In Collaboration with the Global Future Council on Net-Zero Transition and the Alliance of CEO Climate Leaders

WORLD ECONOMIC FORUM

Net-Zero to Net-Negative: A Guide for Leaders on Carbon Removal

WHITE PAPER

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Three things need to happen to limit global warming to safe levels in line with the Paris Agreement: greenhouse gas emissions need to be halved by 2030; net-zero emissions must be achieved by 2050; and global emissions will need to become net-negative emissions after 2050.

First and foremost, holding on to a stable climate requires a drastic reduction of emissions. This will require an economic transformation that reimagines how we produce and use energy and most commodities. And yet, that will still not be enough. As a complement to reductions, carbon removal solutions are needed. Not only will some emissions – for example, in agriculture and heavy industry – be very difficult to reduce, we also need to draw down the Earth's own emissions resulting from the natural feedback loops of a warming planet and also reverse the build-up of emissions that have accumulated, and continue to accumulate, in the atmosphere over time.

This paper offers a timely guide for business and policy leaders determined to accelerate the transition to an economy compatible with maintaining a safe climate. It describes the landscape of existing carbon removal opportunities – from nature-based to technological and hybrid solutions – discusses the relative merits and challenges associated with these, and recommends a set of actions to begin speeding up their deployment today. Key among these are committing to: learning about and interrogating the concept of carbon removals to understand the trade-offs; using removals to address current, future and, importantly, past emissions; and seeking a leveraged, systemic impact rather than taking a tactical, least-cost approach.

Two of the World Economic Forum's communities collaborated to develop this paper: the Global Future Council (GFC) on Net-Zero Transition and the Alliance of CEO Climate Leaders' Carbon Removals Climate Action Group. This collaboration also produced a presentation – from CEOs to CEOs – summarizing the critical role of carbon removal and how companies can use it both credibly and smartly.

We are grateful for the many contributions from both of these groups, which also yielded a series of articles published on the Forum's Agenda blog, and in particular to Eli Mitchell-Larson of the Oxford Net Zero initiative and Carbon Gap for his work in drafting and collating many diverse perspectives. This diversity has generated a robust set of recommendations for leaders who are ready to deliver this important piece of the climate puzzle.

Executive summary

Planning for the active removal of carbon dioxide from the atmosphere coupled with storage (CDR), is an integral part of any comprehensive net- zero strategy. This white paper is a guide for decision-makers to some of the key challenges and opportunities they must consider when engaging with carbon removals.

When to use removals?
The use of carbon removals needs to follow the mitigation hierarchy: the first priority is always to reduce or avoid emissions where possible. Carbon removal is appropriate if used for one of three purposes:

1. Compensating for emissions that result directly from an actor's activities but which are difficult or impossible to reduce.

2. Compensating for the Earth's emissions resulting from climate change itself (and hence indirectly from past or future emissions)

3. For actors with high ambitions and strong leadership, going further – achieving net-negative emissions to address the legacy of past emissions, tackling the build-up of carbon dioxide in the atmosphere and beginning to restore the climate

How should leaders engage with removals?
We highlight three key considerations:

Understand carbon removal and its limitations – it is essential to consider the complete end-to-end carbon removal and storage challenge. Carbon removal techniques can broadly be divided into categories according to the method of removal, and the form of subsequent format of storage, some of which are considered "nature-based", "engineered", or a hybrid of the two. To deliver the carbon removal volume necessary to meet the Paris Agreement, all of these methods will need to be scaled up over the coming decade. In selecting a safe carbon removal strategy, leaders should keep in mind:

1. **Where to put removed carbon?** Consider the capacity of carbon storage options and how they are distributed among the atmosphere, geosphere (rocks), and biosphere (marine and terrestrial plants and soils). Durable net- zero strategies involve balancing emissions and removals like-for-like (e.g. compensating for ongoing fossil fuel use by returning carbon dioxide to the geosphere).

2. **When is carbon removed?** Not all removals are realized instantaneously, and care must be taken not to borrow from the future.

3. **How long will carbon stay removed?** Consider the risk of reversal to the atmosphere of stored carbon and anticipate a need to transition to options offering greater permanence and lower risk. Ensure robust ongoing performance monitoring.

Plan to address future, present and past emissions – ambitious corporate leaders seeking to determine the scale of carbon removal required by their businesses should prioritize unavoidable present and future emissions, but also be prepared to address past emissions back to an agreed date.

Seek systemic impact – finally, when considering carbon removal options, corporations need to reflect on the impact they want to have and their level of ambition. Leaders in business, finance and policy can act now to support a wide array of removals options. This includes both established methods that are ready for scale plus emerging techniques where urgent, early-stage support will deliver systemic, far-reaching impacts beyond the decision-maker's own remit.

How best to take action?
The brief closes with a call to action, under the overarching appeal to use removals only to address emissions that cannot be reduced or avoided, prioritizing emission reductions above removals across the full value chain. Corporations engaging with carbon removal must:

1. Build expertise, seek advice and support existing carbon removal initiatives

2. Support emission reductions and nature-based climate solutions in their own right

3. Seek a diversified portfolio of removals spanning biological and geological options

4. Consider the use of removals to compensate for past emissions

5. Prepare for the future, including potential liability for future emissions

6. Balance emissions from high-durability sources with high-durability storage

7. Advocate for ambitious climate policies

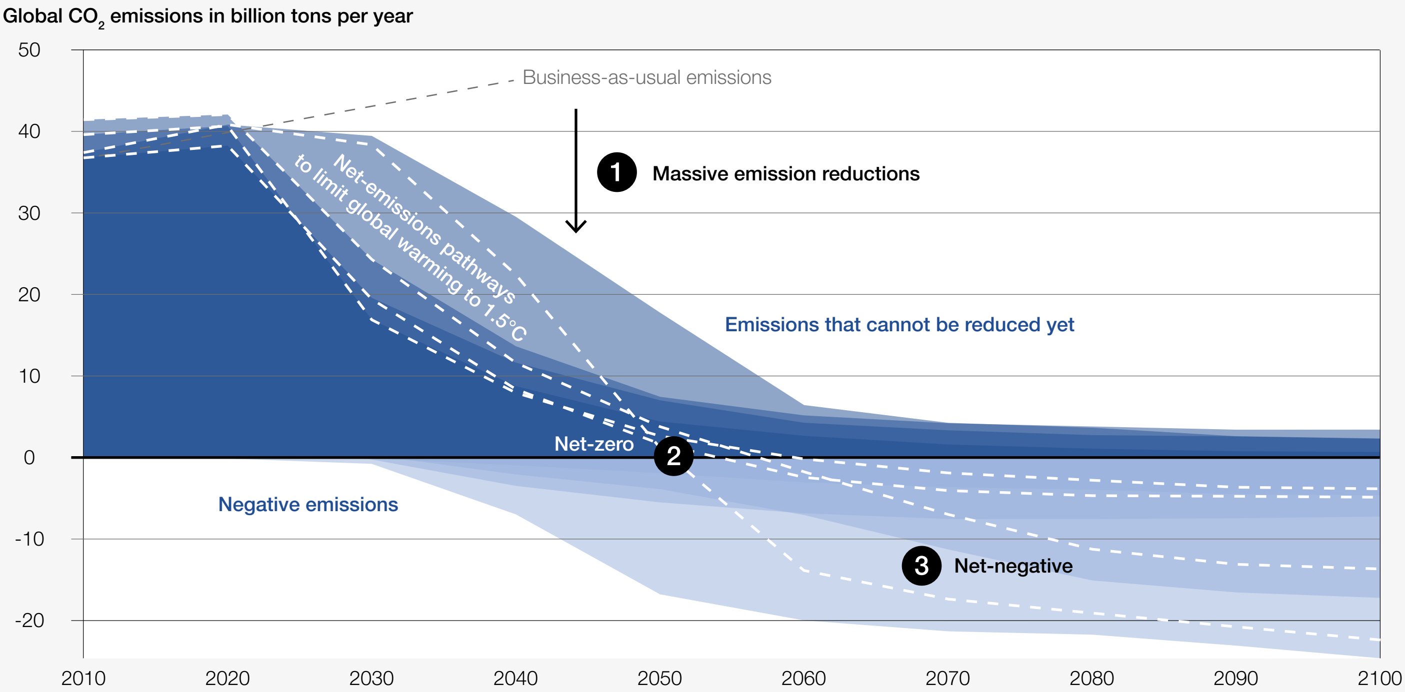
Introduction

To ensure a safe climate, we must cut carbon dioxide emissions by 50% or more by 2030, reach net-zero emissions before 2050 and stay at net-negative emissions throughout the second half of the century.

This paper focuses on carbon dioxide removal (CDR) and its role in complementing emission reductions and reducing the stock of carbon already in the atmosphere. Achieving net-zero – removing and storing greenhouse gas emissions at the same rate as they are emitted – is an important waypoint towards absolute zero.

In quantifiable terms: to keep warming below the Paris threshold of 2°C, or preferably 1.5°C, massive year-on-year emission reductions are needed in addition to the safe removal and storage of 5 billion to 20 billion tons of CO_2 from the atmosphere every year by mid-century (compared to today's emissions of ~40 billion tons CO_2 per year).[1]

FIGURE 1 **1.5°C pathway**



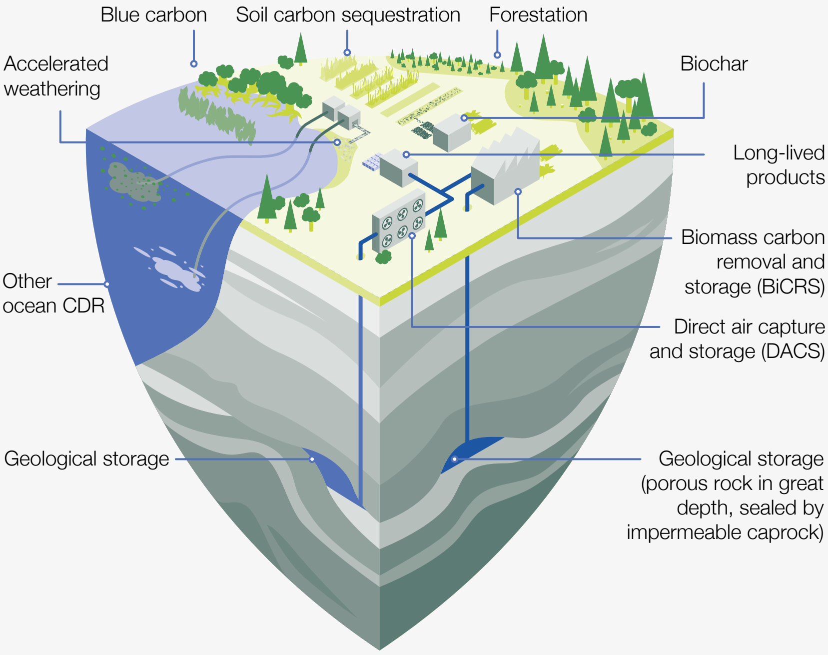
Source: Adapted from the Intergovernmental Panel on Climate Change 2018 SR15, P1–P4
Carbon removal plays a critical role in enabling the neutralization of some very hard-to-abate emissions: (1) achieving net-zero by mid-century in time to keep peak warming below Paris thresholds; and (2) delivering net-negative emissions to cool the planet and begin restoring the atmosphere.

Removals are a complement to deep emission cuts, not a replacement for them. Removals should not distract from emission cuts and are therefore always the final step in a mitigation hierarchy and corporate mitigation strategy.

There are various methods of removing and storing carbon, each with unique advantages, disadvantages, costs and other attributes (see Figure 2 and the Annex for a brief overview, and the CDR Primer for additional details). Options include nature-based removal methods, many of which are currently available at relatively low costs, and engineered and hybrid solutions, some of which, although they may still be expensive, are ready to be scaled up, while others are at earlier stages of development. The billions of tons of removals required cannot be delivered by any one technique; it is therefore necessary to explore and scale up a broad array of removal methods.[2]

FIGURE 2 | Carbon removal methods

The carbon-removal landscape spans across nature-based, hybrid and technological solutions



Forestation
Plant, manage and grow forests to remove and store carbon

Soil sequestration
Increase the soil carbon content through changes in land management (e.g. no-till)

Blue carbon
Increase the carbon content of coastal zones and wetlands through changes in ecosystem management (e.g. mangroves)

Other ocean CDR
Other methods to enhance the oceans' ability to absorb carbon in ecosystems and ocean chemistry

Biochar
Produce charcoal from biomass and use e.g. as soil amendment or chemical additive

Other biomass carbon removal and storage (BiCRS)
Strip biogenic CO_2 from flue gas or other processes, store it permanently. Includes bioenergy with carbon capture and storage (BECCS).

Accelerated weathering
Of natural minerals to react with, and thereby fix, atmospheric CO_2

Direct air capture and storage (DACS)
Filter CO_2 directly from the air and store it permanently

Source: Adapted from Swiss Re, 2020 SONAR Report

Carbon removal techniques take many forms, which can be categorized according to the means of removal from the atmosphere (e.g. photosynthesis powered by organisms, enhanced natural geochemical processes such as weathering, "engineered" filtering of CO_2 from air) and the means of subsequent carbon storage (e.g. in organic matter, mineralized forms, geological reservoirs, the built environment, long-lived products, ocean sediments or other sinks). These eight broad categories above are "end-to-end" removal and storage pathways; for example, bioenergy with carbon capture and storage (BECCS) involves photosynthetic capture coupled with storage in geological reservoirs, whereas "forestation" involves removal by and storage into the same material (the above- and below-ground biomass of the forest itself). Carbon removal solutions are sometimes grouped according to those that are considered "nature-based" versus those that are "technological/engineered", or those that are a "hybrid" of the two, but these distinctions can be subjective and occasionally controversial (e.g. reforestation is universally considered a nature-based solution, whereas afforestation is not).

Carbon removal can serve at least three distinct purposes in delivering climate action:

– **Compensating for hard-to-reduce emissions:** Some emissions are dispersed or very difficult or expensive to eliminate. Removals can compensate for these until technological, political and economic conditions allow for their absolute decarbonization.[3] However, such removals must not compromise progress on absolute decarbonization or deter more ambitious action in the short term. Those emissions that are considered "hard-to-reduce", and therefore appropriate to address with removals, must be continually reassessed.

– **Compensate for the Earth's emissions resulting from climate change:** Removals can also counteract increased emissions from the biosphere itself that result directly from historical and future emissions having warmed the planet, but which are difficult to attribute to any specific actors.

– **Tackling the build-up of emissions in the atmosphere:** Removals also allow those parties that have made the biggest contribution to the carbon build-up to address their legacy of contributing to warming. It is critical to stop present-day emissions and reduce the stock of carbon that has built up in the atmosphere. Once global net-zero emissions have been achieved, ongoing global net-negative emissions will have the effect of reducing CO_2 concentrations, cooling the planet and restoring the climate towards a pre-industrial state.

Despite the critical importance of removals, confusion about their appropriate use abounds. This paper describes some of the issues that need to be considered when including carbon removal in net-zero strategies and offers a vision of what credible support for removals looks like. The three key pillars that follow offer a starting point for corporate leaders who wish to responsibly guide their firms' engagement with carbon removal.

1 Understand carbon removal and its limitations

What does a safe and enduring global net-zero state look like, and how does this goal inform the actions currently needed to begin the transition?

Techniques to remove and store carbon vary widely in their impacts, benefits, costs and the fundamental value they deliver. These different attributes have implications for those who wish to use removals to compensate for fossil fuel emissions to deliver a stable and maintainable net-zero emissions state, both for their organization and the planet as a whole. Three key characteristics of removals are highlighted, including:

- How much room is left to store removed carbon?
- How quickly can carbon be removed and stored?
- How easy is it for stored carbon to escape back into the atmosphere?

1.1 Where to put removed carbon?

The faster we reduce emissions, the less carbon removal will be needed. By mid-century, a new journey from net-zero to absolute-zero emissions will need to be well under way, as every ton of carbon removed to first achieve and then sustain net-zero or net-negative emissions must be stored somewhere. At large volumes, storage space will run out.[4]

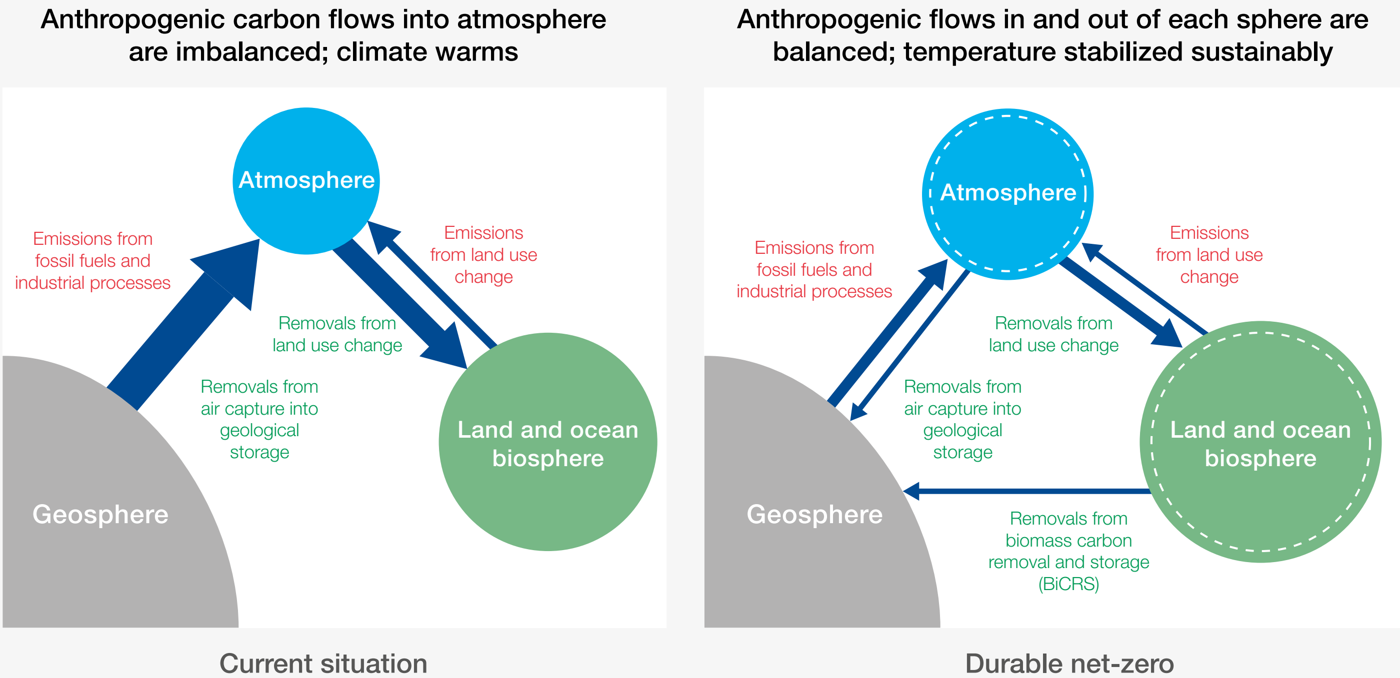
Most readily available carbon removal techniques today store removed carbon in the biosphere (e.g. vegetation and soils) or in the geosphere (e.g. in mineralized forms above or below the Earth's surface). Biosphere storage has the potential advantage of providing valuable non-carbon co-benefits, while geosphere storage is both vast and effectively permanent if implemented well.

Other carbon-storage options include mineralization at the Earth's surface, in the deep ocean and in deep-sea sediments, and in the built environment (e.g. structural timber) to displace carbon-intensive materials such as cement and steel, as well as in other long-lived products.

Different carbon-storage options have different available capacities. Although the maximum potential for nature-based removals is substantial,[5] it is orders of magnitude smaller than the geological carbon-storage resource. When an offset purchaser finances nature-mediated removals using carbon credits, they implicitly convert fossil carbon (emissions) into biological carbon (purchased removals). This is a one-way net flow of carbon from the very large geological carbon stock into the biological carbon stock. Biological carbon stocks are large, but inevitably constrained by both the availability of land and by competing uses, such as food and fibre production. This is not sustainable: all carbon stocks must be stabilized by ensuring that carbon extracted from them is replaced with carbon back into the same stock.

Enhancing biological carbon stocks serves many purposes beyond sequestering carbon, all of which can be valued and promoted. However, through the lens of delivering a balance of sources and sinks, it is useful to map flows among the key carbon stocks. Figure 3 illustrates an imbalanced (left) and balanced (right) state for these three carbon stocks (atmosphere, geosphere and biosphere).

FIGURE 3 **Carbon stocks**



Source: Figure adapted from Fankhauser et al., "The Meaning of Net Zero and How to Get It Right", Nature Climate Change, 2021, in preparation

The flows among three key carbon stocks relevant to carbon removal are currently out of balance, with a net flow of carbon from fossil fuel reserves (in the geosphere) into the atmosphere and biosphere. This represents a net conversion of fossil fuels into first atmospheric and subsequently biological carbon. Right: an illustrative durable global net-zero state is shown in which the three stocks are in balance overall, with no net accumulation of carbon in any stock. Note the much larger relative size of the geosphere carbon stock in both scenarios, and the increase in total stored carbon in the biosphere and atmosphere stocks on the right relative to current levels (dotted lines indicate the original sizes). This represents both the atmosphere and biosphere nearing their maximum sustainable capacity to store carbon (exhaustion of the 1.5°C-compatible carbon budget), hence the need to achieve a balance of sources and sinks. Sizes of the stocks are approximate and illustrative only.

1.2 When is carbon removed?

> Carbon removal credits that companies use to compensate for fossil fuel emissions must therefore count carbon as 'removed' only once it is safely stored.

Carbon removal and storage techniques are also constrained by the fact that not all removals can be realized instantaneously, which, in some cases, limits the overall contribution they can make before mid-century.[6] Trees (and other forms of biomass) begin removing and storing carbon from the moment they are planted, but the speed of sequestration is capped, occurring over several decades depending on the species and conditions. During this time, land managers must mitigate the risk that carbon reverses back into the atmosphere. Carbon removal credits that companies use to compensate for fossil fuel emissions must therefore count carbon as "removed" only once it is safely stored – not borrow from the future through a promise of carbon sequestration that may or may not occur. This time dependency provides a motivation to scale and deploy nature-based removals more urgently to restore depleted biological carbon stocks. However, it also offers a warning that long-term corporate net-zero plans cannot rely too heavily on any one set of solutions, given carbon-storage space limitations and the risk that global warming itself may destabilize some biospheric carbon stores.

Some forms of carbon removal such as direct air capture and storage (DACCS),[7] mineralization and many forms of biomass carbon removal and storage (BiCRS) can remove and store carbon "on demand".[8] However, these are constrained by cost and the time required to design, finance and deploy the necessary infrastructure. For any carbon removal and storage option that relies on biomass feedstock, care must be taken to avoid unintended consequences such as biodiversity impacts or competition with other land uses for food and fibre. Some of these risks can be mitigated by sourcing waste rather than virgin biomass. A wide variety of hybrid and engineered carbon removal and storage techniques need more early-stage support in order to reduce costs and be available for use in time to help achieve and maintain a safe and stable climate.

1.3 How long will carbon stay removed?

Some forms of carbon storage are riskier than others. Carbon is "removed" only for as long as it remains in safe and carefully monitored storage. If it is released back into the atmosphere, responsibility for remedial storage must be apportioned. Temporary forms of storage are valuable. However, relying heavily on short-term carbon storage builds up systemic risk, since the sudden or gradual reversal of stored carbon into the atmosphere represents a new source of emissions. Unfortunately, due to a combination of direct pressure on forests and the exacerbating influence of human-caused warming (e.g. wildfires, peatland fires, heat intolerance, pests, disease, hurricanes, etc.), the biosphere is an increasingly risky place to store carbon. That said, nature-based climate solutions can enhance the resilience of biospheric carbon stocks, if designed well (e.g. promoting biodiverse ecosystems rather than vulnerable monocultures). It is therefore necessary to invest in nature while recognizing its limitations.

Mineralized and geologically stored carbon have lower risks of physical reversal. These forms of storage have the advantage of a limited above-ground land footprint; however, they provide fewer non-carbon co-benefits. All forms of carbon storage, including geological storage, carry reversal risks that must be researched, monitored, constrained and remediated if necessary. Public understanding and acceptance of these technologies remains low and must be taken into account and addressed before any large-scale deployment.[9]

2

Plan to address future, present and past emissions

Ambitious corporate leaders seeking to determine the scale of carbon removal required by their businesses should prioritize unavoidable present and future emissions, but also be prepared to address past emissions back to an agreed date.

If there is still a question as to whether organizations are responsible for their past emissions, there is no doubt that they are responsible for ongoing and future emissions. Future emissions include both emissions from planned future activities and the rerelease, or reversal into the atmosphere, of carbon that was previously removed and stored. This situation may require setting aside funds or buying insurance to ensure that the costs of remediating future reversals of removed carbon will be covered.

Emissions from the biosphere due to Earth system feedbacks is another more insidious problem. Despite massive releases of carbon from agricultural expansion and soil destruction since 1850, the biosphere currently absorbs and stores about 6.2 billion tons of CO_2 more than it releases each year.[10] Setting aside increased fire, disease and other risks, and assuming that deforestation and other forms of intentional ecosystem destruction can be halted and reversed, there are fears that the biosphere will still flip from net sink to net carbon source due to Earth system feedbacks. These include CO2 and methane release from melting tundra and drying wetlands and the response of tropical forests to warming. Estimates of this release are comparable in scale to optimistic assumptions of the maximum rate of enhanced uptake that can be created in forests, soils and wetlands.[11] Therefore, all available nature-based removals could be applied to simply preventing the biosphere from further exacerbating global warming, which would leave no additional biological storage capacity available for use in offsetting ongoing fossil fuel use. For this reason, it is critical to distinguish between the scaled-up deployment of nature-based removals overall, and their specific use as a means of compensating for emissions of fossil CO_2 using carbon credits.

Finally, massive uptake of voluntary net-zero commitments is proof that the social contract between business and society is changing when it comes to climate. It could be anticipated that individuals, companies and countries will eventually be expected to take responsibility not only for their ongoing, planned and unplanned future emissions but also for their cumulative contribution to climate change. Determining when entities began to be responsible for their emissions is open to debate, but some companies have already accepted that the clock started well before the signing of the Paris Agreement in 2015. More ambitious leaders may choose to date responsibility back to the 1992 Rio Earth Summit, when climate change was first universally acknowledged, or perhaps even earlier, such as to a company's inception date.[12]

“ Massive uptake of voluntary net-zero commitments is proof that the social contract between business and society is changing when it comes to climate.

3 Seek systemic impact

A final consideration for corporate leaders looking to support carbon removal is the type of impact they wish to create.

Options available to corporate leaders include committing to purchase carbon removal credits to improve the business case for carbon removal providers, directly supporting nascent removal techniques, and moving beyond voluntary action by agitating for policies that help progress the carbon removal ecosystem as a whole and create a level playing field for all emitters.

Some established nature-based removal options such as reforestation are ready for scaling, but need stronger monitoring, reporting and verification standards to ensure credible, safe and effective deployment. Soil carbon credits remain nascent due to outstanding uncertainties in accurately measuring baselines, and ensuring the permanence and additionality of the resulting carbon credits. However, if these uncertainties can be resolved, the opportunity to mobilize farmers to both enhance soil quality and remove carbon is enormous. Corporate support for projects and initiatives that help advance legitimate, science-based standard-setting and improved, scalable measurement and verification techniques may deliver systemic improvement in this space.

Emerging solutions such as mineralization, direct air capture and storage, biomass carbon removal and storage (BiCRS) and ocean carbon removal need support to help drive down costs and establish their efficacy. Recognizing the need for these more expensive options in the medium and long term, some companies are opting to prioritize ecosystem-wide impact over immediate progress on their own net-zero goals, offering direct funding for research and development in earlier-stage carbon removal pathways without focusing on the number of removal credits they receive in exchange for their contribution.[13]

One key challenge is that the supply of high-quality removals on the voluntary carbon market, whether nature-based, engineered or hybrid, is extremely low.[14] Investments that increase the supply of removals for the whole market are therefore premium.

Conclusion

Bearing in mind the three pillars above for carbon removal engagement, corporate leaders are urged to take ambitious action to support this emerging set of climate solutions.

Educate yourselves – this briefing, alongside the CEO slide deck, provides high-level guidance for approaching this new set of climate solutions, highlighting a few of the most important considerations. However, ambitious and first-moving firms should prepare by building in-house expertise, soliciting external guidance or supporting industry-wide CDR education initiatives.

Support emission reductions and nature-based climate solutions in their own right – reducing emissions, whether in your own operations, your own supply chain, that of your customers or simply your broader stakeholder community, helps everyone on the path to net-zero. Likewise, the long-term need to transition away from reliance on nature-based carbon credits to compensate for fossil fuel emissions does not mean reducing support for nature-based solutions as a category of climate solutions. Financing must be expanded for ecosystem preservation and restoration in its own right; for instance, contributing towards these activities through other models that do not generate voluntary carbon credits. This leaves fossil fuel emissions to be addressed through other means: absolute emissions reductions first and foremost, supplemented by high-durability carbon removal where necessary. Furthermore, residual non-fossil emissions from agriculture, for example, must be compensated for with carbon absorption in soils and land.

Encourage a portfolio of removal options – a responsible corporate policy that incorporates carbon removal must include support for both biological- and geological-timescale carbon storage, with the type of backing offered reflecting the different maturities of these technologies. There must be a plan for early engagement and then transitioning to technological removal and storage options that deliver lower-risk storage at scale in the 2030s and 2040s.

Proactively address emissions, past and present – corporates should be prepared to use removals to compensate for present and future emissions, but rely on removals to address only those emissions that cannot be reduced. Ambitious corporates can also use removals to address past emissions – which continue to warm the planet until they are removed – first by establishing an ambitious and defensible “responsibility start date”. Some companies will wish to do so from inception (e.g. 1975 for Microsoft).

Prepare for the future – potential liability for future emissions must be considered. This includes specific responsibility for any physical reversals back into the atmosphere of temporarily stored carbon that formed part of net-zero claims, and shared responsibility for emissions from the biosphere itself that result from warming.

Balance emissions from high-durability sources with high-durability storage – globally, climate models compatible with 1.5°C peak warming require that the percentage of carbon emissions from high-durability carbon stocks (e.g. fossil fuel reserves, limestone formations) that are compensated for with permanent carbon storage increase from <1% today to roughly 10% by 2030, ~50% by 2040 and 100% or greater by 2050. To lead on climate, companies therefore need a plan to remove and permanently store a minimum 10% of their fossil fuel emissions by 2030, and ideally significantly more.

Advocate for ambitious climate policies – the maximum scope of voluntary action is inherently limited, and voluntary commitments must not be used as a shield to delay regulation and policy regimes that internalize climate damage. For most industries, no one company can unilaterally make the massive expenditures needed to deliver net-zero on a voluntary basis without becoming uncompetitive. Therefore, the most systemic impact corporate chief executive officers can have is to proactively push for policy change that creates a level playing field and unlocks the reductions and removals required to achieve net-zero.

Annex

This table summarizes qualitative assessments of the status of eight groups of carbon removal techniques across a range of criteria. The carbon removal market is nascent and assessments shown here, including costs, are necessarily indicative and may change as the market matures. Assessment of the strengths and weaknesses of each family of carbon removal techniques can be found here and in the CDR Primer.

Removal pathway	Risk of non-additionality/ inflated baseline	Risk of indirect carbon leakage	Risk of physical reversal	Cost of removal credit ($/t$CO_2$) and availability	Other considerations
Forestation	**Moderate to high** For otherwise disused or unforested land, risk of non-additionality can be low, but for many forests this remains an important concern with carbon-credit integrity. Quality of projects is highly heterogeneous and site-specific	**High** Land conversion pressures for agricultural and industrial uses are high; use of land to remove and store carbon in one area may lead to increased conversion elsewhere to meet constant or rising demand for food and fibre products	**Moderate to high** Reversal risk from physical (fire, disease, weather), economic (illegal harvest) and political pressures/ disturbances can be high	**$25–$30** Costs reflects high-quality projects in countries with strong regulatory frameworks Supply is moderate, but has large potential to scale	– Mature and ready for scale-up – Cost-effective, at-scale MRV and understanding of non-CO_2 fluxes represent some unresolved uncertainties – Can provide large non-carbon co-benefits, including ecosystem restoration and habitat value – Afforestation can be controversial due to potential for negative ecological or human impacts. Reforestation is less controversial – Credits must be generated on an ex-post basis (sequestration already complete) – Competes with other land use for food and fibre production
Soil sequestration	**High** Yield increases from regenerative agricultural practices undermine the financial additionality of soil carbon credits Accurate and scalable soil carbon measurement is still nascent	**Variable** Yield increases (decreases) at the project site relieve (increase) pressure on other farmland to produce, potentially freeing up (requiring more) land and generating a carbon benefit (cost)	**High** Research to determine long-term resistance of soil carbon to rerelease is ongoing Changed farming practices must be maintained to retain carbon, e.g. through long-term land ownership or easements	**$0–$50** Costs can be negative when the associated new agricultural practices lead to sustained yield improvements, potentially sabotaging financial additionality Supply is moderate, but has large potential to scale	– Potential for strong non-carbon co-benefits including yield increases (which may undermine additionality) and habitat value – Validation of permanence and efficacy still ongoing – Scalable measurement and verification techniques still in development and evaluation
Blue carbon	**Moderate** Risk of non-additionality can be low where increased rates of carbon capture and removal by coastal ecosystems are unlikely to occur without deep human intervention. However, attributing subsequent removals to anthropogenic action may prove difficult. Baseline measurement is an area of ongoing research	**Low** Most candidate coastal ecosystems are not used for other substantive economic production, limiting the risk of economic indirect carbon leakage Some impacts on carbon fluxes outside of the project area may occur and must be constrained or corrected for	**High** Research to determine long-term resistance of coastal carbon stores to reversal is ongoing. Susceptibility to changes in sea level, temperature and other impacts of climate change itself may be high Changed coastal management practices must be sustained to retain stored carbon	**Uncertain** Cost estimates highly uncertain, vary widely based on region and technique. Blue carbon monitoring costs may initially be in the order of $100/tCO2, but may plateau considerably lower ($10–50) with experience Pathways are nascent, availability is low	– Often requires government involvement and financing, given coastal legal regimes – The very early stage of this set of proposed carbon removal pathways means that initial support for R&D is still highly impactful, whereas commercial investments may still be high-risk
Other ocean CDR methods	**Low** Large gap between cost of activity and current carbon prices makes additionality easier to ensure	**Low** In deep ocean contexts, few economic interactions reduce the likelihood of indirect carbon leakage	**Low to moderate** R&D ongoing, but strong potential for ultra-long duration storage in ocean sediments or deep ocean water, which is isolated from the surface carbon cycle by thousands of years	**Uncertain** Cost highly uncertain, set to drop with scale of deployment Very low supply, R&D stage	– Materials use and sourcing could be controversial – Marine life impacts must be better understood and constrained – Public acceptability concerns

Annex *(continued)*

Removal pathway	Risk of non-additionality/ inflated baseline	Risk of indirect carbon leakage	Risk of physical reversal	Cost of removal credit (\$/tCO_2) and availability	Other considerations
Biochar	**Moderate** For pureplay biochar production, costs still substantively exceed carbon prices, making additionality easier to ensure. However, when used as a soil amendment, financial additionality may be compromised	**Moderate** Highly dependent on feedstock: for virgin biomass, same indirect leakage concerns as for forestation. For waste biomass, indirect effects on other carbon fluxes may exist but are likely to be less pronounced	**Moderate** Longer-term studies still needed to confirm duration of stable storage in soils. Depending on the quality, type and use of biochar, storage could be for tens, hundreds or potentially thousands of years	**\$30–\$120** Technology is mature, but commercial deployment is immature. Lower costs may be achievable through use of unused waste biomass Low but rapidly growing supply	– Biochar made from waste biomass feedstock will be less controversial, and potentially deliver a higher-quality carbon credit than virgin feedstock – Accurate life-cycle accounting from biomass growth to pyrolysis to use/application is critical – Biochar production method, quality and longevity vary widely, differentiated certification required
Other biomass carbon removal and storage (BiCRS) Includes bioenergy with carbon capture and storage (BECCS)	**Moderate** High costs mean additionality is easier to ensure Ensuring a solid baseline and carbon benefit requires accurate and complete life-cycle emissions for source biomass	**Moderate** Pressures on land for agricultural production and other uses are high; must correct for the degree to which use of land to produce biomass increases emissions elsewhere. Use of waste feedstocks may help avert indirect leakage	**Very low** When carbon is stored geologically on multi-thousand-year timescales **Moderate** When carbon is used or stored in a location with higher reversal risk, such as the built environment or in long-lived products	**\$50–\$100** Cost set to drop with scale of deployment Low supply	– Uncertain scalability due to land-use pressures and limited biomass capacity – Fate of carbon is important: short-duration storage in some products eliminates much of the climate impact – Accounting for biomass life-cycle emissions is challenging
Accelerated weathering and mineralization	**Very low** Large gap between cost of activity and current carbon prices makes additionality easier to ensure	**Very, varies** Land-use requirements minimal for most pathways. Materials used (e.g. silicate/ carbonate minerals) are abundant and unlikely to cause knock-on economic effects in medium term	**Very low** Carbon is stored in geologically stable forms on multi-thousand-year timescales or permanently contributes to ocean alkalinity	**~\$20–\$1,000** Price highly uncertain and dependent on specific application, set to drop with scale of deployment Very low supply	– For ocean-enhanced weathering, concerns over marine ecosystem impacts from dissolved trace metals are unresolved – For terrestrial applications, broader ecosystem effects from scaled activity may require further research to constrain them – New technologies are enabling the storage of removed, mineralized carbon in useful products (e.g. building materials)
Direct air capture with carbon storage (DACCS)	**Low** Large gap between cost of activity and current carbon prices makes additionality easier to ensure	**Low to moderate** Increased costs of DAC-enabled products may shift consumption patterns. High energy use could have knock-on effects on energy consumption patterns and prices with at-scale deployment	**Very low** When carbon is stored geologically on multi-thousand-year timescales **Moderate** When carbon is used or stored in a location with higher reversal risk, such as the built environment or in long-lived products	**~\$350–\$700** Prices set to drop with scale of deployment, targeting \$100–\$200 Low supply	– Very high energy requirement, life-cycle analysis needed to calculate the net carbon benefit – Two technologies are ready for scale, others in early development

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Endnotes

1. Intergovernmental Panel on Climate Change (IPCC), Special Report: Global Warming of 1.5°C – Summary for Policymakers, 2018, https://www.ipcc.ch/sr15/chapter/spm/.
2. Fuss et al., Negative Emissions – Part 2: Costs, Potentials and Side Effects, Environmental Research Letters, vol. 13, no. 6, p. 063002, June 2018, doi: 10.1088/1748-9326/aabf9f.
3. Davis et al., Net-Zero Emissions Energy Systems, Science, vol. 360, no. 6396, p. eaas9793, June 2018, doi:10.1126/science.aas9793.
4. Estimates indicate the biosphere (vegetation and soils) has enough "headroom" to store one to two decades' of emissions at today's rates. The geosphere (subsurface storage and remineralization) has a much larger capacity in principle, decades to centuries of today's emissions, albeit at higher upfront cost (the cost of keeping carbon stored in a stock is also a function of the durability of that storage, or its resistance to being rereleased to the atmosphere, which is very low for geosphere storage).
5. Estimates of the maximum rate of uptake by nature-based solutions vary. Reforestation, for example, may be able to provide 3–18 $GtCO_2$/yr of removals over several decades until the available land becomes "saturated" and cannot store more carbon. Total additional "headroom" in the global forest carbon stock is highly uncertain, due to unknown potential reforestation extent (345–1,779 Mha) and sensitivity to assumptions about future agricultural production; Griscom et al., Natural Climate Solutions, 2017, https://www.pnas.org/content/114/44/11645.
6. Girardin et al., 2021, Nature-Based Solutions Can Help Cool the Planet – If We Act Now, Nature, vol. 593, no. 7858, pp. 191–194, doi:10.1038/d41586-021-01241-2.
7. For clarity, "direct air capture" in this brief refers to direct air capture with carbon storage (DACCS), a family of technologies that extract CO_2 from ambient air, and typically compress the captured CO_2 to later be placed into permanent geological storage. CO_2 captured directly from air (DAC) may be transported and stored using the same infrastructure that is coupled with conventional carbon capture and storage (CCS) equipped to industrial point source emitters, as is contemplated, for example, with Norway's "open-source" offshore CO_2 storage system. Despite this potential for shared infrastructure, this brief does not discuss or address conventional CCS, which brings a host of more complex considerations and issues, and which is, with some exceptions, primarily an emissions reduction measure that does not constitute carbon removal.
8. Carbon can be injected into geological formations rapidly, but the ongoing mineralization of that stored carbon into the surrounding rock takes time. The risk of physical reversal must be monitored at the point of storage, but it declines over time as more of the carbon becomes fully chemically immobilized.
9. Cox et al., 2020 Public Perceptions of Carbon Dioxide Removal in the United States and the United Kingdom, Nature Climate Change, vol. 10, pp. 744–749, 2020, https://www.nature.com/articles/s41558-020-0823-z.
10. Friedlingstein et al., Global Carbon Budget 2019, Earth System Science Data, vol. 11, no. 4, pp. 1783–1838, 2019, https://essd.copernicus.org/articles/11/1783/2019/.
11. Ambitious maximum attainable rates of mitigation using natural climate solutions are in the order of 10–20 $GtCO_2$/yr by mid-century (2 $GtCO_2$/yr by 2030 if scale-up is rapid); Griscom et al., Natural Climate Solutions, 2017, https://www.pnas.org/content/114/44/11645. Estimates of cumulative additional emissions from typically under-represented Earth system feedbacks, dominated by CO_2 and methane release from melting tundra and drying wetlands, range from 0 to 500 $GtCO_2$ by 2100, even under a scenario in which warming is limited to 2°C (up to 350 $GtCO_2$ under a 1.5°C scenario; Lowe & Bernie, The Impact of Earth System Feedbacks on Carbon Budgets and Climate Response, Philosophical Transactions of the Royal Society, 2018, https://royalsocietypublishing.org/doi/10.1098/rsta.2017.0263. Hence the rate of carbon release by the biosphere may exceed 10 $GtCO_2$ per year by 2100 through the impact of global warming alone, even under ambitious mitigation scenarios, with higher rates if mitigation efforts fail.
12. Microsoft has committed to remove all carbon it has emitted to the atmosphere since inception in 1975. See Microsoft, Microsoft Will be Carbon Negative by 2030, 16 January 2020, https://blogs.microsoft.com/blog/2020/01/16/microsoft-will-be-carbon-negative-by-2030/.
13. See initiatives by Klarna, Klarna Partners with Milkywire for Their Sustainability Initiative Give One, 23 April 2021, https://news.cision.com/milkywire/r/klarna-partners-with-milkywire-for-their-sustainability-initiative-give-one,c3332304; Shopify, Shopify's Sustainability Fund, https://www.shopify.ca/about/environment/sustainability-fund?itcat=sustainability-fund&itterm=inter-environment; Stripe, Remove Carbon as You Grow Your Business, https://stripe.com/en-gb/climate, and others.
14. See recent analyses from Carbon Plan, Insights from Analyzing a New Round of Carbon Removal Projects, 17 March 2021, https://carbonplan.org/research/microsoft-2021-insights; and Carbon Direct, Carbon Direct Commentary: Release of the Voluntary Registry Offsets Database, April 2021, https://carbon-direct.com/wp-content/uploads/2021/04/CD-Commentary-on-Voluntary-Registry-Offsets-Database_April-2021.pdf.

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