low additionality. Therefore, seeking to buy carbon removal certificates as cheaply as possible can be counterproductive.

Additionality is an important factor to consider for those who are looking to remove as much carbon as possible with their purchase of carbon removals. However, additionality can be inversely correlated with co-benefits. Methods that provide new or increased incomes in other ways than selling carbon removals can have low additionality but at the same time be a socially sustainable way of removing carbon. (This indicates that there can be trade-offs between carbon removal strategies that seek to remove as much carbon as possible versus strategies that seek to combine creating social good with removals.)

Permanence: For how long, and with what security is the carbon stored? Many techniques have low or insecure permanence where it is not known for how long the carbon will be stored. The techniques can still contribute to solving the climate crisis, but the unknown or low permanence must be taken into account when comparing methods and emissions.

Speed: How fast is the carbon captured with the technique? CO_2 start warming the earth quickly after it is emitted, reaching peak warming after around 10 years. [3] Methods of capturing carbon that takes decades or longer will allow harmful warming to happen in the meantime.

Social and environmental risk

Are there significant risks with the technology for ecosystems, animals, or health or social risks for humans? For example, can the deployment of the technique harm people directly or push them off their land into poverty? Can it increase food prices hurting people in poverty? Are there risks to biodiversity or pollution? Removals must be done in a way that respects people’s rights and have safeguards including free prior and informed consent (FPIC) of IPs and local communities affected.

Several methods can both deliver benefits for people in poverty *or* create harm depending on how they are performed.

Other relevant indicators looked at for each technique are:

Obstacles: Are there obstacles that can hinder the deployment of the method or risk to make it less effective?

Co-benefits: Are there other benefits of deploying the method unrelated to carbon removal?

Price: What one removed tonne of CO_2 is sold for on the market today and what the future price is projected to be. Note that estimates of price might not take into consideration what it costs to remove carbon in a social and environmentally responsible way.

Potential: The estimated maximum global potential for carbon removal with the method per year by 2050 or 2100.

Maturity: How well researched is the technology, how many questions remain to be resolved?

Chosen methods

Methods assessed are those who are found available on the market today and from which carbon removals certificates are sold. It is worth noting that most of the techniques are very niche even though they are available on the market. Forestation is by far the most common method used today and completely dwarfs the others in scale. For most other methods only one or two companies sell carbon removal certificates from it today.

Carbon removal technologies not considered in this overview since they are not available to buy removals with today are ocean alkalization, marine carbon sequestration (for example with seaweed), and bioenergy carbon capture and storage (BECCS). Peat and wetland restoration has the potential to remove carbon and is on the market but is sold as an emission reduction method, not as carbon removal. It is also difficult to find scientifically published estimates on how large the net climate effect of peat/wetland restoration is, considering restoration can lead to increased methane emissions.

AVAILABLE METHODS FOR CARBON REMOVAL

	Effectiveness				Other indicators			
Name	*Additionality*	*Permanence*	*Speed*	*Social and environmental risk*	*Obstacles*	*Co-benefits*	*Price per tCO2*	*Maturity*
Biochar	Medium	Medium to high. Hundreds of years.	High	Low	Medium. Decreased albedo. Black carbon emissions. Competition for biomass.	High. Increases yields. Natural method. potential for small scale production Bioenergy.	Medium. Between US$ 90- 120. Sells for 150 euros at a supplier.	Medium
Soil carbon sequestration	Medium (hard to estimate)	Low/uncertain. Only as long as methods used.	High	Low/Medium It can hurt smallholder farmers if markets are extended to low-income countries.	Low.	High. Increased yields. Natural, mature technology.	Low. Could be negative. Sells for US$ 17-45 at suppliers.	High
Storage in the built environment (wood)	Low	Medium	Medium	Low	Low.	High. Besides sequestering CO2 emissions from construction is reduced substantially.	Low (wood). Could be negative. Sells for around US$20 at suppler.	High
Direct air capture with storage	Very high	Very high	Very high	Low	Medium. Large energy requirements (heat and electricity).	Low	Very high. US$ 600-1000 /tCO_2. Sells at supplier for 600-1000 euros /tCO_2.	Medium
Forestation	Medium	Medium, decades to centuries.	Medium, decades.	Medium High land requirements. Risk competing with food production. Risk pushing vulnerable people of their land.	Medium. Decreased albedo if not in tropics. Possible leakage effects.	High. Increased biodiversity. Well established and easy to scale up. If done well in tandem with agroforestry and consistent with customary rights, it can support traditional livelihoods and sustainable economies.	Low. US$ 5–50 tCO_2. (Might however not be a socially sustainable price). Sells at numerous suppliers for around US$ 10-30.	High
Enhanced weathering	Very high	Very high. Millennia	High to Low depending on method. From years to centuries.	Medium Possible soil contamination. Risks from increased mining and transports.	Medium. Increased mining and transports.	High. Increased yields when used on farmland. Decreased ocean acidification when applied to seawater.	Medium. US$ 50–200/tCO_2 Sells at supplier for 42 euro /tCO_2.	Low

Biochar

Overall assessment

Biochar is a promising technique to remove carbon. It keeps the carbon stored for a relatively long time and has large co-benefits but at the same time, some questions on its effect and safety are unresolved. The positive climate effects of using waste biomass for biochar also vary with local conditions and each biochar project needs to be analysed separately. However, small-scale projects can help increase the knowledge about how biochar functions in soils and could be a good option for an organization or individual that wishes to invest in carbon removal if done sustainably following best practice.

Description

Biomass converted to biochar through pyrolysis (decomposition through high temperatures without oxygen) creates a stable charcoal carbon storage that then can be added to soils for carbon storage and to increase yields and does not easily break down. The most effective biochar production requires commercial-grade equipment, but some less industrial options such as 'slash and char' as an alternative to 'slash and burn' farming may also be available, though not without risks.

Social and environmental risk

Low. Biochar has the potential to be done safely [4] but there are some risks. There are theoretical environmental risks with contamination of soils if the source of the biochar is contaminated. There can also occur emissions of other greenhouse gases such as nitrous oxide, but the net effect is estimated to be positive, reducing warming.[5]

Biochar dust can be spread with the wind when biochar is produced and applied to soils which can decrease air quality and increase short-term warming. This can be kept to a minimum if the right methods, such as wetting the biochar before application, are applied.[6]

Removing too much biomass residues from forests and crops can potentially have a negative impact on the forest ecosystem and soil health.[7]

Small amounts of biochar can also theoretically dissolve and leak into water systems, something that could decrease the sequestration potential and possibly be toxic.

The land-use requirements are essentially zero if only waste biomass is used. But if the biomass used is taken from primary forests or energy crops it can fuel competition for land with food production. Further, if markets for biochar take off, it could spike demand in ways that lead to functional 'biochar' plantations, which would lead to different calculations than waste-based biomass and could lead to some of the same tenure and agricultural tensions as forest plantations and biofuels.

Social risks could occur if the demand for biomass increases in a way that changes land-use.

Additionality

High. Biochar is a niche market today. It could theoretically become profitable for farmers to use it for soil enhancement, but it does not seem to be the case today.[8, 9] Income from emission reductions seems very likely to lead to increased biochar production and usage by farmers.

If there is a shortage of waste biomass then biomass used for biochar might have had an alternative use where it also captures or reduces carbon emissions. This would affect additionality negatively.

Where to best use waste biomass is a complex question, the answer to which likely depends on local conditions. In an energy market with high fossil fuel use in the energy sector, it could be more beneficial to use the biomass for energy production and heating. Even though the production of biochar also creates energy it creates even more energy to completely burn the biomass.[10] [11] However, if the increased local agricultural productivity that biochar achieves is very high this can change the picture and make biochar a more attractive option than burning the biomass. In an energy market with low fossil fuel use, it is more likely that biochar will be the best use of biomass.

In the question of how to best use biomass, there is a difference between what a single actor like a company or individual can do and what should be done on a national level. Politicians designing policy should strive to use biomass where it decreases CO_2 the most. However, an individual cannot easily replace coal with biomass but can purchase biochar to capture carbon. Unless there is a high demand for biomass and using biomass for biochar will lead to increased fossil fuel usage, it is likely positive for the climate for a company or individual to fund the production and usage of biochar.

Permanence

High. The likely timeframe for storage for much of the carbon contained in biochar is hundreds of years, as the carbon is gradually released.[12] According to the IPCC, at least 80 percent of biochar added to soil stays for over 100 years.[13] The permanence, however, depends on the stability of the biochar which in turn depends on the type of biomass used and at which temperatures the biochar is produced. Intensive agricultural practices like tilling and ploughing and the use of heavy machinery can potentially reduce the permanence.

Speed

Medium/high. The biomass that is used (forest or crop residues) would decompose in a matter of years (crop waste and small forest waste) or decades (shrubs etc) and release its carbon content if not used. What biochar sequestration using waste biomass does is preventing 'natu-ral' biogenic emissions from happening, thus reducing carbon in the atmosphere compared to a reference scenario.

Obstacles

Medium. The application of biochar can decrease albedo of the soil which leads to increased warming due to the darker soil absorbing more heat. This can decrease biochar's effectiveness as a technique to reduce warming with 10%, sometimes much more.[14] [15] It is possible to use methods to keep this at a minimum such as tilling the biochar below the layer of topsoil, however that is a more expensive technique. The effect of albedo change can also depend on vegetative cover and can differ between regions, potentially being less of a problem in tropical regions where soils are covered by crops year-round.

Competition for waste biomass can also be an obstacle as discussed above.

Co-benefits

High. Yields can go up substantially (estimation of 10% mean increase [16]) which in turn has the potential to (but is not certain to) reduce land use and emissions. Biochar can also reduce the need for synthetic fertilizers. Yield increases will vary widely depending on the type of soil and region. Some evidence points to the effect mainly happen in the tropics with low or no yield increases in temperate regions where soils are less degraded. [17]

Energy from the pyrolysis producing biochar can be used for local heating or energy.
Other valuable products such as bio-oil are also created in the process of making biochar.

Creating and applying biochar to soils could also benefit small scale producers, both providing income and increased yields.

Price

Medium. Estimates range between US$ 90/tCO2 and US$ 120/tCO218 for producing as much biochar as needed to remove 1 tonne of CO2. The world market price for biochar is currently between 500-600 euros per tonne.[19] Since biochar sequesters around three times more CO2 than its weight this would translate to a price of 166-200 euros per tonne of CO2 captured if the whole cost of biochar production was paid for by carbon certificates. Carbon certificates from biochar are sold today for around 150 euros per tonne by one company. 20 However, the cost when including increased yields could be negative in some cases. 21 Costs for small scale production in developing countries could be significantly lower.

Potential

Medium. Biochar is estimated to be able to remove 0,3-2 GtCO2 per year globally.[22] If purposely grown biomass (competing with forestation and food production) is used estimates become much higher. Total biochar sink potential in soils could be somewhere between 180–410 GtCO2, (after which all suitable soils are saturated).[23] This does not take into account that biochar also could potentially be stored in other ways, for example in building materials.[24]

Maturity

Medium. It is a technique that has been used for millennia to improve soil fertility. However, many effects of biochar are still uncertain, such as how its stability is affected by modern farming techniques as tilling and its effect on yields in different types of environments. [25] Other questions that need more research are around albedo effects, competition for biomass, sustainable use of waste biomass, effects on agricultural productivity, soil and water, and about black carbon/biochar dust. Also, considering that the application of biochar to soils is irreversible more research is likely needed before biochar can be deployed on a very large scale.

Storage in the built environment

Overall assessment

Using wooden infrastructure is a safe and cheap way to store carbon in the short to medium term. However, it remains unclear if the use of wooden products in the built environment leads to increased carbon removals. It is also unclear if the purchase of carbon certificates from wooden building elements leads to more carbon being removed due to low additionality. Because of these two factors buying carbon removal certificates from wooden elements in the built environment risks being a very inefficient strategy to remove carbon.

Description

Carbon captured in building elements in houses or infrastructure is being sold as carbon removals, primarily using wood. It can be seen as a medium-term removal method if new trees are planted to replace those used in construction and if that leads to more carbon being captured than by the mature trees.

Storage in carbonated building elements is also being sold as carbon removal but is not assessed here since it is a method of storing carbon captured with a separate removal technology (for example direct air capture). It should be noted that the CO2 used in carbonated concrete often comes from industrial processes burning fossil fuels, then the process is an example of carbon utilization and not carbon removal.

Social and environmental risk

Low. There is a theoretical risk that a largely increased usage of wood in buildings could increase competition for land and deforestation. Increased logging can also be a risk to biodiversity.

Additionality

Low. For carbon certificates from wood as a construction material additionality is probably low. If the price of the carbon removal sold as storage in wooden buildings is low then this extra income for producers seems unlikely to lead to a large increase in production and increased carbon storage compared to a base scenario.[26] Even if the cost of the wood was paid in full by the actor buying the carbon certificate the cost of a wooden frame is just a small cost of building a house.

Even if the purchase of a carbon certificate would lead to one more tonne sequestered in wooden products the net climate mitigation effect could still be low. The calculation to determine the net carbon effect of harvesting wood products and replanting trees is very complex. Research shows that mature trees left in the forest continue capturing carbon for a very long time and then store the carbon for many decades in dead tree trunks that decompose very slowly.[27] Storing the wood as construction material in a house for 50 years or in a dead tree trunk for the same period does not make a difference for the climate. (However, wooden houses replace concrete and reduce emissions as discussed under co-benefits but this is not a carbon removal effect).

Permanence
Medium. The carbon removed is released when wooden houses are demolished. This can be countered by recycling the wood for bioenergy with carbon capture and storage, by reusing the wood for new construction or by converting it to biochar.

Speed
Medium/Uncertain. The carbon capture theoretically happens when a mature tree (assumed not to capture carbon at a fast pace anymore) is cut down and preserved, letting a new tree grow that captures carbon more quickly (taking 20-100 years to reach full carbon sequestration potential depending on tree type and region). But as discussed under additionality these assumptions are uncertain.

Obstacles
Low. There can be practical obstacles to using hardwood products in high buildings, one that has been raised is the risk of fire.

Co-benefits
High. Building with wood reduces construction-related emissions substantially since it often replaces high-emission materials such as concrete. This probably has a much bigger effect than the CO_2 storage potential and should probably be the primary reason to promote using wooden products as building materials.

Price
Low. For wood the cost is low or zero since building with wood does not affect the cost of building much. The price per tonne has been 17-22 euros in carbon removal auctions.

Potential
Low. Total global potential is estimated to 0.5 to 1 $GtCO_2$ [28] per year with no clear number on total cumulative potential.

Maturity
High. For wood, the technique is very well established and understood.

Soil carbon sequestration

Overall assessment
A method to store large amounts of carbon in the short-term without using new land, at the same time potentially creating large co-benefits. The lack of clarity around additionality makes it difficult to give a clear judgement on whether soil carbon sequestration is a suitable method to fund for those wanting to remove as much carbon as possible. On one hand, income from carbon certificates can help make the practice widespread resulting in more carbon captured. On the other hand, one cannot be certain that it would not have happened anyway.

Insecurities around permanence could potentially be overcome by combining the technique with other medium- and long-term storage techniques such as reforestation and enhanced weathering that does not capture carbon immediately. Short-lived techniques such as soil carbon sequestration could also possibly be used to offset methane emissions that have a much shorter lifespan in the atmosphere than carbon emissions. [29] However, implementation must be done in a way that does not risk harm small-scale farmers and people in poverty.

Description
Using farming methods that increase the carbon content of the soil, such as no-tilling, crop covering, crop rotation, and several other methods. The potential for carbon storage varies between different regions and depending on local conditions. Soils in good health have less potential to capture carbon since it already stores a lot. Drylands with weak nutrient loads have large opportunities to capture more carbon with more nutrients, which can benefit pastoralist and agro-ecological food systems in particular.

Social and environmental risk
Low/Medium. Farms need to be over a certain size to be able to cover the costs of certification and monitoring of their soil sequestration. If soil carbon sequestration markets are created in countries with smallholder farms this might drive harmful consolidation of farms, bringing smallholders out of business and/or of their land. Funding carbon removal with soil sequestration in developing countries requires extreme caution to avoid social risks.

Not all methods that enable soils to store more carbon also increase yields. Regardless, the permanence of carbon sequestered in soils can vary significantly.

Additionality
Medium/Uncertain. Although quite a lot of farmers already use these methods, and they in theory are profitable, adoption is not widespread and income from carbon removal could help spread them.[30] Different methods can be used to determine additionality, but most are costly and all uncertain. There is the same relation to price as with sequestration in the built environment. Too low prices risk that additionality stays low. Additionality can also change with time. If the practices become profitable and widely adopted without the income from selling carbon certificates additionality drops to zero.

Research shows that different soil sequestration practices have different additionality. In the US it has been estimated that few farmers would implement cover crops without payment, but many would implement no-till practices regardless of payment. [31]

Sellers of carbon certificates from soil carbon sequestration do not, as far as we have seen, conduct additionality tests but assume a farmer who did not previously use soil carbon sequestration techniques would not have done so in the absence of the income from carbon certificates.

Permanence
Low/Uncertain. The soil only stores carbon for as long as the farming practices are upheld. The permanence is very insecure.[32]

Speed
High. Soils start capturing carbon as soon as the methods are put into practice and reach saturation after 10-100 years.

Obstacles
Low. Not all soils are suitable for the method since some already store near their maximum carbon potential.

Co-benefits
High. Soil carbon sequestration can increase agricultural yields at the same time as it stores carbon. This has the potential to increases food production and could ease the pressure on arable land.

Although there are risks with expanding carbon removal markets to developing countries there is also large potential for smallholders to benefit from the technology if done right. For example, through increased yields and income.

Price
Low. The cost could theoretically be negative when including income from increased yields.[33] The estimation of cost is US$0–100/tCO2.34 It sells today for US$ 17-45 per tonne CO2. [35,36]

Potential
Medium. The global potential for soil sequestration is between 1-11 GtCO2 globally per year according to one estimate[37] and 2,3-5-3 GtCO2 in Fuss et al.[38] However soils reach saturation after a few decades 39 and the technique can only be used to capture carbon for as long as there is agricultural land available. The technique will reach saturation a couple of decades after there are no new farmers to pay to use the technique. The total cumulative potential is uncertain but may be 100-200 GtCO2 gigatons given the above constraints.

Maturity
High. Soil carbon sequestration is well understood, and the methods have been used for a very long time by farmers. However, there is weak consensus on how to measure soil sequestration.

Direct air capture and storage (DACCS)

Overall assessment
If renewable electricity and waste heat is used, and the electricity either is purposely built for DACCS or cannot be used to substitute fossil energy[40] then DACCS is a promising option for effectively removing carbon from the atmosphere. However, for the same cost, tens of times more carbon can be removed with other options, (although rarely as fast or permanent and with as much additionality as with DACCS). An individual or company wanting to invest in removing carbon could consider allocating some of their investment into DACCS to help further the development of the technique and bring down costs.

Description
The technique works by sucking CO2 out of the air with large machines and capturing CO2 in filters which is then separated by heating the filters. The CO2 is then stored, for example in geological formations either as gas or turned into stone.[41,42] Direct air capture without storage (when using the carbon in greenhouses, making fuels, for enhanced oil recovery or other uses) is not a carbon removal technique. There is no theoretical limit of potential other than storage room (which is in large supply) and energy inputs.[43]

Social and environmental risk
Low. Few direct risks to humans or ecological systems (besides occupational risks of building and maintaining industrial infrastructure).

Direct air capture has low land requirements compared to other techniques such as afforestation/reforestation. 100 million tCO2 captured per year would require 4000-15 000 hectares. This can be compared to between 3 to 6 million hectares if using BECCS with wood biomass to capture the same amount.[44] However, when the increased energy usage from DACCS is taken into account land use (from new energy sources) will also increase.

Additionality
High. Basically 100% when life cycle emissions are taken into account. There is no other reason to use DACCS than to remove carbon from the atmosphere.

Permanence
High. Very high for solid-state storage. When turned into solid form, the carbon is fixed practically forever. If pumped as a gas into geological storage gas could leak out but the method is estimated by IPCC to retain 99%of CO2 after 1000 years in well-selected, designed, and managed carbon capture and storage sites.[45] Less well-selected, designed, and managed sites likely have higher risk or re-release.

Speed
High. Very fast. Once plants and are in operation they capture carbon continuously.

Obstacles
Medium. Enormous energy requirements (heat and electricity). Minimum 0.68 GJ/ 0,19MWh per tCO2 captured, but likely 10 times as much. 46 That would mean that removing 10 Gt CO2 (about 30 % of current global emissions) would require between minimum 1888 and (more likely) 18 888 TWh (1,2-12 % of the world's primary energy consumption).[47]

Besides energy, there are also huge infrastructure needs for building the plants and storage facilities as well as transporting the captured CO2 if the capture facility is not put where the CO2 is stored.

Co-benefits
Low. There are no large evident co-benefits, CO2 captured with DACCS could be used in building materials, replacing regular concrete.

Maturity
Low. Several companies are working with direct air capture and at least one in operation use direct air capture with storage but at the time the companies are still in early start-up phases. More research and deployment is needed to advance the technique and bring down costs.

Price

High. Estimates for costs today are US$ 600-1000 /tCO2 but may decrease to US$ 100-300/tCO2 as the technology is scaled up.[48]

Sold by one supplier with solid storage for 600-1000 Euro per tonne to the public and businesses.[49]

Potential

High. The potential is mainly limited by cost and energy supply but can in theory be many times larger than current GHG emissions. One estimate limits potential due to practical constraints to 0.5–5 GtCO2 yr−1 by 2050.[50]

Forestation (afforestation and reforestation)

Overall assessment

Reforestation or afforestation on marginal land with suitable types of trees in countries that recognizes and protects customary land-rights is a carbon removal strategy with significant potential, although with medium permanence.

For policy reasons, removals based on forestation in countries with poor protections for customary rights, human rights, and social safeguards to protect indigenous peoples, traditional communities, and poor farmers may not be justified based on the adverse impacts and risks that people are not pushed of their land and that it does not compete with food production.

It should be noted that the net climate benefit of forestation in boreal regions is difficult to assess due to changed albedo and other climate effects.

Description

Reforestation means replanting trees where there used to be a forest. Afforestation means planting trees on new land. None of these techniques involve protecting standing forests, an effective method to combat climate change and avoid emissions, although it has some potential for removals too it is not primarily a carbon removal technique. Forestation is the most widely used technique of all described in this guide.

Social and environmental risk

Medium. Depending on socioeconomic, tenure, hunger, and human rights factors, forests have a high potential for both sustainable outcomes and unacceptable/unsustainable outcomes. If not done the right way, forestation activities run high risks of competing with food production and pushing people in poverty of their land. Numerous forestation projects have led to conflicts with local populations notwithstanding the good intentions the creators of the projects had.

Land-use change from forestation can also have unintended environmental effects. If for example monoculture forests are planted this can decreased biodiversity and increase the vulnerability of the forest. Certain types of trees can also increase water stress.

Additionality

Medium. It is a complex analysis to determine additionality for forestation, but various tests are used such as if a project is not financially viable without the income from carbon certificates. Forestation can lead to leakage, that increased forestation in one area might lead to deforestation in another area if arable land is used which must also be accounted for.[51] Various standards have different ways to determine additionality and some projects might be highly additional while others may have low additionality.

Permanence

Medium. The carbon is only sequestered for as long as the trees remain. (Unless it is stored in for example hardwood products or used with bioenergy carbon capture and storage. Both these options are treated as separate removal methods in this paper). Logging without replantation, fires or diseases can re-release the carbon. New research also points to that forests can stop being carbon sinks and even start emitting carbon partly due to global heating.[52]

The method should be seen as a short to medium-term carbon sequestration with a need to further safeguard against subsequent release of forest carbon.

Speed
Medium. Removals start as the trees start to grow. It takes between 20-100 years for forests to reach their maximum sequestration potential depending on species and local conditions.[53] Carbon certificates sold from forestation are counting the total amount removed.

Obstacles
Medium. Planting trees can decrease albedo by reducing the grounds reflection of sunlight. If forests are planted in the snow-covered boreal region, they can potentially even create a net warming effect.[54] In temperate areas, the cooling effect of forestation is substantially reduced by changed albedo.[55] Increased aerosols from forestation that have a cooling effect might offset some, or all of the warming effect of decreased albedo.[56] The net effect on climate from forestation in especially boreal regions is uncertain even if the carbon removal effect is well established. Because of albedo and faster growth, it is mainly forestation in the tropics that is considered suitable for carbon removal purposes in the literature; however, forests in key geographies the tropics can become sources as opposed to sinks in the future, due to climate change.[57]

Co-benefits
High. Forestation is a natural way of capturing carbon that has the potential for co-benefits for biodiversity and local ecosystems health, although there are perhaps equally large risks of conversion to mono-cropped fast-growing tree plantations engineered for their carbon sequestration potential. Yet if done in the right way, especially agroforestry projects can lead to poverty reduction, greater food security, and more sustainable livelihoods and other social co-benefits, see for example the ‘Great green wall’ case study of the regreening of the Sahel. [58,59]

Forestation, agroecological approaches, and ecosystem restoration efforts could also have beneficial biodiversity co-benefits if done in the right way. Forestation is also relatively cheap, well established, and easy to scale up.

Price
Low. Price: US$ 5–50 tCO2.[60] However, forestation projects that ensure that there are no social risks in the project might be more expensive.

Potential
Medium. It has been estimated that 500 million hectares in the tropics not being used productively could be available for reforestation. That land could potentially sequester 3.7 GtCO2 per year.[61]

The technique can only be used to capture carbon for as long as there is available land to plant forests on and will eventually reach saturation (unless the carbon from cut down forests are stored elsewhere). The total cumulative potential is estimated to be between 80 and 260 GtCO2.[62]

Maturity
High. Forestation is a well-established and understood technique to remove and sequester carbon. However, there are still questions to answer, such as how forestation in different geographies affect the climate, how carbon in the soil is affected by forestation, for how long forests continue to capture carbon and the social, ecosystem, tenure, rights, and governance considerations associated with land-use decisions at the scale required to meaningfully serve carbon removal functions.

Enhanced weathering

Overall assessment
Enhanced weathering has significant potential for carbon removal, but more research is needed to answer questions such as potential environmental adverse effects and speed of removal. Funding research projects about enhanced weathering where carbon is removed as part of the project could be a strategy to consider for companies and individuals wanting to remove carbon. That the method under some applications can take a very long time to capture carbon must also be considered when comparing with other methods. Life cycle assessments need to be made for every removal project funded to determine the removal efficiency.

Description
A way to speed up the earth's natural way of sequestering CO_2. It is done by grinding minerals, such as olivine or basalt, to a fine size and spreading it over farmland, in seawater, or as a replacement for sand or gravel in for example landscaping projects. The ground minerals react with rain or seawater binding and storing CO_2 over time.

Social and environmental risk
Medium. There are risks for soil contamination and disturbed ecosystems, for example by increased heavy metal concentration in soils. Certain minerals have higher risks for this than others. There are also potential environmental and social risks derived from increased mining activities. To some extent, this can be mitigated by using mine tailings and other waste materials instead of mining for new minerals. There are possible health risks from grinding minerals to very fine sizes which can be inhaled.[63]

Additionality
High. Additionality is probably close to 100% at the time for enhanced weathering. The distribution of minerals such as olivine on soils or usage of the minerals to replace other materials in for example construction is very likely not profitable and would not happen without income from carbon removal certificates. This could change in a later stage if potential increased agricultural yields of using enhanced weathering on farmland make it profitable.

Permanence
High. A low-tech way of permanently storing CO2 without risk of re-release on a human time scale.

Speed
Uncertain. The speed of uptake of carbon depends on many factors but it can be very slow. There are uncertainties in how fast the minerals weathers and captures carbon.[64] Estimates are mostly based on models and lab experiments and vary greatly depending on grain size, water pH, temperature (warmer is faster), and local conditions. Olivine that is ground to very fine sizes can probably sequester carbon in a few years, but with larger grains it can take centuries.[65]

Note that emissions from mining, grinding, and transporting the minerals happen today but the removals can take a very long time depending on projects. There is a risk that with certain projects harmful warming can happen over decades before the net effect of the project becomes carbon negative.

Obstacles
Medium. Large scale deployment would entail a huge increase in mining to produce the minerals. It would also take a lot of energy to grind the minerals to small sizes and increased transportation needs to get the minerals to soils and other places of application. There are losses in carbon removal efficiency from the production and application phases. How large depends mainly on how fine the minerals are ground, if renewable energy can be used and length of transportation. Projects that sell carbon removal certificates from enhanced weathering needs to make life-cycle assessments calculating the net removal effect of the activity.

Co-benefits
High. Application on farmland will likely increase yields and food production and reduce the need for synthetic fertilizers.[66] This can in turn indirectly reduce emissions. When applied to seawater it can counter ocean acidification.[67] It has also been suggested that enhanced weathering can be used with forestation projects, aiding forest growth.

Price
Medium. Cost of 50–200/tCO2. 68 One company sells carbon removal certificates through enhanced weathering of olivine for 42 euro tCO2 using olivine as a replacement for sand or gravel in construction or landscaping projects. This is probably a low-risk way of using the mineral, but it also takes a long time to capture CO2. According to the company's data, 25% of the total removal potential of the olivine would be captured after 30 years when using sand with a 0-3 mm grain size.[69]

Potential
High. The theoretical potential is huge but estimates vary widely depending on different assumptions, the mineral used, grain size, etc, from 0.72–95 GtCO2 per year globally.[70] A well-cited overview put the likely potential to 2–4 GtCO2 yr and cost of 50–200/tCO2.[71] The total theoretical potential is almost unlimited.

Maturity

Low. Enhanced weathering is the least researched technique covered in this paper. More research is needed to understand the possible side effects when applied to soils or oceans, on the weathering rates, life-cycle emissions, and possible health risks.

DISCUSSION

Carbon removals are an important part of the solution of the climate crisis. Hundreds of gigatons of CO_2 will likely need to be removed from the atmosphere this century with the help of a wide range of negative emission technologies. Companies and individuals can help accelerate this by funding carbon removals in a safe and effective way.

However, no carbon removal method is always effective and safe; rather, it depends on how it's used and under which circumstances and what kinds of social and environmental safeguards and rights protections are in place to avoid negative consequences of otherwise well-intentioned carbon removal efforts. Without appropriate protections, there are significant risks that 'net zero' efforts could create harm for people and the environment and shift the responsibility to vulnerable people in poverty, those who are least likely to have contributed to the problem in the first place.

It's also worth noting that a lot of carbon removal methods might be effective and sustainable on a smaller scale, for example, reforestation on marginal land in countries with strong land rights, biochar using waste biomass, direct air capture using intermittent renewable energy and waste heat and other techniques. But when techniques are scaled up massively new risks occur that were not present on a small scale. For example, forestation, biochar, and techniques using biomass could compete with food production and risk pushing vulnerable people of their land when deployed on a large scale. Soil carbon sequestration markets might be harmful if it is expanded all over the world in a way that leads to small farms in low-income countries being wiped out. Direct air capture might lead to continued fossil fuel use if it is scaled up to a level where there is not enough waste-heat and renewable energy to satisfy demand. Therefore, what is an effective and sustainable way to remove carbon for an individual or a single company today might not be applicable for a large group of companies or governments wanting to do a massive investment in reaching their net-zero targets. As carbon removal efforts ramp up, there is an urgent need for policymakers to carefully safeguard people and ecosystems across the globe. Removal efforts must also be done equitably so that people in low-income countries will meaningfully benefit and not be harmed by such efforts.

Companies and individuals should strive to do as much good (and as little harm) as possible with any carbon removal efforts. This can entail buying more expensive and effective solutions, putting money into underinvested technologies so that they can grow and costs come down, and to abstain from investing in projects that have a high risk of harming people or the environment. Responsible companies and individuals should also reduce their emissions aggressively and not use removals as a license to continue emitting greenhouse gases. Companies and individuals can also consider funding carbon removal methods that deliver co-benefits for people in poverty, also contributing to fulfilling other sustainable development goals.

NOTES

[1] Kriegler et al. Pathways limiting warming to 1.5°C: a tale of turning around in no time? https://doi.org/10.1098/rsta.2016.0457 The Royal society (2018)

[2] Rogelj et al. Chapter 2. Mitigation pathways compatible with 1.5°C in the context of sustainable development. *IPCC Special Report on global warming of 1.5°C*. https://archive-ouverte.unige.ch/unige:110427 (2018)

[3] Ricke & Caldeira, Maximum warming occurs about one decade after a carbon dioxide emission, *Environmental Research Letters*, https://iopscience.iop.org/article/10.1088/1748-9326/9/12/124002 (2014)

[4] Tissurant & Cherbini, Potentials, Limitations, Co-Benefits, and Trade-Offs of Biochar Applications to Soils for Climate Change Mitigation *Land* (2019) "Overall, our review finds that biochar in soils presents relatively low risks in terms of negative environmental impacts and can improve soil quality and that decisions regarding feedstock mix and pyrolysis conditions can be optimized to maximize climate benefits and to reduce trade-offs under different soil conditions"

[5] Tissurant & Cherbini, Potentials, Limitations, Co-Benefits, and Trade-Offs of Biochar Applications to Soils for Climate Change Mitigation *Land* (2019)

[6] Verheijen et al, Biochar Application to Soils A Critical Scientific Review of Effects on Soil Properties, Processes and Functions, *Office for the Official Publications of the European Communities*, (2010) http://eusoils.jrc.ec.europa.eu/esdb_archive/eusoils_docs/other/EUR24099.pdf

[7] Verheijen et al, (2010)

[8] Interview with David Andersson at the company Ecoera selling Biochar.

[9] Whitman et al. Biochar projects for mitigating climate change: An investigation of critical methodology issues for carbon accounting. *Carbon management* (2010)

[10] Meyers et al, Albedo impact on the suitability of biochar systems to mitigate global warming. https://www.ncbi.nlm.nih.gov/pubmed/23146092 *Environ Sci Technol* (2012)

[11] Azzi et al, Prospective Life Cycle Assessment of Large-Scale Biochar Production and Use for Negative Emissions in Stockholm https://pubs.acs.org/doi/abs/10.1021/acs.est.9b01615) *Environ. Sci. Technol* (2019)

[12] Tissurant & Cherbini, Potentials, Limitations, Co-Benefits, and Trade-Offs of Biochar Applications to Soils for Climate Change Mitigation *Land* (2019)

[13] 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories Appendix 4 Method for Estimating the Change in Mineral Soil Organic Carbon Stocks from Biochar Amendments: Basis for Future Methodological Development https://www.ipcc-nggip.iges.or.jp/public/2019rf/pdf/4_Volume4/19R_V4_Ch02_Ap4_Biochar.pdf (2019)

[14] Verheijen et al, Reductions in soil surface albedo as a function of biochar application rate: Implications for global radiative forcing Article in *Environmental Research Letters* (2013)

[15] Meyers et al, Albedo impact on the suitability of biochar systems to mitigate global warming. https://www.ncbi.nlm.nih.gov/pubmed/23146092 *Environ Sci Technol* (2012)

[16] National academy consensus report https://www.ncbi.nlm.nih.gov/books/NBK541439/ (2018)

[17] Verheijen et al, Biochar boosts tropical but not temperate crop yields, https://www.researchgate.net/publication/320273037_Biochar_boosts_tropical_but_not_temperate_crop_yields Conference paper, (2017)

[18] Fuss et al, Negative emissions—Part 2: Costs, potentials and side effects https://iopscience.iop.org/article/10.1088/1748-9326/aabf9f/meta *Environmental Research Letters*, Volume (2018)

[19] SOU 2020:4 Vägen till en klimatpositiv framtid, Swedish committee of inquiry on negative emissions https://www.regeringen.se/48ec20/contentassets/1c43bca1d0e74d44af84a0e2387bfbcc/vagen-till-en-klimatpositiv-framtid-sou-20204 page 683 (2020)

[20] Ecoera (seller of biochar offsets) website www.ecoera.se accessed Jan 2020

[21] Hepburn et al, The technological and economic prospects for CO2 utilization and removal https://www.nature.com/articles/s41586-019-1681-6.pdf *Nature articles* (2019)

[22] Fuss et al, Negative emissions—Part 2: Costs, potentials and side effects https://iopscience.iop.org/article/10.1088/1748-9326/aabf9f/meta *Environmental Research Letters*, Volume (2018)

[23] Tissurant & Cherbini, Potentials, Limitations, Co-Benefits, and Trade-Offs of Biochar Applications to Soils for Climate Change Mitigation *Land* (2019)

[24] Bates & Draper, Burn – using fire to cool the earth, *Chelsea green publishing,* White River Junction, Vermont (2019)

[25] Verheijen et al, (2010)

[26] Price per tonne of removed CO2 has been around 17-22 euros in carbon removal auctions. That income is a very small part of the cost (a few percent) of the wood that stores the carbon and therefor seems unlikely to lead to large production increases, thus additionality seems very low.

[27] Pukkala, Carbon forestry is surprising, *Forest Ecosystems* DOI 10.1186/s40663-018-0131-5 (2018)

[28] Greenhouse gas removal, the Royal Society and Royal Academy of Engineering (2018)

[29] Not all carbon capturing techniques necessarily need be permanent since not all greenhouse gases are. If a carbon removal technique only stores carbon for example 12 years it could be used to "offset" methane emission which lifetime is 12 years. However, then a different a calculation for methane's warming potential must be used, calculating its warming effect in 12 years not 100 years as is normally done. One tonne of methane's warming potential is equal to 25 tonnes of CO2 over a 100-year time period but 86 tonnes of CO2 over 20 years. (IPCC 4)

[30] "Even though there may not be a financial opportunity cost in such a situation, incentivisation of some type will still likely be required to prompt practice change." Thamo & Panell Challenges in developing effective policy for soil carbon sequestration: perspectives on additionality, leakage, and permanence, https://doi.org/10.1080/14693062.2015.1075372 *Climate policy* (2015)

[31] Claassen et al. Additionality in U.S. Agricultural Conservation and Regulatory Offset Programs, ERR-170, U.S. Department of Agriculture, Economic Research Service, http://www.ers.usda.gov/publications/err-economic-research-report/err170 July 2014

[32] Thamo & Panell, Challenges in developing effective policy for soil carbon sequestration: perspectives on additionality, leakage, and permanence, https://doi.org/10.1080/14693062.2015.1075372 *Climate policy* (2015)

[33] Hepburn et al, The technological and economic prospects for CO2 utilization and removal https://www.nature.com/articles/s41586-019-1681-6.pdf *Nature articles* (2019)

[34] Fuss et al, Negative emissions—Part 2: Costs, potentials and side effects https://iopscience.iop.org/article/10.1088/1748-9326/aabf9f/meta *Environmental Research Letters*, Volume (2018)

[35] Nori website www.nori.com accessed Jan 2020

[36] Website Ökoregion Kaindorf https://www.oekoregion-kaindorf.at/index.php?id=187 accessed 27 April 2020

[37] Greenhouse gas removal, the Royal Society and Royal Academy of Engineering (2018)

[38] Hepburn et al, The technological and economic prospects for CO2 utilization and removal https://www.nature.com/articles/s41586-019-1681-6.pdf *Nature articles* (2019)

[39] Fuss et al, Negative emissions—Part 2: Costs, potentials and side effects https://iopscience.iop.org/article/10.1088/1748-9326/aabf9f/meta *Environmental Research Letters*, Volume (2018)

[40] Iceland for example has a nearly fossil free energy production and cannot easily export its excess energy to other countries.

[41] Carbfix website https://www.carbfix.com/ accessed Jan 2020

[42] Snæbjörnsdóttir et al, Carbon dioxide storage through mineral carbonation https://www.nature.com/articles/s43017-019-0011-8#Sec20 *Nature reviews Earth & Environment* (2020)

[43] Fuss et al, Negative emissions—Part 2: Costs, potentials and side effects https://iopscience.iop.org/article/10.1088/1748-9326/aabf9f/meta *Environmental Research Letters*, Volume (2018)

[44] In-depth analysis in support on the COM(2018) 773: A Clean Planet for all - A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy, https://ec.europa.eu/knowledge4policy/publication/depth-analysis-support-com2018-773-clean-planet-all-european-strategic-long-term-vision_en page 189 European commission (2018)

[45] IPCC Carbon capture and storage (2005) https://www.ipcc.ch/report/carbon-dioxide-capture-and-storage/

[46] Greenhouse gas removal, the Royal Society and Royal Academy of Engineering (2018)

[47] Authors calculation using IEA statistics found on https://www.iea.org/data-and-statistics Accessed Jan 2020.

[48] Fuss et al, Negative emissions—Part 2: Costs, potentials and side effects https://iopscience.iop.org/article/10.1088/1748-9326/aabf9f/meta *Environmental Research Letters*, Volume (2018)

[49] Climeworks website www.climeworks.shop accessed Jan 2020

[50] Fuss et al, Negative emissions—Part 2: Costs, potentials and side effects https://iopscience.iop.org/article/10.1088/1748-9326/aabf9f/meta *Environmental Research Letters*, Volume (2018)

[51] Schwarze et al, The Forest Leakage Problem https://forestindustries.eu/content/forest-leakage-problem, The Nature Conservancy and The Royal Society (2002)

[52] Hubau et al, Asynchronous carbon sink saturation in African and Amazonian tropical forests, www.nature.com/articles/s41586-020-2035-0 *Nature* (2020)

[53] Greenhouse gas removal, the Royal Society and Royal Academy of Engineering (2018)

[54] Chen et al, Strong cooling induced by stand-replacing fires through albedo in Siberian larch forests https://www.nature.com/articles/s41598-018-23253-1 *Nature* (2018)

[55] Kirschbaum et al, Implications of albedo changes following afforestation on the benefits of forests as carbon sinks https://www.biogeosciences.net/8/3687/2011/bg-8-3687-2011.pdf *Biogeosciences* (2011)

[56] Spracklen et al. Boreal forests, aerosols and the impacts on clouds and climate, *Triennial Issue 'Earth science,* Royal society https://doi.org/10.1098/rsta.2008.0201 (2008)

[57] Fuss et al, Negative emissions—Part 2: Costs, potentials and side effects https://iopscience.iop.org/article/10.1088/1748-9326/aabf9f/meta *Environmental Research Letters*, (2018) "*There is high agreement that the low albedo of boreal forests renders AR in high latitudes counterproductive" temperate AR has uncertain or net neutral benefits for global temperature reduction, particularly if substituting for relatively high albedo agricultural land uses. Tropical AR, due to higher productivity, moderate albedo effects, and its potential to generate evaporative cooling, i.e. the local cooling effect resulting from evapotranspiration, holds the greatest potential for net temperature reduction—up to three times that of boreal forests per unit of land."*

[58] Article: The "Great Green Wall" Didn't Stop Desertification, but it Evolved Into Something That Might https://www.smithsonianmag.com/science-nature/great-green-wall-stop-desertification-not-so-much-180960171/ accessed Feb 2020.

[59] Upcoming Oxfam paper by John Magrath, Regreening the Sahel, (2020)

[60] IPCC Global Warming of 1.5 ºC (2018) Chapter 4.3.7 https://www.ipcc.ch/sr15/chapter/chapter-4/ .

[61] Fuss et al, Negative emissions—Part 2: Costs, potentials and side effects https://iopscience.iop.org/article/10.1088/1748-9326/aabf9f/meta *Environmental Research Letters*,(2018)

[62] Fuss et al, Negative emissions—Part 2: Costs, potentials and side effects https://iopscience.iop.org/article/10.1088/1748-9326/aabf9f/meta *Environmental Research Letters*, Volume (2018)

[63] IPCC Global Warming of 1.5 ºC (2018) Chapter 4.3.7 https://www.ipcc.ch/sr15/chapter/chapter-4/ .

[64] Fuss et al, Negative emissions—Part 2: Costs, potentials and side effects https://iopscience.iop.org/article/10.1088/1748-9326/aabf9f/meta *Environmental Research Letters*, Volume (2018)

[65] Strefler et al. Potential and costs of carbon dioxide removal by enhanced weathering of rocks *Environ. Res. Lett.* https://doi.org/10.1088/1748-9326/aaa9c4 (2018)

[66] Beerling et al, Farming with crops and rocks to address global climate, food and soil security, *Nature plants,* https://doi.org/10.1038/s41477-018-0108-y (2018)

[67] Fuss et al, Negative emissions—Part 2: Costs, potentials and side effects https://iopscience.iop.org/article/10.1088/1748-9326/aabf9f/meta *Environmental Research Letters*, Volume (2018)

[68] Fuss et al, Negative emissions—Part 2: Costs, potentials and side effects https://iopscience.iop.org/article/10.1088/1748-9326/aabf9f/meta *Environmental Research Letters* (2018)

[69] Greensand website https://www.greensand.nl/en/about-greensand/faqpage Accessed 2020-01-30

[70] IPCC Global Warming of 1.5 ºC (2018) Chapter 4.

[71] Fuss et al, Negative emissions—Part 2: Costs, potentials and side effects https://iopscience.iop.org/article/10.1088/1748-9326/aabf9f/meta *Environmental Research Letters* (2018)

Oxfam Discussion Papers

Oxfam Discussion Papers are written to contribute to public debate and to invite feedback on development and humanitarian policy issues. They are 'work in progress' documents, and do not necessarily constitute final publications or reflect Oxfam policy positions. The views and recommendations expressed are those of the author and not necessarily those of Oxfam.

For more information, or to comment on this paper, email Robert.hoglund@oxfam.se

© Oxfam Sweden August 2020

This work is licensed under the Creative Commons Attribution 4.0 International License. To view a copy of this license, visit http://creativecommons.org/licenses/by/4.0/ or send a letter to Creative Commons, PO Box 1866, Mountain View, CA 94042, USA.The information in this publication is correct at the time of going to press.

Published by Oxfam Sweden in August 2020.
Lindhagengatan 133, 11251 Stockholm, Sweden

Cover Photo: The Hellisheidi Power Plant in Iceland where CO_2 is captured from the air and stored as rock in the ground. Photo: Arni Saeberg // Climeworks // The Helena Group Foundation / CC BY-SA

OXFAM

Oxfam is an international confederation of 20 organizations networked together in more than 90 countries, as part of a global movement for change, to build a future free from the injustice of poverty. Please write to any of the agencies for further information or visit www.oxfam.org.

Oxfam America (www.oxfamamerica.org)
Oxfam Australia (www.oxfam.org.au)
Oxfam-in-Belgium (www.oxfamsol.be)
Oxfam Brasil (www.oxfam.org.br)
Oxfam Canada (www.oxfam.ca)
Oxfam France (www.oxfamfrance.org)
Oxfam Germany (www.oxfam.de)
Oxfam GB (www.oxfam.org.uk)
Oxfam Hong Kong (www.oxfam.org.hk)
Oxfam IBIS (Denmark) (www.oxfamibis.dk)
KEDV (Oxfam Turkey)

Oxfam India (www.oxfamindia.org)
Oxfam Intermón (Spain) (www.oxfamintermon.org)
Oxfam Ireland (www.oxfamireland.org)
Oxfam Italy (www.oxfamitalia.org)
Oxfam Mexico (www.oxfammexico.org)
Oxfam New Zealand (www.oxfam.org.nz)
Oxfam Novib (Netherlands) (www.oxfamnovib.nl)
Oxfam Québec (www.oxfam.qc.ca)
Oxfam South Africa (www.oxfam.org.za)

Oxfam Sweden (public engagement office)
(www.oxfam.se)

www.oxfam.org

OXFAM