WWF

CLIMATE & ENERGY

POSITION PAPER

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CARBON DIOXIDE REMOVAL, INCLUDING CARBON SEQUESTRATION IN NATURAL SYSTEMS

Position Summary

1. Most current scenarios that keep global warming within the Paris Agreement's 1.5°C limit rely on removing large amounts of carbon dioxide from the atmosphere using a mix of land-based carbon sinks and technological removal approaches, in addition to accelerated action to cut emissions.
2. Immediate efforts must **prioritise cutting greenhouse gas emissions rapidly and deeply**, as less emissions entering the atmosphere means there is less need for carbon dioxide removal later in the century. Relying on carbon dioxide removal to any significant extent is a high-risk approach given uncertainties to its deliverability at scale. Thus:
   - Carbon dioxide removal must not delay or replace efforts to cut greenhouse gas emissions.
   - Pathways that rapidly cut emissions and minimise the need for carbon dioxide removal must be prioritised.
3. However, **some carbon dioxide removal is likely needed** to limit global temperature rise to 1.5°C, both to cancel out hard-to-mitigate residual emissions and/or to reduce atmospheric carbon dioxide concentration in the event of temperature overshoot scenarios.
4. **There are a range of approaches** that could, in principle, be used to remove carbon dioxide from the atmosphere at very large scale, but all carry risks and their social acceptability can differ depending on the context.
   - All carbon dioxide removal approaches have potential trade-offs and/or scale limitations and no single approach will be the full removal solution in the most 1.5°C scenarios.
   - We should prioritise those approaches which remove carbon dioxide from the atmosphere and permanently sequester it in natural systems – particularly those which have proven benefits for people and nature as well as climate.
   - The reliability, costs and benefits, impacts, and risks of many approaches are not well-understood. Further research and development will help to ascertain whether they can be part of the climate solution, and their tradeoffs if so.
5. To the extent that carbon dioxide removal approaches are implemented, they should adhere to strict environmental and social safeguards in order to minimise negative consequences.

Position Statement

1. **Rapid and deep cuts to greenhouse gas emissions is the top priority in climate change mitigation** as it is better to prevent emissions getting into the atmosphere in the first place than it is to remove them later. Any chance of achieving the Paris Agreement's 1.5°C or well below 2°C global warming limit requires an immediate and ongoing increase in emissions reduction.
2. Relying on carbon dioxide removal to any significant extent is a high risk approach given uncertainties to its deliverability at scale, so **carbon dioxide removal must not delay or replace efforts to cut greenhouse gas emissions**. The feasibility, effectiveness and social acceptance of large-scale use of carbon dioxide removal is uncertain, therefore carbon dioxide removal must be about lowering the risks associated with higher global temperatures and not about enabling continued or additional burning of fossil fuels.
3. **More rapid and deeper emissions cuts in the short-term reduces the need for riskier carbon dioxide removal in the longer term.** Therefore, **pathways that minimise the need for large-scale carbon dioxide removal must be prioritised.**
4. However, alongside rapid and deep greenhouse gas emissions cuts, **some removal of carbon dioxide from the atmosphere will likely be needed to limit global temperature rise to 1.5°C / well below 2°C**, both for overshoot and non-overshoot scenarios[1].
    a. To achieve net-zero, or net-negative, emissions, **carbon dioxide removal will be needed to cancel out residual emissions in hard-to-mitigate sectors** such as aviation and agriculture.
    b. To reduce atmospheric carbon dioxide concentration in the event of temperature overshoot scenarios **carbon dioxide removal would be needed to pay back the carbon budget when it becomes overdrawn.**
5. **A range of approaches would be required to remove carbon dioxide at large scale**, as each potential approach has scale limitations, constraints and trade-offs – for example with land use, water and biodiversity. The costs and benefits of each potential carbon dioxide removal approach, and their different institutional and economic contexts and geographies, need to be carefully considered.
6. WWF considers that the following carbon dioxide removal approaches are among those which would **increase carbon sequestration in natural systems and have other benefits which together outweigh the costs**. Such approaches should be prioritised provided they adhere to strict environmental and social safeguards and consider storage permanence – i.e. they have benefits for nature, people and climate:
    a. **Enhancement of forest carbon stocks** through:
        i. **Restoration** of ecological functioning of degraded forest landscapes – comprising peatlands, mangroves, coastal wetlands/ecosystems or low productive land – by promoting multifunctional landscapes, including reforestation and afforestation.
        ii. **Natural regeneration of forests**, assisted or otherwise.

[1] A 1.5°C "overshoot" scenario is one in where the global temperature rise exceeds the 1.5°C limit for a number of years before returning to below 1.5°C by the end of the century. Non-overshoot scenarios always remain below the temperature limit.

b. **Enhancement of soil carbon** through:

   iii. **Carbon sequestration in agricultural soils**, which also enhances soil health and productivity.

   iv. **Soil sequestration using sustainable production of biochar**.

7. WWF considers that for the following approaches **the balance between costs and benefits and the unknown risks, is not yet clear**. Further research and development is needed to ascertain whether these potential carbon dioxide removal approaches can be part of the climate solution, as such, **they should neither be ruled out nor actively supported**.

   a. **Afforestation** at scale on non-degraded land, which may not compensate the opportunity costs of land conversion, and may produce negative social impacts;

   b. **Bioenergy with carbon capture and storage (BECCS)** is land-intensive and limited in spatial suitability but could, in appropriate circumstances and with adequate safeguards, provide carbon dioxide removal;

   c. **Direct air capture and storage** is expensive and energy intensive but has large potential and fewer and less severe land-competition impacts; and

   d. **Enhanced weathering of minerals on land** requires large volumes of materials implying negative impacts from mining and transport but could permanently store a sizable amount of carbon dioxide.

8. Based on current evidence WWF considers a number of proposed carbon dioxide removal approaches are **not suitable for use at this time** since, at present, **the ecological and social uncertainties far outweigh the known benefits**. Examples include but aren't limited to:

   a. **large-scale ocean fertilisation** as it has a high potential for unintended and damaging side effects for ocean ecosystems; and

   b. **Enhanced weathering of minerals added to the oceans** appear to have environmental and other costs that outweigh the potential climate benefits.

9. To the extent that carbon dioxide removal approaches are implemented, they should adhere to strict environmental and social safeguards in order to minimise negative consequences. These consequences could include land and water resource conflict with food production or impacts on local people's livelihoods.

10. Cancelling out the hard-to-mitigate residual emissions will need all the removals available so those sinks already in existence must also be protected – while not an additional carbon dioxide removal opportunity, we should also ensure the future of forests that are currently significant net sinks of carbon dioxide. We should also continue good practice to avoid emissions through protection of forests of high biodiversity and carbon value, especially primary forests; and responsible management of forests. Many land-based conservation techniques which halt deforestation or prevent degradation and conversion of natural ecosystems have biodiversity and social benefits and are also cost-effective approaches to cut greenhouse gas emissions.

Prioritise: benefits outweigh the costs.
• **Enhancement of forest carbon stocks** through:
  o **Restoration** of ecological functioning of degraded forest landscapes – comprising peatlands, mangroves, coastal wetlands/ecosystems or low productive land – by promoting multifunctional landscapes, including reforestation and afforestation.
  o **Natural regeneration of forests**, assisted or otherwise.
• **Enhancement of soil carbon** through:
  o **Carbon sequestration in agricultural soils**, which also enhances soil health and productivity.
  o **Soil sequestration using sustainable production of biochar**.

Further research and development is needed to ascertain whether these approaches can be part of the climate solution: balance between costs and benefits, and the unknown risks is not yet clear. • **Afforestation** at scale on non-degraded land, which may not compensate the opportunity costs of land conversion, and may produce negative social impacts; • **Bioenergy with carbon capture and storage (BECCS)** is land-intensive and limited in spatial suitability but could, in appropriate circumstances and with adequate safeguards, provide carbon dioxide removal; • **Direct air capture and storage** is expensive and energy intensive but has large potential and fewer and less severe land-competition impacts; and • **Enhanced weathering of minerals on land** requires large volumes of materials implying negative impacts from mining and transport but could permanently store a sizable amount of carbon dioxide.
Not suitable for use at this time since: the ecological and social uncertainties far outweigh the known benefits. • **large-scale ocean fertilisation** as it has a high potential for unintended and damaging side effects for ocean ecosystems; and • **Enhanced weathering of minerals added to the oceans** appear to have environmental and other costs that outweigh the potential climate benefits.

Table 1: Summary of WWF's position on Carbon Dioxide Removal, including Carbon Sequestration in Natural Systems

Annexure: Summary of Evidence

1. The IPCC defines mitigation of climate change as *a human intervention to reduce the sources or enhance the sinks of greenhouse gases*[2]. This paper addresses efforts to "enhance the sinks of greenhouse gases" and focuses on carbon dioxide as the most amenable of the greenhouse gases to be removed and subsequently stored away from the atmosphere.

2. The Paris Agreement demonstrated the political will to limit global temperature rise and other climate impacts. Nearly all scenarios in line with the Agreement suggest that carbon dioxide removal (sometimes known as "negative emissions") will be necessary on a massive scale concurrent with rapid and deep emissions cuts. Large-scale removals of carbon dioxide (i.e. removals in the order of hundreds of billions of tonnes of carbon dioxide ($GtCO_2$) in the period to 2100) from the atmosphere are needed for two main reasons:

   - to compensate for emissions that are difficult to prevent entirely with current technologies, such as those from agriculture, aviation and shipping – sectors for which some residual emissions will remain even with the most ambitious mitigation efforts; and
   - to remove past emissions from the atmosphere.

3. Generally, removals start now and scale up to achieve net negative emissions around mid-century (range 2055-2075).[3] The year when "net zero" greenhouse gas emissions is reached is inversely correlated with emissions in 2030.[4] Typically Integrated Assessment Models (IAMs) use large-scale afforestation or bioenergy with carbon capture and storage (BECCS) as the main removal technology.

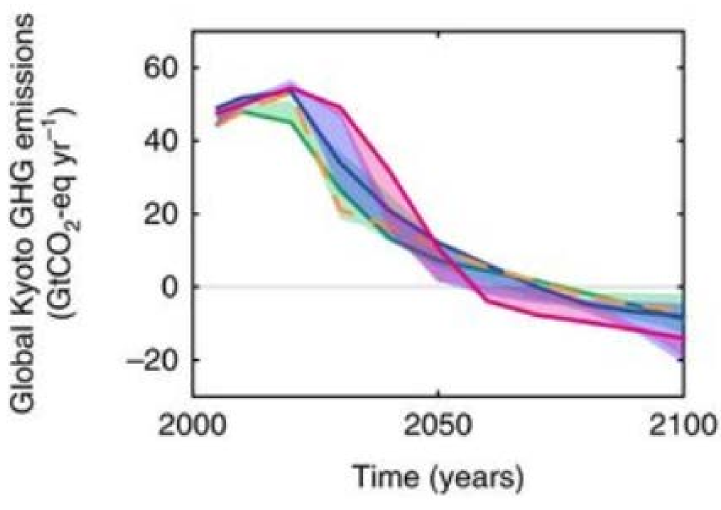

Figure 1. Global Kyoto greenhouse gas emissions. Shaded areas show the range per Shared Socioeconomic Pathway (SSP), solid lines the marker scenario for each SSP and dashed lines single scenarios that are not markers. Green refers to SSP1, blue SSP2, orange SSP4 and red SSP5. (Rogelj et al. 2018)

4. Scenarios have been developed that limit carbon dioxide removal and these require more immediate and much higher rates of sustained carbon dioxide emissions reduction (e.g. greater than 4 per cent

[2] IPCC. WGIII AR5 Glossary
[3] Rogelj et al., Scenarios towards limiting global mean temperature increase below 1.5°C Nature Climate Change 2018
[4] Rogelj et al., Scenarios towards limiting global mean temperature increase below 1.5°C Nature Climate Change 2018

per annum globally).[5] Models suggest this rate of reduction is not economically feasible unless the remaining carbon budget is at the higher end of the range of estimates.[6]

5. There are alternative mitigation scenarios that reduce the level of need for carbon dioxide removal technologies (see Table 1 and Figure 2). Most alternative mitigation scenarios lead to considerably lower land use, reducing the area for food production or bioenergy, or both. In the low non-CO_2 and lifestyle change scenarios, the amount of pasture and cropland to produce animal feed is reduced by 20–25%, resulting from reduced animal meat consumption. This allows for an increase in forest area, critical for terrestrial carbon storage. In the agricultural intensification scenario, a similar result is obtained, but due to increasing efficiency in agriculture and livestock farming.[7]

Scenario	Short name	Description and key assumptions
Baseline	SSP2	SSP2 implementation[19].
Default 2.6	DEF_2.6	Climate policy is implemented by introducing a uniform carbon tax in all regions and sectors from 2020 onwards; the radiative forcing level is 2.6 W m^{-2} in 2100[19].
Default 1.9	DEF_1.9	Climate policy is implemented by a uniform carbon tax in all regions and sectors from 2020 onwards; the radiative forcing level is 1.9 W m^{-2} in 2100[23].
Efficiency	Eff	Rapid application of the best available technologies for energy and material efficiency in all relevant sectors in all regions.
Renewable electricity	RenElec	Higher electrification rates in all end-use sectors, in combination with optimistic assumptions on the integration of variable renewables and on costs of transmission, distribution and storage.
Agricultural intensification	AgInt	High agricultural yields and application of intensified animal husbandry globally.
Low non-CO_2	LoNCO2	Implementation of the best available technologies for reducing non-CO_2 emissions and full adoption of cultured meat in 2050.
Lifestyle change	LiStCh	Consumers change their habits towards a lifestyle that leads to lower GHG emissions. This includes a less meat-intensive diet (conforming to health recommendations), less CO_2-intensive transport modes (following the current modal split in Japan), less intensive use of heating and cooling (change of 1 °C in heating and cooling reference levels) and a reduction in the use of several domestic appliances.
Low Population	LowPop	Scenario based on SSP1, projecting low population growth.[29]
All	TOT	The combination of all the options described above.

Note: The affixes _2.6 and _1.9 refer to scenarios that assume climate policies are enacted aiming to reach 2.6 and 1.9 W m^{-2} forcing targets by the end of the century, respectively.

Table 1. Alternative scenario framework (van Vuuren et al. 2018)

[5] Alice Larkin et al. What if negative emission technologies fail at scale? Implications of the Paris Agreement for big emitting nations, Climate Policy (2017)
[6] Kriegler et al. Pathways limiting warming to 1.5°C: a tale of turning around in no time? Philosophical Transactions of the Royal Society (2 April 2018)
[7] van Vuuren et al. 2018. Nature Climate Change, VOL 8, MAY 2018, 391–397. Alternative pathways to the 1.5 °C target reduce the need for negative emission technologies.

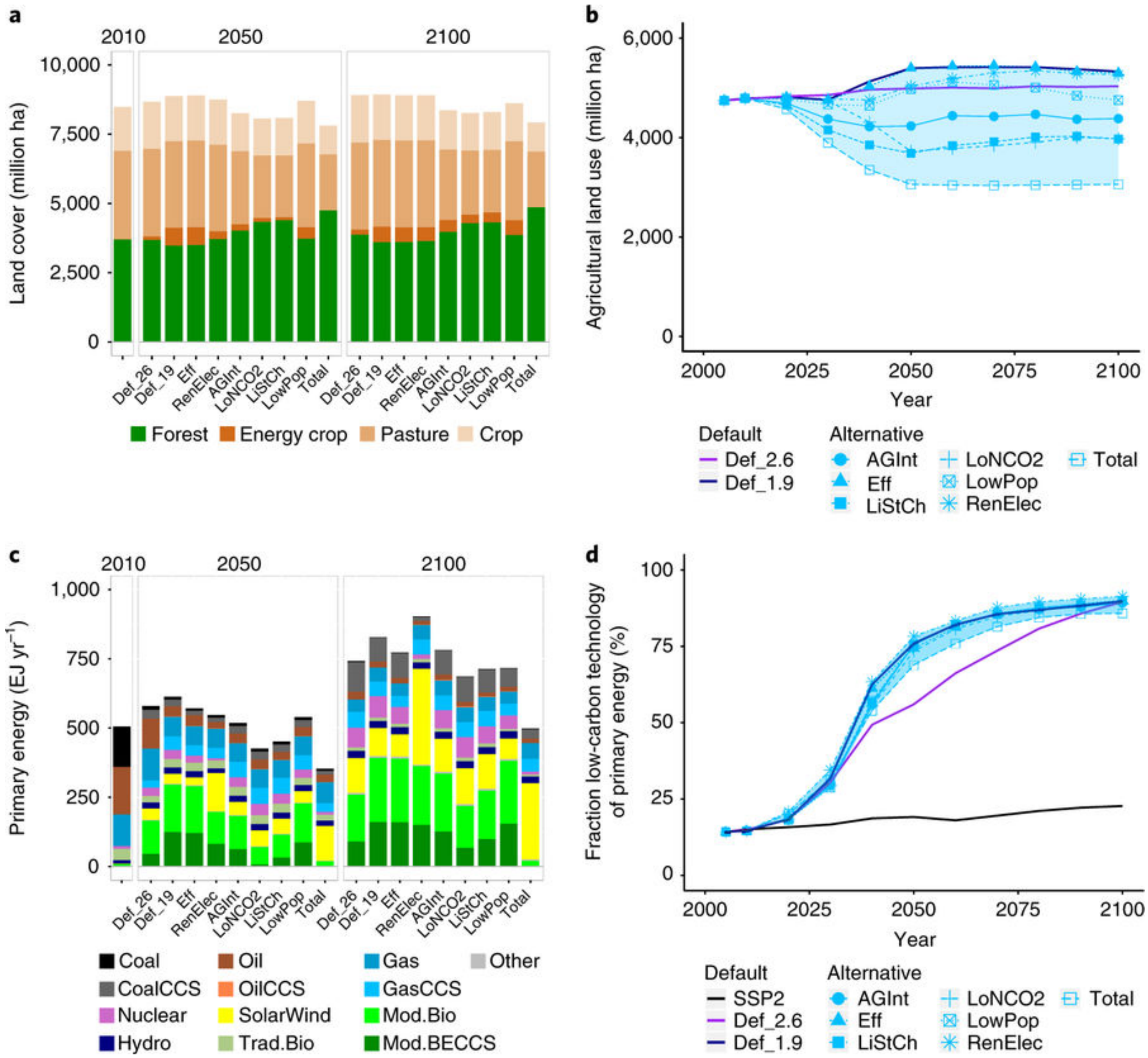

Figure 2. Transformations in land use/cover and energy use: **a**, **b**, Land cover for agriculture crops, pasture, energy crops and total forest area (natural and managed) by category (**a**) (remaining natural land cover types are not included) and the evolution of agricultural land use (the sum of crop, pasture and bioenergy area in **a**) over time (**b**). **c**,**d**, Primary energy use per energy carrier (**c**) and the share of low-carbon technology in total primary energy (**d**). Low-carbon technology is defined as solar, wind, nuclear power, bioenergy (traditional and modern), hydropower and fossil fuels (coal, oil, natural gas) with CCS (van Vuuren et al. 2018).

6. There are a range of approaches that can, in principle, be used to remove carbon dioxide from the atmosphere – these can broadly be broken down into approaches which enhance the natural carbon cycle and those more “engineered” approaches (see Figures 3, 4 and 5). All approaches have significant trade-offs and scale limitations (see paragraphs below) and each carbon dioxide removal method has different technological readiness, environmental impact, cost and the degree to which carbon is permanently stored.[8]

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[8] Smith et al. Biophysical and economic limits to negative CO2 emissions Nature Climate Change (Dec 2015).

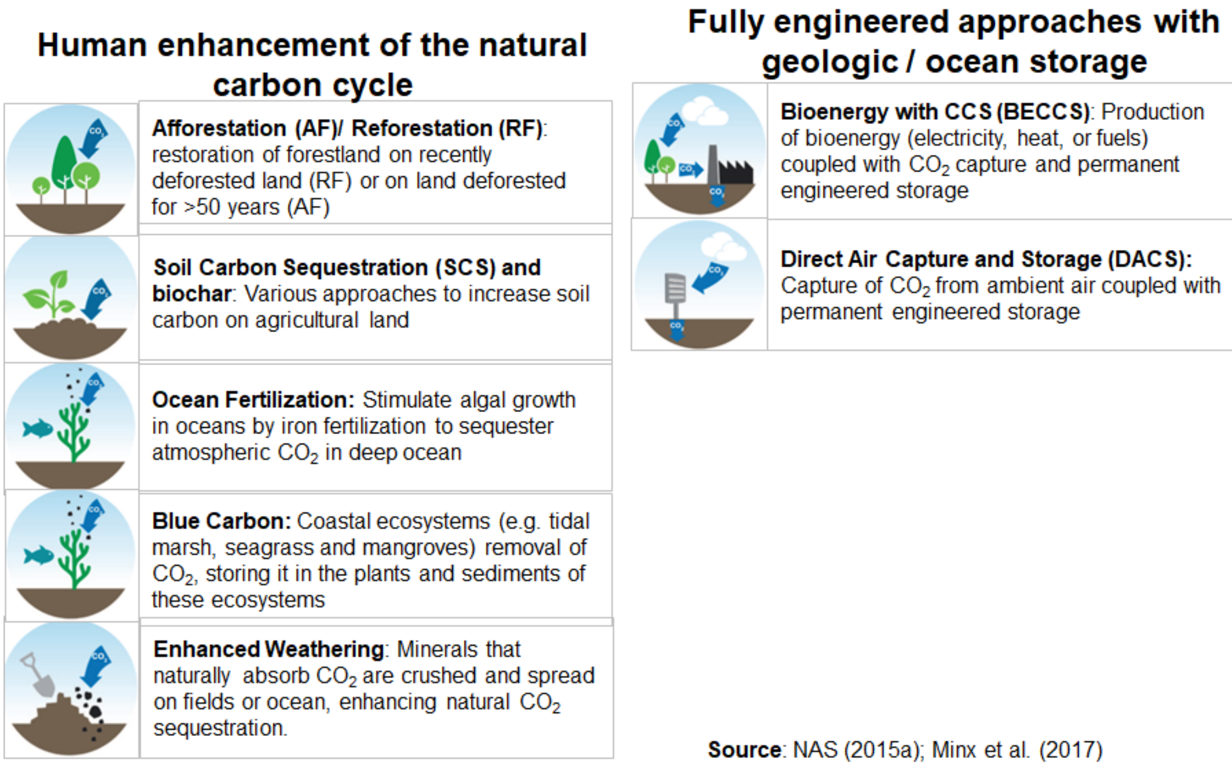

Figure 3. Approaches to removing carbon dioxide from the atmosphere.

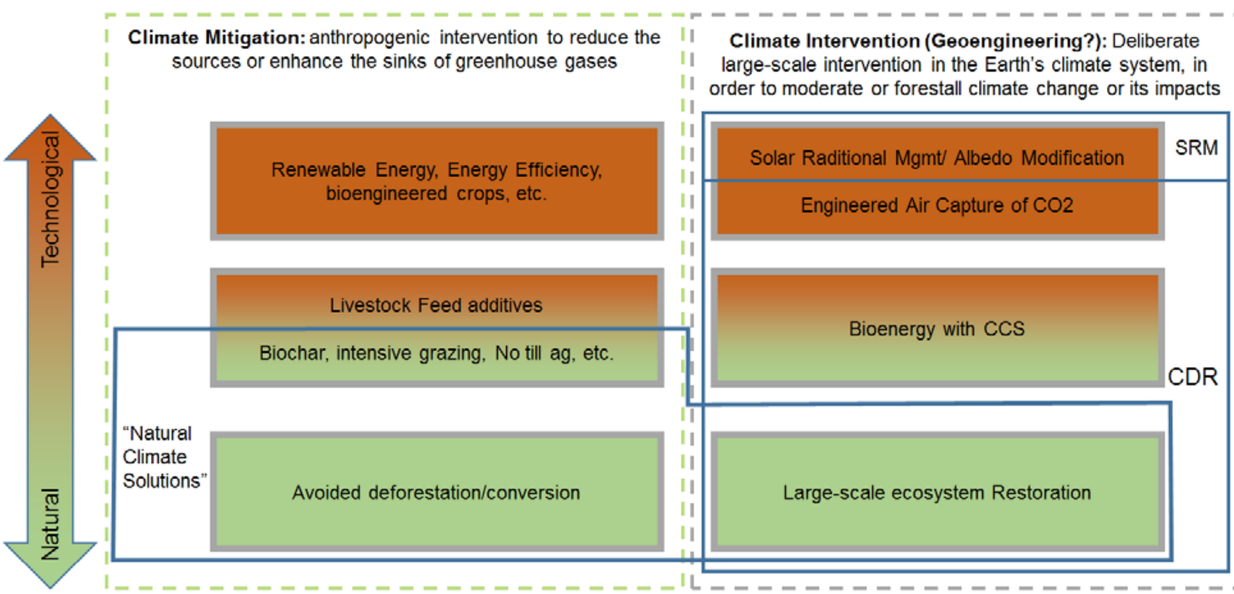

Figure 4. Overview of carbon dioxide removal terminology

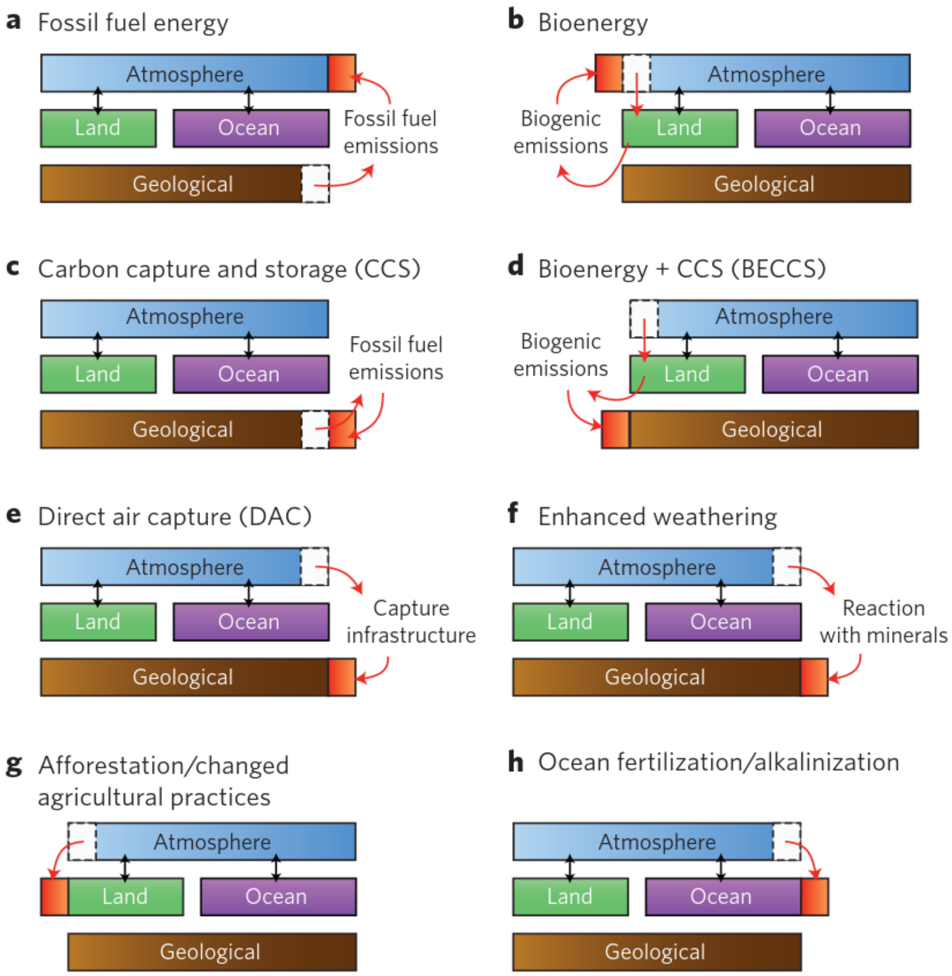

Figure 5 Schematic representation of carbon flows among atmospheric, land, ocean and geological reservoirs (Smith et al. 2015).

7. The fact that plants greatly influence the atmospheric CO_2 concentration is seen in the seasonal fluctuation in the Keeling curve.[9] The Keeling curve tracks higher photosynthetic activity in the summer – where plants consume CO_2 from the atmosphere – and less in the winter. Seasonal swings in CO_2 are most pronounced in the Northern Hemisphere forests, where the seasonal changes in temperature result in large differences in plant photosynthesis from summer to winter. Carbon is sequestered in standing living trees but also in deadwood and soils. Maintaining and restoring forests and soils is important for carbon sequestration.

8. Carbon dioxide removal approaches that enhance the natural carbon cycle (sometimes called *carbon sequestration in natural systems*[10]) include approaches to enhance forest carbon stocks (see below); techniques for improving land management to fix carbon in soils and the restoration of landscapes, particularly coastland wetlands and mangroves (called Blue Carbon). These approaches are expected to be lower cost in some locations than the technical/engineering ones and can bring ecological benefits. Further, some 'natural' approaches (e.g. responsible forest management, soil carbon sequestration) do not involve a net change in land use and may be more feasible from a social standpoint.

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[9] https://scripps.ucsd.edu/programs/keelingcurve/
[10] Confusingly, 'nature-based' or 'natural solutions' often include both carbon dioxide removal approaches and avoided emissions (e.g. avoided deforestation which are not net removals from the atmosphere).

Maintaining forest carbon sinks and enhancing forest carbon stocks

9. Forests provide carbon dioxide removal opportunities in multiple ways: stable forests acting as sinks, managed forests enhancing their carbon stocks, and new tree cover through afforestation and reforestation. Standing forests represent a major global resource for carbon management, in addition to the value they provide through other ecosystem services. While conventionally thought to be in equilibrium in terms of carbon fluxes, recent science finds that mature forests are, in fact, removing carbon from the atmosphere in far greater quantities than previously expected; with removal estimates of up to 436.5 ± 31.0 Tg C yr–1 from forest growth.[11,12,13] To give a sense of scale, stable Amazon rainforests may have offset all anthropogenic emissions from all sources in the region since the 1980's. Multiple lines of evidence point at tropical uptake of carbon, approximately balancing net deforestation.[14]

10. Responsible management of forests, restoration of degraded forests and (forest-) landscapes, reforestation, and natural regeneration of forests (see Box 1 below for definitions) are all approaches that can enhance (forest-) carbon stocks. However, if forests are created or managed only for the purposes of carbon sequestration, there is greater chance of biodiversity and social tradeoffs and risks.

11. Afforestation and plantations also have a role to play in sequestering carbon. Carbon and energy policies need to carefully promote only sustainable and landscape integrated approaches to be sure to avoid conflict with other land uses, while considering broader implications for food systems and other biomes. It has been estimated that to remove 1.1-3.3 GtC/yr would require 320 - 970 million hectares of land (approximately 20-60% of all current global arable land).[8]

12. Forestry practices may cause soil disturbance during preparation for planting that can release soil carbon so it may take several years before newly forested areas act as net sinks. Carbon dioxide removal by afforestation and plantation will require large areas of land thus increasing competition with other uses such as food. Depending on the type of forests planted, the water and fertiliser needs may also be significant, increasing competition for water and leading to higher N_2O emissions from the fertiliser.

13. Considering the other functions of forests and demands on land, forest carbon policies and other related policies need to be integrated at landscape scale. Forest landscape restoration can be designed in way to conserve biodiversity and protect natural forests, provide timber and services to meet human needs, and mitigate climate change[15]. Activities may comprise responsible FSC certified forest management and measures, including reforestation and afforestation such as promoted under the New Generations Plantations concept. Well-managed (planted) forests must maintain ecosystems integrity, protect and enhance high conservation values, be developed through effective stakeholder involvement processes, and contribute to economic growth and employment. If these are achieved, reforestation and afforestation can provide a positive, low-cost approach to remove carbon dioxide from atmosphere, while restoring degraded land for conservation and production[16].

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[11] Phillips, O. L. el al. Carbon uptake by mature Amazon forests has mitigated Amazon nations' carbon emissions. Carbon Balance Management. 12, (2017);
[12] Qie, L. et al. Long-term carbon sink in Borneo's forests halted by drought and vulnerable to edge effects. Nature Communications. 8, (2017).
[13] Lewis, S. L. et al. Increasing carbon storage in intact African tropical forests. Nature 457, 1003–1006 (2009).
[14] Baccini, A. et al. Tropical forests are a net carbon source based on aboveground measurements of gain and loss. Science 358, 230–234 (2017).
[15] From a biodiversity perspective: risks, trade- offs, and international guidance for Forest Landscape Restoration (2017)
[16] Silva, L.N., et al. Production, restoration, mitigation: a new generation of plantations New Forests (2018)

14. Forests have wider effects on climate than just from the carbon cycle, including for example albedo changes and emissions of volatile organics and microbes, which can increase cloud formation. The impact of these effects depends on latitude, forest structure and management.

15. Captured carbon may be re-released due to low rotation periods and products without a cascaded use (e.g. paper, firewood, oneway wood products (pallets), by changes in forest management, plant diseases, fires, droughts and/or climate change. For instance, many drivers of tropical tree mortality are expected to increase with climate change, including drought, fire, wind, and temperature.[17]

Box 1. Definition of Forest Terms

Afforestation: Establishment of forest through planting and/or deliberate seeding on land that, until then, was not classified as forest.

This implies a transformation of land use from non-forest to forest

Reforestation: Re-establishment of forest through planting and/or deliberate seeding on land classified as forest.

This implies no change of land use, includes planting/seeding of temporarily unstocked forest areas as well as planting/seeding of areas with forest cover, includes coppice from trees that were originally planted or seeded, but excludes natural regeneration of forest.

Planted Forest (Plantation): Forest predominantly composed of trees established through planting and/or deliberate seeding.

In this context, this predominantly means that the planted/seeded trees are expected to constitute more than 50% of the growing stock at maturity. It includes coppice from trees that were originally planted or seeded but excludes self-sown trees of introduced species.

(Source: FAO)

Forest and Landscape Restoration (FLR): The long-term process of regaining ecological functionality and enhancing human well-being across deforested or degraded forest landscapes.

(Source: Global Partnership on Forest Landscape Restoration http://www.forestlandscaperestoration.org/what-forest-and-landscape-restoration)

Natural regeneration: The process by which woodlands (and forests) are restocked by trees that develop from seeds that fall and germinate in situ.

(Source: Forestry Commission of Great Britain https://www.forestry.gov.uk/fr/infd-5z5gfe)

Land management

16. Soils are a major carbon reservoir, however anthropogenic impacts on soil organic carbon can either turn it into a net sink or a net source of greenhouse gases.[18] Various techniques are available to increase soil organic systems (referred to as soil carbon sequestration (SCS)) including low or no-till systems, growing cover crops and water regime restoration of wetland, mires, wet forest by closing drainage. Some studies have suggested potentials of the order of 4 $GtCO_2$ per year.[19] However, others

[17] McDowell et al. Drivers and mechanisms of tree mortality in moist tropical forests, New Phytologist (2018)
[18] FAO report Soil organic carbon the hidden potential (2017)
[19] Smith et al. Biophysical and economic limits to negative CO2 emissions Nature Climate Change (Dec 2015)

doubt whether this potential could be achieved and maintained. Managing soils for soil health will deliver many benefits, including higher soil carbon stock.

17. Another approach is to add bio-char (product similar to charcoal) to soil, which acts as a fertiliser and increases the carbon content of the soil. The potential contribution from bio-char is estimated at around 2-4 $GtCO_2$ per year.[20] The use of bio-char is likely to be more expensive than other soil carbon options but has additional benefits in terms of fertilisation for many soil types.[21] It may darken some soil types and increase heat adsorption. Using biomass for bio-char production will compete with other uses for biomass.

Other Ecosystem restoration

18. In addition to restoration and regeneration of forests, certain other ecosystems provide high density storage of carbon. These include peatlands and coastal wetlands including mangroves, tidal marshes and seagrass meadows. Many of these ecosystems have been degraded and their restoration would increase their ability to sequester carbon. Carbon stored in coastal wetlands is often referred to as Blue Carbon.
19. As well as increasing carbon sequestration, restoration of coastal wetlands can contribute to building resilience to the effects of climate change – supporting healthy fisheries and protecting against floods.
20. Although wetlands store carbon, they are can also be a significant source of methane. There may therefore be some short term emissions of methane during the restoration stage.[17]
21. Other carbon removal approaches use engineered quasi-'natural' processes to enhance carbon removal and storage. These include adding iron or alkali to oceans to increase the uptake of carbon dioxide (ocean liming or ocean fertilisation) and enhanced weathering of minerals.

Ocean fertilisation

22. Ocean fertilisation is the addition of nutrients to the ocean to increase the rate of phytoplankton production and hence carbon dioxide uptake. Although much of the carbon dioxide will be re-released when the phytoplankton is consumed, some particles will drift to the ocean floor and be sequestered. The main discussion is around adding iron in areas of ocean where iron is the limiting nutrient or lime to counteract acidification of the oceans.
23. The effectiveness of ocean fertilisation in removing carbon dioxide over meaningful timescales is very uncertain and unless the rate of re-release is very low is likely to be costly (>$400/$tCO_2$).[22]
24. Even if it were effective at removing carbon dioxide, the ecological impact on oceans is very unpredictable. Changes in nutrient supply could impact on marine biodiversity and on fisheries. Some experiments have also demonstrated that iron fertilisation results in toxic algal blooms. The impact on ocean biogeochemistry is also uncertain and may influence the production of trace gases.[23]

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[20] EASAC report 35 Negative emission technologies:What role in meeting Paris Agreement targets? February 2018
[21] Bruckman V. *et al.* (eds) (2016). *Biochar: a regional supply chain approach in view of climate change mitigation*. Cambridge University Press
[22] EASAC report 35 Negative emission technologies:What role in meeting Paris Agreement targets? February 2018
[23] EASAC report 35 Negative emission technologies:What role in meeting Paris Agreement targets? February 2018

Enhanced weathering

25. Enhanced weathering (EW) is the acceleration of the natural process of mineral carbonation. The main method discussed is to spread finely ground mineral silicate rocks over large areas of land. Suitable minerals such as feldspar and olivine are abundantly available.

26. Other methods discussed include reacting ground carbonate minerals with CO_2 in engineering plants and releasing the resultant solution to the ocean or converting carbonate rocks to lime (by heating) and adding this to the ocean. This would increase the alkalinity of the ocean, although both are energy intensive.

27. The mining, grinding and transportation of the minerals though has high cost and energy requirements and potentially health risks from mining.[17] The amount of land required is also large, although it may be possible to use that land for agriculture.

28. An alternative use of the same geochemical process is to pump CO_2 into volcanic rock where it reacts with the basalt to form carbonate minerals. This has been successfully tested in a project in Iceland.[24] This offers an alternative to the conventional ways of storing CO_2 but uses large amounts of water, although this could be seawater.

29. There are also more technological / engineering approaches that involve capturing carbon dioxide and subsequent geological storage including BECCS and Direct Air Capture (DAC).

Bioenergy with Carbon dioxide Capture and Storage (BECCS)

30. BECCS refers to the use of biomass as fuel in an energy conversion plant and the capture and geologic storage of the CO_2 emissions from that plant. Integrated assessment models generally rely on large scale BECCS to provide the required carbon dioxide removal to keep to 1.5°C scenarios. Although often thought of as a power sector option it can be used in other sectors – in the recent 1.5°C specific scenarios, the largest BECCS share is from liquid biofuel and/or hydrogen production mainly related to sectors such as long-distance air travel which cannot be electrified.[25]

31. BECCS has the potential to scale to tens of $GtCO_2$/yr but has large water, nutrients and land use requirements. The limits to provide the biomass sustainably – protecting both ecosystems and livelihoods have not yet been determined. BECCS is therefore particularly divisive amongst NGOs because of the potential trade-offs with land and water needed for food, biodiversity, and the land tenure of existing owners or users.

32. Both the bioenergy and carbon capture and storage aspects of the technology exist and there are some small-scale demonstration projects. However, the large-scale commercial deployment of BECCS is not proven and the infrastructure needed not yet developed. In the last decade carbon storage in underground geological formations was heavily debated in several countries. Another possibly pathway is a bioenergy to carbon capture and utilisation, were the captured carbon is used in industrial applications such as the like chemical industry that need carbon as raw material – though the quantities are likely to be relatively small compared to storage. The efficiency of carbon removal over the life cycle is also subject to some debate. Given current assumptions about the development of the technology, BECCS is expected to be relatively cost effective (see Figure 6 below).

[24] CarbFix project www.or.is
[25] Rogelj et al., Scenarios towards limiting global mean temperature increase below 1.5°C Nature Climate Change 2018

Direct Air Capture

33. Direct Air Capture uses liquid or solid adsorbents that filter carbon dioxide from the air, which is then released as a concentrated form for storage. The technologies already exist and prototypes are operating. Commercial development of the technology is being driven by the possibility of using the concentrated carbon dioxide – although in this case it is not a carbon dioxide removal approach.

34. DAC is expected to require minimal land but is currently very expensive (\$200-\$1000/tCO_2)[26] and requires significant energy to regenerate the absorbent. It will also, like BECCS, require carbon storage infrastructure which has not yet been developed.

35. Figure 6 summarises the resource requirements and relative costs for the different technologies.

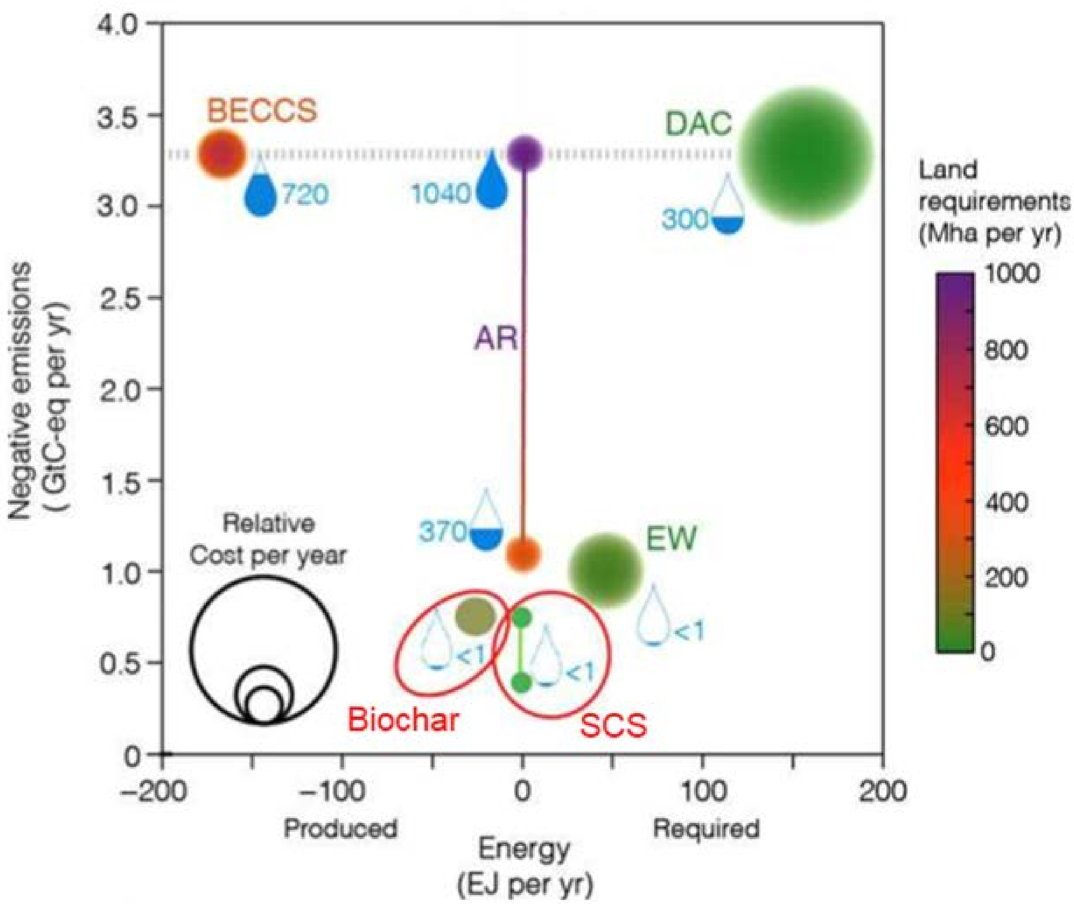


Figure 6 For simplicity midpoints are shown in place of ranges. Figure dimensions show required energy (x axis), scale (y axis), cost (size of circle), land requirements (color), and water requirements (droplet). AR is afforestation and reforestation (from Smith et al. 2015)

The transport and storage element of CCS

36. Both DAC and BECCS rely on transport and geological storage of the captured carbon. Transport would generally be in pipelines and ships to a suitable storage site such as depleted hydrocarbon

[26] EASAC report 35 Negative emission technologies:What role in meeting Paris Agreement targets? February 2018

reservoirs, deep saline formations or the basalt formations discussed earlier in the section on enhanced weathering.

37. Leakage of CO_2 would be possible from all stages of CCS. Leaks that occur in the capture and transport processes would be detected and managed by safety systems mandated by regulations. The geological formations used for storage will be selected to give a very low likelihood of CO_2 leakage and monitoring systems would be in place. If CO_2 were to leak from the storage site this may not be so easily detected and management of such leaks might be more complex than from capture and transport.

38. The infrastructure for transport will also need to be developed and will add to the costs and have impacts such as visual appearance (pipelines) and energy use (ships).

39. Injection of large volumes of CO_2 into rocks has the potential to induce earthquakes. Seismic modelling and optimised injection processes can reduce this risk. However, this and the fear of leakage has led to strong public opposition to storage, particularly for onshore sites.

Carbon dioxide removal in integrated assessment models

40. The main approaches used in the climate scenarios are BECCS and afforestation and reforestation, partly because these are thought to have the largest potential but also because others are not yet sufficiently defined to be included in the models. The balance between the use of BECCS and reforestation depends on the assumptions on the sociological development and the model. In the latest 1.5°C specific scenarios, the range of removals via BECCS is 150-1200 $GtCO_2$ (equivalent to about 4-30 years of current annual emissions). [27]These values represent projections of cost-effective BECCS deployment and do not include explicit limits on its contribution.

41. Recent modelling to examine alternatives to carbon dioxide removal found that its use could be reduced significantly but not fully eliminated.[28] A number of different pathways exist but all require a rapid transformation in energy and resource consumption and land use.

42. Research is still underway to determine the potential for, and limits on, any of the carbon dioxide removal approaches. Available land and water for carbon sequestration in natural systems and for BECCS is strongly dependent on scenarios of land use more generally, for example linked to population growth, diets and agricultural productivity.

43. The existing scenarios nearly all assume that carbon dioxide removal ramps up to operate at a large scale by 2100. Given the uncertainty on the performance of carbon dioxide removal approaches both in efficiency and costs and the doubts about the wider impacts, this brings a higher risk that if they are ineffective there will be even higher temperature rises. Some commentators have therefore argued that for intergenerational equity it would be better to start carbon dioxide removal as soon as possible, with the aim of reducing peak deployment.[29] This implies more rapid research and development and the early establishment of governance and accounting principles. It also implies that investment costs in the early periods may be higher than under a theoretical least cost pathway.

[27] Rogelj et al., Scenarios towards limiting global mean temperature increase below 1.5°C Nature Climate Change 2018
[28] Van Vuuren et al. Alternative pathways to the 1.5°C target reduces the need for negative emission technologies. Nature Climate Change 2018
[29] Obersteiner et al. How to spend a dwindling greenhouse gas budget. Nature Climate Change | VOL 8 | JANUARY 2018 | 2–12 |

Governance and policies for carbon dioxide removal

44. With the exception of ocean fertilisation/liming, the carbon removal approaches would be expected to be mainly subject to national or subnational governance. However, there will be a need for international governance to agree standards for accounting, monitoring, reporting and verification.[30]

45. Governments also have a role in setting incentives for the private sector to develop the options, research support and subsidies. In addition, because of the potential for carbon removal approaches to compete for land and water with other uses, then governments should have a role in setting frameworks to ensure that development is in line with the Sustainable Development Goals and that ecosystems are protected.

46. In 2008, the Parties to the London Protocol of the London Convention agreed that the treaty covered ocean fertilisation and a resolution was adopted that exempted legitimate scientific research from the definition of dumping[31]. Activities apart from legitimate scientific research however are not exempt and are therefore banned.[32] It was further agreed that "Scientific research proposals should be assessed on a case-by-case basis using an assessment framework to be developed by the Scientific Groups; and until specific guidance is available, Parties should be urged to use utmost caution and the best available guidance to evaluate scientific research proposals to ensure protection of the marine environment consistent with the Convention and Protocol."[33]

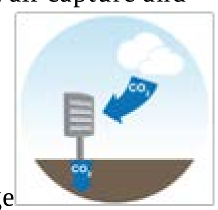
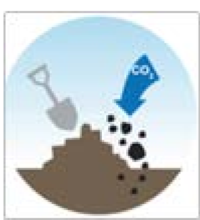
Arguments for and against potential carbon dioxide removal approaches

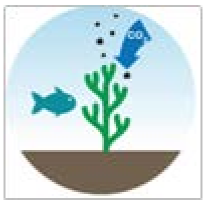
47. Pros and cons for different carbon dioxide removal approaches:

CARBON DIOXIDE REMOVAL APPROACH	PROS	CONS
Ecosystem restoration 	• Realises biodiversity benefits • Can be beneficial to build resilience to the effects of climate change	• Excluding forests, the overall contribution to carbon sequestration limited due to availability of suitable ecosystems • Few systems in place to value ecosystem restoration • Reversible unless safeguards in place

[30] Carnegie Climate Geoengineering Governance Initiative (C2G2) – Our Approach (2018)
[31] International Maritime Organization – Ocean Fertilization under the London Convention / London Protocol
[32] Royal Society Geoengineering the climate Science, governance and uncertainty (2009)
[33] International Maritime Organization – Ocean Fertilization under the London Convention / London Protocol

Reforestation 	• Could realise biodiversity benefits if carried out in the right way, c.f. ecosystem restoration • Can be beneficial to build resilience to the effects of climate change	• Potential local conflicts with alternative use of land • Could result in short term release of carbon from soil disturbance • Sequestration vulnerable to the effects of climate change and forest fires
Afforestation 	• Could realise biodiversity benefits if carried out in the right way • Could help build resilience in some areas • Can be combined with agriculture to some degree (e.g. planting windbreaks)	• If needed at scale will require significant land and water resources and could conflict with other demands such as food • Could result in short term release of carbon from soil disturbance • Sequestration vulnerable to the effects of climate change and forest fires
Soil carbon sequestration – agricultural practices such as no-till 	• If properly done it should not conflict with food production and may improve productivity of some agriculture • May bring wider environmental benefits such as improved soil structure and improve resilience to climate change	• Effectiveness in terms of sequestration is disputed • Reversible unless safeguards in place • Can reduce crop production
Soil carbon sequestration – use of biochar 	• Can improve soil fertility and increase agricultural productivity • Estimates suggest this has a higher potential than other soil sequestration	• Could darken soil and reduce albedo • Effectiveness in terms of sequestration at scale is not proven and may be location dependent • Use of biomass for biochar may compete with other uses of biomass and have land and water implications

Bioenergy with Carbon Capture and Storage (BECCS). 	• Can be used to provide renewable energy for power generation or high temperature heat • Carbon can theoretically be stored permanently • Both bioenergy and CCS technologies are well understood although not demonstrated together commercially • Theoretically could be implemented at scale • The CCS component could be implemented first for hard-to-mitigate industrial emissions to cut emissions sooner and reduce peak load on biomass production and DAC	• Potentially has high land, nutrient and water implications with impacts on biodiversity and human societies • Life cycle effectiveness of carbon removal disputed – will be partly dependent on the biomass used • There are risks associated with storing carbon underground such as leakage and seismic activity • Infrastructure for carbon storage not yet developed • Both use of biomass and carbon capture and storage face public opposition
Direct air capture and storage	• Flexible technology and could be used to scale • Few negative side effects • Potential to store carbon permanently • Much smaller requirement for land and water than BECCS	• High cost • Uses significant energy (although combining DAC with renewable energy has potential to manage that risk) • Large scale capture and storage infrastructure required
Enhanced weathering of minerals – land based 	• Makes use of common materials and a process that is well understood • Carbon can be stored permanently • Storage in-situ in volcanic rock could offer an alternative to conventional techniques for storing carbon	• Requires large volumes of materials implying negative impacts from mining and transport • Large scale infrastructure would need to be developed • Would require large areas of land and side effects on soil not established • Potential economic scale of in-situ storage not clear

Enhanced weathering of minerals – ocean based 	• Large potential • Could reduce ocean acidification	• Requires large volumes of materials implying negative impacts from mining and transport • Impacts on ocean ecosystems not understood • Large scale infrastructure would need to be developed
Ocean fertilisation 	• Would reduce acidification of surface waters (but not deep ocean) • If iron is used the costs may be relatively low	• High potential for unintended and damaging side effects for ocean ecosystems • May increase anoxic regions of the ocean • May increase acidification of deep oceans

Why we are here

To stop the degradation of the planet's natural environment and to build a future in which humans live in harmony with nature.

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