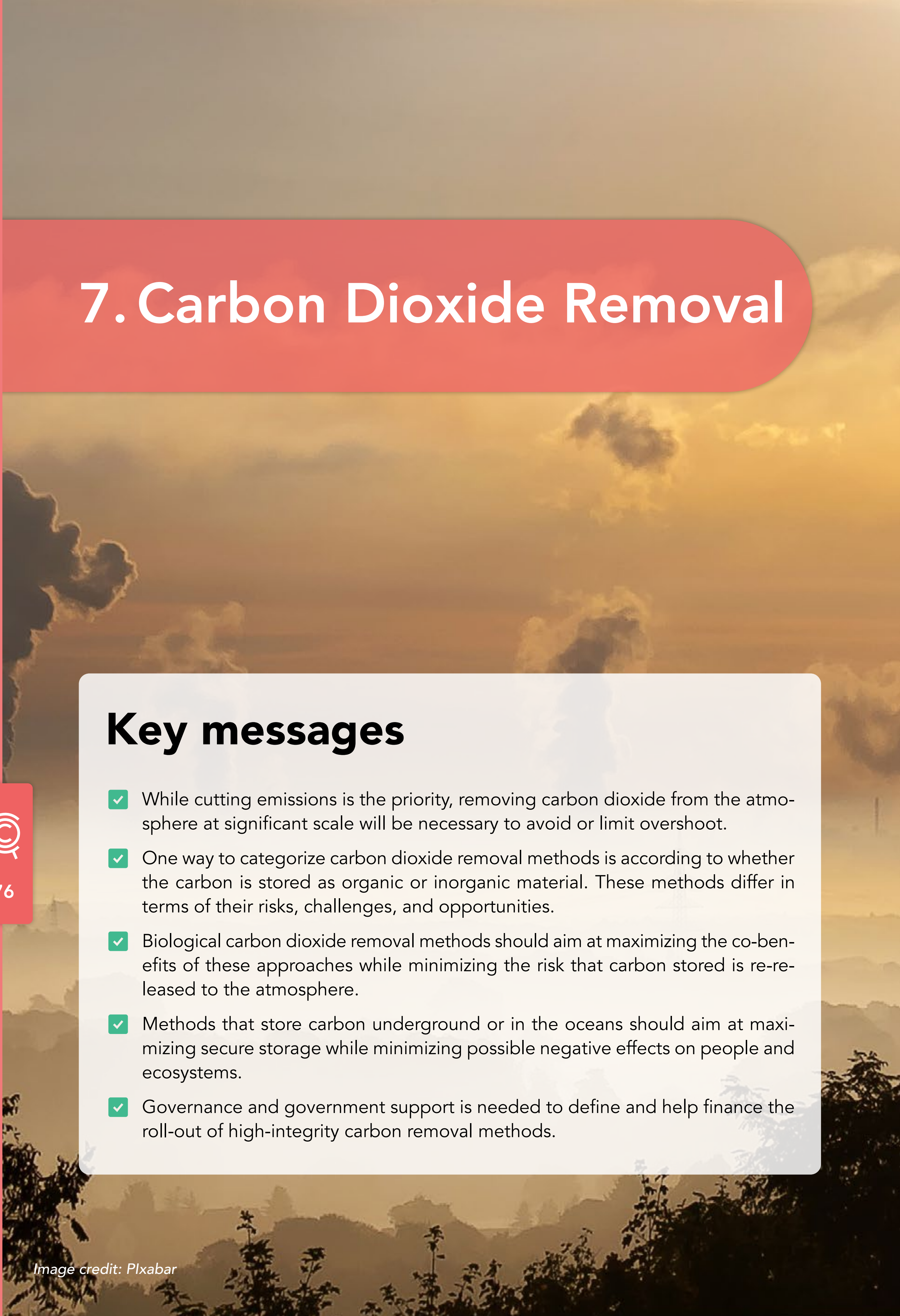
CLIMATE OVERSHOOT COMMISSION

REDUCING THE RISKS OF CLIMATE OVERSHOOT

Emerging Approaches

04

SEPTEMBER 2023



7. Carbon Dioxide Removal

Key messages

- While cutting emissions is the priority, removing carbon dioxide from the atmosphere at significant scale will be necessary to avoid or limit overshoot.
- One way to categorize carbon dioxide removal methods is according to whether the carbon is stored as organic or inorganic material. These methods differ in terms of their risks, challenges, and opportunities.
- Biological carbon dioxide removal methods should aim at maximizing the co-benefits of these approaches while minimizing the risk that carbon stored is re-released to the atmosphere.
- Methods that store carbon underground or in the oceans should aim at maximizing secure storage while minimizing possible negative effects on people and ecosystems.
- Governance and government support is needed to define and help finance the roll-out of high-integrity carbon removal methods.

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Background

While cutting emissions by replacing fossil fuels with cleaner energy sources must be the primary strategy to tackle climate change, the problem remains of accumulated carbon emissions already in the atmosphere.

Unless we remove these stocks of CO_2, the best we can do is stop additional global warming beyond whatever heating has been caused by prior emissions. If we exceed average global warming of 1.5°C, then CDR will be required to bring temperatures back down.

In addition, since emissions will not drop to zero immediately, CDR is needed to slow the growth of atmospheric concentrations of CO_2 during the transition.

CDR poses many challenges – as well as potential opportunities. The first set concerns the uncertainty, costs and trade-offs surrounding the various approaches proposed to remove and store atmospheric CO_2, some of which remain immature or untested. The Climate Overshoot Commission's Youth Engagement Group wrote that "we should not assume without evidence that CDR technologies and methods have carbon removal potential on the scale required to make a significant difference to global warming." The Commission agrees that decision-makers must be aware of and cautious regarding assumptions of future technological developments.

The second major challenge is to build governance mechanisms that promote high-integrity carbon removal that is equitable and just, provides broadly shared economic dividends, and in no way undermines or detracts from the primary goal of phasing out fossil fuels. CDR cannot be used as an alternative to emissions cuts and cannot be relied on alone to avoid overshoot.

A third set of challenges concern who should pay for and finance carbon removal, and who should benefit from the opportunities it could offer. Most IPCC emissions pathways that limit warming to 1.5°C or even 2°C assume scaling up carbon removal to the size of today's fossil fuel industry in the span of a few decades, and with mostly public funding.

Such an expansion would entail one of the more ambitious collective public endeavours in human history, and it is far from clear how it would be paid for. Currently, international carbon markets are neither extensive nor well-controlled enough to provide the necessary incentives. They will require substantial changes, including linking compliance markets and regulating voluntary markets more effectively.

Governments, private businesses and civil society are all struggling with these questions right now, even as the carbon removal sector shows signs of rapid acceleration, and the conclusions they reach will likely have consequences for decades.

The Commission cannot provide answers to all these questions – including the economic challenges and opportunities of scaling up CDR. Rather, it aims to lay out certain key principles that can guide others as they craft policy and allocate resources.

In particular, the Commission focused on the governance gaps remaining to ensure safe and equitable scale-up of CDR, the issue of who should pay, and the need to promote a variety of approaches.

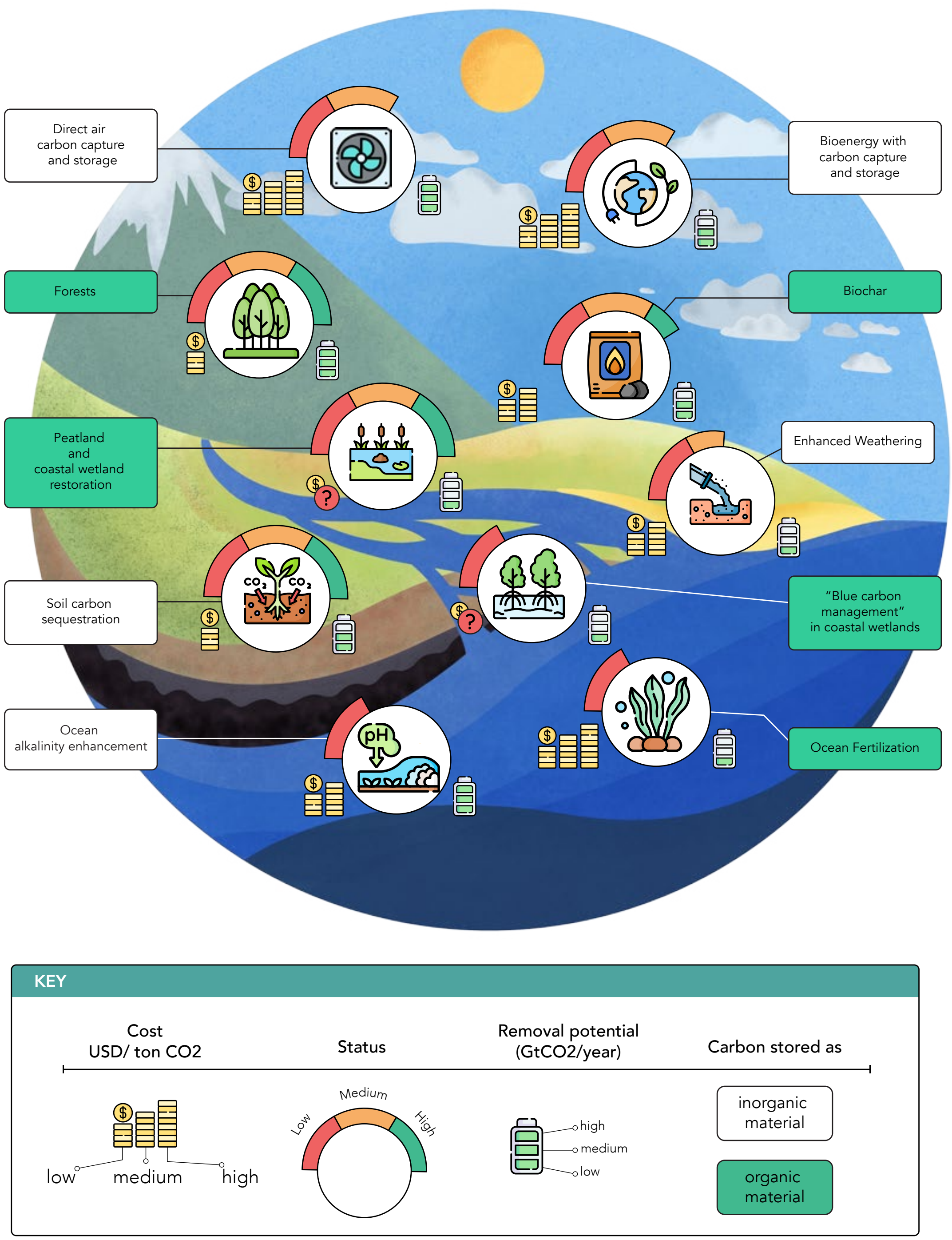
Technical characteristics

CDR refers to a set of technologies and practices that remove CO_2 from the atmosphere and store it for periods ranging from years to millennia. CDR is not the same as CCS, which aims to capture carbon pollution at point sources (such as power plants) to *avoid CO_2 emissions*, rather than *remove CO_2 from the ambient air*.

CDR could be used to remove excess atmospheric CO_2 at a faster rate than would naturally occur, but significantly reducing atmospheric CO_2 concentrations and associated climate risks will require CDR at large scale and means to store CO_2 securely and reliably. The IPCC has concluded that CDR is an "essential element" of net emissions scenarios that would likely limit warming to 1.5°C or below 2°C.[68] CDR would also allow for offsetting hard-to-abate emissions from activities like steel production and rice cultivation (although innovation could change what qualifies as "hard-to-abate" over time). Carbon removal is slow to act, and the types of CDR with the largest potential are more expensive than most emissions cuts. Risks associated with CDR tend to be local in nature but vary according to method.

One way to categorize CDR methods is according to whether the carbon is stored as organic or inorganic material. (See Figure 6.) Biological CDR techniques that store organic carbon rely on the uptake of CO_2 by plants to remove carbon from the atmosphere and store it in materials such as wood, soils, and marine sediments. Some of these methods involve intensive agro-industrial processes such as biochar or no-till farming. Methods that restore degraded environments such as ecosystem restoration, reforestation, no-till farming, and enhancement of wetlands, if implemented properly, offer ecological benefits and improvements in agricultural productivity that are separate from and additional to carbon removal.[70] Methods based on organic carbon storage are relatively mature and can be implemented today. An example is Africa's Great Green Wall. (See Box 2.) Biological CDR methods have much in common and substantially overlap with nature-based solutions. (See Box 3.)

FIGURE 6 Carbon dioxide removal methods.[69]



Box 2: The Great Green Wall

The Great Green Wall of Africa is an ambitious, large-scale land restoration project spanning 7,000 kilometres from Senegal to Djibouti. The African Union initiated the project in 2007 to combat the drought and desertification that affects around 45% of the continent's land area by restoring degraded land and planting trees and other vegetation. However, the project will also make a significant contribution to tackling climate change, aiming to capture 250 million tonnes of CO2 as well as preserve biodiversity, enhance food security, and bolster resilience.

The Great Green Wall project seeks to rehabilitate 1 million square kilometres by 2030, which is expected to create 10 million jobs. To date, 11 countries have contributed to its progress, rehabilitating 40,000 square kilometres. A broader group of 21 African countries is committed to achieving its goals.

Financing is essential. Governments need to secure 4 billion USD annually for the next decade to make this vision a reality. Ultimate success will require not only significant financial resources but also improved regional coordination among governments and subnational communities; attention to potential synergies and trade-offs; and an adaptive, integrative management approach.

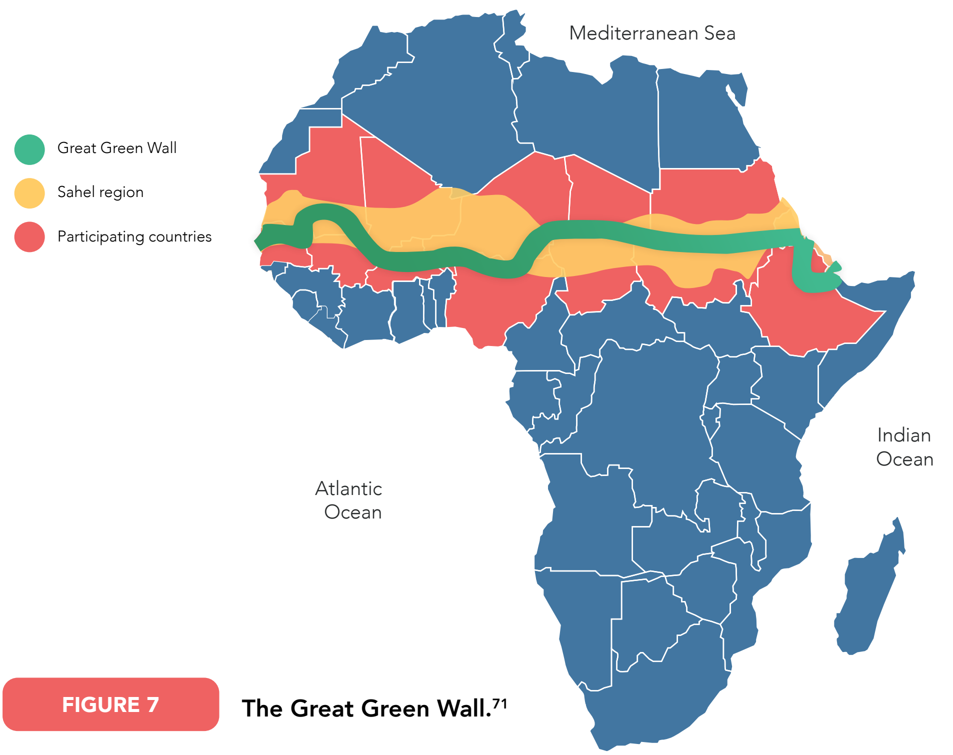


FIGURE 7 **The Great Green Wall.**[71]

Box 3: Nature-based solutions

Nature-based solutions (NBS) focus on how protecting and restoring natural environments can generate societal benefits including sustainable development, climate action, strengthened agriculture, and biodiversity conservation. Recently, the UN Environment Assembly (UNEA) formally defined NBS as "actions to protect, conserve, restore, sustainably use and manage natural or modified terrestrial, freshwater, coastal and marine ecosystems which address social, economic and environmental challenges effectively and adaptively, while simultaneously providing human well-being, ecosystem services, resilience and biodiversity benefits."[72]

A distinctive feature of NBS is that they can be designed to address multiple challenges, including multiple aspects of climate change.[73] Some climate-relevant NBS address adaptation by bolstering resilience against climate impacts; these are often referred to as ecosystem-based adaptation measures. Some climate NBS remove CO2 from the atmosphere. Some do both. Because NBS perform multiple functions, they may be subject to competing uses.

NBS are widely supported, such as through the Montreal-Kunming Global Biodiversity Framework of the UN Convention on Biological Diversity, which calls for mobilizing 700 billion USD per year by 2030 from public and private sources, domestic and international, for biodiversity finance, including for NBS. Other initiatives such as the Positive Conservation Partnerships, launched at COP27 in Sharm El Sheikh, compensate countries that agree to protect critical carbon sinks.

NBS are also vulnerable to climate change, however, precisely because they are nature-based. Unless accompanied by deep and rapid emissions cuts and pursued within a general framework of ecosystem restoration and protection, NBS will be under the same threats of ecosystem disturbance, degradation, and species loss as the rest of nature. The level of vulnerability will vary according to type of NBS, local climate, and management approach.

Climate change thus imposes limits to adaptation provided by NBS and exacerbates the risk that carbon stored by NBS is re-released to the atmosphere. This risk can be mitigated through policy measures, for example, requiring buffer accounts with credits set aside for surrender in the event of reversal, clarifying liability in the event of reversals, or aggregating multiple NBS projects.

To minimize confusion, the Commission refrains from using the term NBS elsewhere in this report and instead refer to biological CDR methods, nature-based adaptation measures, or actions that perform both functions.

A variety of methods can store carbon in inorganic forms. Bioenergy with carbon capture and storage (BECCS) is a hybrid method that uses biomass to remove carbon from the air but then stores it as CO_2 underground. Direct air carbon capture and storage (DACCS) is an industrial process that captures CO_2 directly from the atmosphere and stores it underground. DACCS is currently a costly method with few co-benefits. However, its costs should decline over time through innovation and learning-by-doing and if economies of scale can be achieved. DACCS facilities can be sited close to both underground storage and renewable energy resources. Both BECCS and DACCS facilities inject compressed CO_2 underground using methods developed for CCS from industrial processes. In its more optimistic scenarios, the IPCC assumes several hundred billion tonnes of CDR could be stored via these two methods through 2100.[74]

Enhanced weathering adds ground minerals to soils where natural processes weather the material, releasing alkaline minerals that run off to the ocean. Ocean alkalinity enhancement would directly add alkaline minerals to the ocean. Both enhanced weathering and ocean alkalinity enhancement aim to accelerate the natural but slow weathering reactions that remove CO_2 from the air and store it as dissolved carbonates in the ocean. Inorganic CDR methods are relatively immature; implementing them at large scale requires investing in research, development, and demonstration now.

Methods that store carbon by injecting it underground generally offer the highest confidence in the quantity of long-term storage. For methods based on increasing ocean alkalinity, carbon storage is secure but challenging to accurately quantify.[75] Methods that store organic carbon on land are relatively simple to quantify in the short term but less certain in the long term because some fraction of the organic carbon is likely to be released back to the atmosphere as a result of wildfires, droughts, or changes in land management.[76] Inorganic methods are also generally more expensive than methods that store organic carbon in ecosystems as well as many existing emissions reduction options with potential for rapid, large-scale expansion.[77] Lastly, they are less developed than biological methods and require more innovation.

Methods vary in associated benefits or risks. The protection and restoration of degraded ecosystems using biological CDR methods will generally offer carbon storage with the largest ecological co-benefits – such as biodiversity conservation, water regulation, and climate resilience – provided that governance systems require such multiple benefits. (Programs and policies often promote biological CDR methods for these reasons.) Enhanced weathering may improve soils and agricultural productivity, and both enhanced weathering and ocean alkalinity enhancement counter ocean acidification. Finally, BECCS would displace fossil fuels but also require biomass harvesting that is often harmful (involving land competition, fertilizer use, water scarcity, and biodiversity loss), whereas DACCS offers no environmental co-benefits and requires significant amounts of energy.

Finally, CDR methods vary in the relative importance to them of ecosystems and industrial processes. At one extreme, natural ecosystems play central roles in biological CDR methods such as reforestation and wetlands restoration, whereas at the other extreme DACCS is wholly industrial. Most methods require some combination of industrial and ecological processes.

Governance challenges

CDR will be costly. Governments will need to either purchase or implement CDR themselves or incentivize or require other actors to do so. Governments can motivate carbon removal using:

- tax credits (as for example in the US Inflation Reduction Act),
- feed-in tariffs,
- contracts for difference (based on a mutually agreed "strike price"),
- results-based payments (for biological CDR, for example),
- carbon takeback obligations requiring fossil fuel companies to remove and store a steadily increasing proportion of the carbon generated by the products they sell, or
- modifications to emissions trading schemes.

Current policies on CDR are limited. The original text of the UNFCCC endorsed carbon removal by "sinks" and storage in "reservoirs," and the Paris Agreement calls for achieving a balance between emissions reductions and removals by sinks in the second half of this century.[78] The Agreement's Article 6.4 Mechanism may eventually issue credits for CDR activities, although moving in this direction has been contentious.[79] The EU is currently considering a CDR Certification Framework that could allow for the integration of removal credits into the EU Emissions Trading System.[80] The US is supporting CDR through funding for research and development, tax credits, grants, and loans.[81] In the absence of dedicated policy, the development of CDR is substantially influenced by intellectual property regimes, raising concerns about access and equity.

Governments will need to undertake five tasks to promote CDR.

- **First**, they should ensure a reliable system for measuring and verifying removals is in place.
- **Second**, they should provide for robust accounting frameworks.
- **Third**, they should safeguard the permanence of CO_2 storage on an unprecedented centuries-long timeframe by, for example, requiring buffer accounts, clarifying liability, or aggregating projects.
- **Fourth**, governments will need to mitigate other risks (such as those associated with biomass harvesting) while encouraging co-benefits, which can be especially large with some biological CDR methods.
- **Finally**, governments will need to prevent cheap removals from weakening incentives for cuts in emissions, by making clear that emissions cuts and removals are not substitutable; for example, by establishing separate targets for CDR and emissions cuts.

At the global level, the enormous costs entailed in using CDR to achieve net-zero emissions, especially methods that store carbon in inorganic form, raise serious concerns about how to ensure an equitable distribution of burdens. Cost-sharing could be guided by the principle that those who cause harm have a duty to remedy it. This could be operationalized by distributing costs across countries based on past and ongoing emissions, wealth, and/or population, for example, or assigning costs to "carbon majors" based on contributions to cumulative emissions.

Recommendations

The Commission recommends the following initiatives relevant to CDR.

01 **First, governments should promote rapid expansion of higher quality CDR featuring co-benefits and permanent storage, at scale and speed sufficient to materially reduce mid-century climate risks and contribute to keeping any overshoot as small and short as possible.**[82] Governments may reasonably choose different portfolios of higher quality CDR featuring different mixes of methods. The approach to biological CDR should aim at maximizing the co-benefits of these approaches while minimizing the risk that carbon stored is re-released to the atmosphere. Some amount of CDR that stores carbon as inorganic material will be necessary, since reducing climate risks and limiting overshoot will require secure and reliable storage.

02 **Second, large-scale CDR will depend on government action, so governments should undertake, require, or incentivize CDR innovation and expansion.** Government policies and programs – including but not limited to carbon markets – should promote research, development, assessment, and rapid scaling of higher-quality CDR. Government initiatives should aim to drive down costs and should provide for robust accounting frameworks and measurement and verification protocols; methodologies should be stringent to prevent greenwashing.

Policies and programs should be designed to safeguard permanence, promote co-benefits, and manage risks of CDR methods while considering specific environmental and socioeconomic contexts. In view of variability in permanence, co-benefits, and risks, policies should *not* treat carbon removals as substitutable for feasible emissions reductions and should potentially establish a proportion between the two or separate targets reflecting their qualitative difference. This separation is essential to ensure that CDR does not displace emissions cuts.


Image credit: Climeworks

03 **Third, in the short to medium term, international cooperative efforts to finance CDR implementation globally should be pursued.** One approach could be through "internationally transferred mitigation outcomes" (ITMOs) as provided for under Article 6.2 of the Paris Agreement. ITMOs would allow bilateral or multilateral transfers of carbon removals among countries.[83] Other approaches, perhaps linked to ITMOs, could develop and expand mechanisms aimed at mobilizing funding to restore carbon sinks, including through results-based payments for carbon removals.

04 **Fourth, countries should follow the principle that those who cause harm have a duty to remedy it as the global basis for apportioning the costs of large-scale CDR, including for carbon take-back obligations.** The polluters identified as responsible for funding large-scale CDR could be countries, enterprises, or some combination of these.

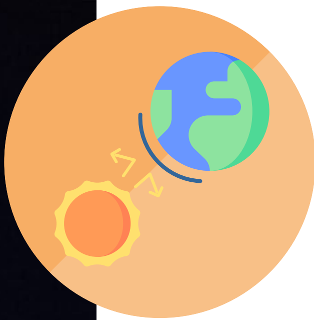
05 **Fifth, given present uncertainties about CDR methods and consequences, policies to promote rapid expansion of higher-quality CDR should be subject to periodic assessment and updating.** Possible areas for assessment include costs, risks, scalability, timing, and policy performance.

8. Solar Radiation Modification

Key messages

- Solar radiation modification is a controversial proposal for reducing global temperatures by reflecting a small portion of incoming sunlight.
- Such methods could reduce the risks of global warming but could also introduce significant new risks.
- Scientific research is in its early stages and is far from supporting informed decision-making about their use or non-use. More research is needed, including in developing countries, to help determine whether to proceed with this technology and if so how.
- Governance discussions about SRM are in their infancy. Inclusive international dialogues should be initiated as soon as possible.
- The present lack of governance poses its own risks, including the possibility of premature deployment. Therefore, countries should adopt a moratorium on the deployment of solar radiation modification and large-scale outdoor experiments that would carry risk of significant transboundary harm, while expanding research, and pursuing international governance dialogues.

Image credit: ActionVance, Unsplash



Background

The Climate Overshoot Commission's ideal outcome would be that the world rallies around massively accelerated emissions cuts to net zero, enhanced adaptation activities, and scaled-up CDR, all in a manner that supports justice and sustainable development. Growing risks, however, have prompted some scientists to explore a controversial, additional potential set of responses to climate risk, which entail reflecting a small portion of incoming sunlight back into space.

These ideas are variously known as solar radiation modification or management (SRM), solar geoengineering, or climate intervention. They are for the most part theoretical, contain many uncertainties, and are highly controversial.

SRM is drawing increasing attention. Recently, UNEP released a scientific review,[84] the European Commission expressed support for an international scientific assessment and dialogues on governance,[85] and the US identified initial steps toward a research plan and governance.[86] The UN Educational, Scientific and Cultural Organization and the UN Human Rights Council will soon release reports that address it.

The Commission approached SRM with the greatest of caution. It did not deliberate on recommendations concerning its use, but only on recommendations concerning its research and the governance of *possible* future deployment. The Commission is particularly mindful to avoid any suggestion that SRM could offer an alternative to other forms of climate action, and to oppose premature deployment.

At the same time, the Commission found there would also be risks in *not* learning more about the risks and challenges of SRM, or about its potential benefits in a climate-stressed world.

Initial research results, though limited, suggest that SRM might have effects that would reduce the risks from overshoot, should other actions fail to achieve desired results.[87] However, this is only a minimal threshold assessment, suggesting no more than that the subject should not be ignored. The reason is that SRM use would also introduce significant new risks of its own.

The Commission considered the effects of two forms of SRM: stratospheric aerosol injection (SAI) and marine cloud brightening (MCB). Other approaches have also been proposed. The Commission concentrated on SAI as it is the most researched SRM method.

A lack of scientific understanding and of governance increases the possibility of premature and ill-considered deployment of these technologies, which would fail to take sufficient account of the needs of different countries and communities around the world and the risks that SRM might pose. At the same time, premature rejection of these ideas could also deny countries a potentially powerful tool to reduce risk and lower suffering.

To be clear: the Commission believes that SRM is not an approach that should be relied on or cited in any form as a reason to slow the urgent acceleration of emission cuts. At the same time, the Commission rejects going too far the other way: that SRM should not be discussed at all, that research should be halted, or governance discussions put on ice.

In its consideration, the Commission also recognized that SRM requires meeting the challenge of a truly equitable global deliberation. Developing countries have been inadequately engaged in debates and research on SRM thus far. The Commission believes that they must be fully involved in research activities and political dialogues going forward.

Technical characteristics

SRM refers to a group of proposed technologies that would reflect a small fraction of incoming sunlight back to space – in most scenarios, 1-2 percent[88] – to partially offset climate change. Research has focused on two techniques. (See Figure 8.) SAI would entail increasing the number of tiny particles in the upper atmosphere to scatter sunlight and reduce temperatures. It is inspired by the observed effects of large volcanic eruptions that release sulphates causing global temperatures to decline for about a year. It appears that SAI would be relatively inexpensive, with annual direct costs for a global deployment estimated in the low tens of billions of dollars.[89]

MCB would involve spraying seawater from ships to increase the reflectivity of low-lying clouds. The amount of cooling that MCB could provide is highly uncertain. MCB may turn out to be more suitable as a local adaptation measure, for example, to cool coral reefs.[90] Less researched proposals include cirrus cloud thinning and space-based reflectors.

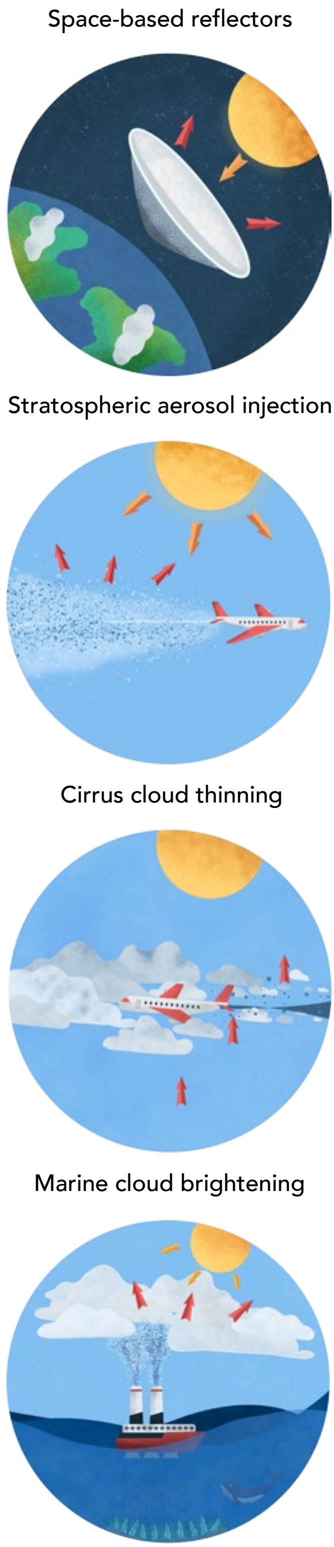
If it were used at large scale, SRM could reduce temperatures within a few years, and would have global effects.[91] To ever be responsible, any such scenario would need to be preceded by a decade-long research program and possibly a multi-decade phased testing period. The climate effects of using SRM would depend strongly on how the changes in reflection are distributed around the world. For a given average cooling, an uneven distribution would cause more climate harm, by shifting aspects of climate such as regional rainfall further away from their preindustrial level, than would an even distribution with the same average cooling[92].

Reflecting sunlight would not address the cause of global warming as it would not affect the levels of greenhouse gases in the atmosphere; it could not substitute for emissions cuts. SRM would not be capable of fully restoring previous climate conditions and could result in unwanted regional climate changes. Poorly planned deployments, for example, using SAI in only one hemisphere, might lower global temperatures overall but could exacerbate climate change in some regions. SRM would also involve environmental impacts such as delayed recovery of the ozone layer, health impacts from particulate matter, and increases in acid rain.[93] SRM would not address the increased ocean acidification caused by the elevated atmospheric CO_2 concentration.

In addition to physical risks, SRM would entail risks related to how it might be used.[94] Implementing, researching, or merely talking about SRM might weaken efforts to cut emissions. Separately, since the effects of SRM would be temporary unless the intervention were continuous or at least repeated, if a large SRM intervention were suddenly halted and not resumed while atmospheric greenhouse gas concentrations remained at unsafe levels, the planet would warm rapidly, producing a potentially very dangerous "termination shock." Finally, the low direct cost of SAI might encourage countries or, at least in principle, private actors to implement the technology unilaterally. Threatened or actual use of SRM could destabilize international politics and raise security concerns.[95] These are the leading reasons why SRM is controversial.

Despite these risks and concerns, the Commission believes it would be imprudent not to investigate or discuss SRM because present evidence suggests the possibility that it could complement other approaches to reducing climate harms in

FIGURE 8 **Solar radiation modification methods.**



ways these others alone cannot, especially in terms of speed – if and when research and testing provides confidence that deployment has acceptable risks.[96] Research to date has been limited, but according to a recent UNEP report, "Modelling studies have consistently shown that climate change (in terms of temperature and hydrological metrics) in nearly all regions is much smaller with a carefully designed SRM deployment than in a world with continued climate change and without an SRM deployment."[97]

Any assessment of the desirability of SRM would need to consider the anticipated costs, risks, uncertainties, and benefits of adding SRM to a world already experiencing climate change.[98] Decisions about SRM will thus inevitably involve difficult and complex risk-risk trade-offs.

Governance challenges

Currently, there is no legally binding governance mechanism dedicated to SRM. Preliminary discussions have taken place, for example, before UNEA in 2019, but have focused only on near-term issues of research and assessment, not concrete governance needs.[99] Yet the existence of governance arrangements for other controversial or novel technologies – such as genetically modified organisms, deep sea exploitation, or even those with stakes as enormous as nuclear, biological and chemical weapons – suggests that governance of SRM is possible, at least in principle.

The prospect of SRM ever being used would present serious governance challenges. Such challenges include reaching international agreement (especially difficult in a fractious geopolitical environment) on whether to use SRM and the scale of any intervention; guarding against the hazard that SRM might

Image credit: Jacek Ulinksi, Unsplash

undermine emissions cuts; establishing effective multilateral or other cooperative mechanisms to prevent unilateral deployment; building reliable management frameworks capable of lasting decades or even centuries under unpredictable geopolitical conditions, to protect against the risk of termination shock; compensating countries demonstrably harmed by SRM; and ensuring meaningful participation in decision-making by communities likely to be affected. Resolving such issues would be very challenging.

The types of governance arrangements noted above, while suggesting that governance is possible, are not perfect analogues for addressing the specific and unprecedented combination of governance challenges that SRM would pose. As such, none of them offers comprehensive guidance for governing SRM in the future. The novelty of SRM and its associated governance challenges, and its potential role in reducing impacts resulting from overshoot, underscore the urgent need to begin international consultations and systematic research on its potential use or non-use of SRM and possible means of governing it. The fact that the impacts of SRM deployment cannot be confined to just one country or region (any intervention large enough to affect the climate in one country or region would also affect climates elsewhere) makes global governance and rules all the more necessary.

The prospect of expanded SRM research also presents governance challenges, less dire but more immediate. SRM research currently under consideration by the scientific community would pose minimal physical risks[100] but may involve socio-political risks like undermining emissions cuts or lock-in. Striking the appropriate regulatory balance between investigation and precaution will be challenging. Additional risk assessment, transparency, and public engagement mechanisms may be necessary.

Recommendations

The Commission recommends the following initiatives pertaining to strengthened SRM governance, strengthened SRM research, and the interactions between them.

01 First, countries should adopt a moratorium on the deployment of SRM and large-scale outdoor experiments. The moratorium should apply to any intervention with risk of significant transboundary harm, regardless of where it occurs, who carries it out or is responsible for it, what form it takes, or for what purpose.[101] Interventions below that threshold should comply with countries' environmental regulatory regimes. (See the second recommendation below.) In view of the time and uncertainty involved in negotiating a formal, legally binding treaty, the moratorium should rapidly be adopted by individual states, particularly those that might plausibly be capable of conducting such SRM activities unilaterally.

Governments adopting the moratorium should also call for its adoption by others, coordinating their adoptions through applicable multilateral institutions such as UNEA. The moratorium should remain in effect until advances in scientific research have created a knowledge base strong enough to support informed decision-making on SRM and until an adequate governance framework exists, if these conditions do come about. Periodic reviews would help in assessing progress toward these goals.

02 Second, governance of SRM research should be expanded. With respect to outdoor experiments, the appropriate governance depends on their scale[102]. Governance of scientific activities should seek to strike a balance between the need to learn more about SRM and the need for precautionary management of physical risks. Following the principle of subsidiarity, most research currently envisioned can be adequately regulated at the national level using existing regulatory frameworks. Various areas of climate and environmental science regularly conduct field experiments that introduce small amounts of material into the air or water, which are governed by existing regulations and protocols[103]. These mechanisms may be adequate to govern SRM experiments similar to or smaller than these, without additional SRM-specific governance.

Any outdoor SRM experiments should take place only in jurisdictions with an effective environmental regulatory regime. Experiments of larger scale, even below the "significant transboundary harm" threshold of the recommended moratorium, will require additional governance mechanisms, in part to address concerns about potential indirect sociopolitical effects of expanded SRM research. The lower threshold at which additional governance specific to SRM is required could be linked to the scale of impact that triggers the jurisdiction's legal requirement to conduct environmental impact assessments. When triggered by the need for such an assessment, additional governance might include mechanisms to enhance transparency (such as public research registries) and to ensure public deliberation and consultation with potentially affected groups. If it appears that experiments pose particular or novel environmental risks, then a group of independent scientific experts should write guidelines and best practices for the activities. As outdoor experiments expand in scale, international coordination and harmonization may be warranted. Only legitimate, non-commercial researchers should be permitted to conduct outdoor experiments.[104]

The data, methods, and findings of SRM research should be transparent, including to international audiences. They should be accessible through mechanisms including disclosure of funding sources and open access to publications and data – including, where appropriate, raw experimental data and programming code. Formal research plans should be peer-reviewed and publicly accessible, and results should be independently reviewed.

SRM research should not be led by for-profit firms and should not be funded by sources with an interest in maintaining greenhouse gas emissions, such as fossil fuel interests. SRM research programs should include clear mileposts and exit ramps to reduce the likelihood of "slippery slopes" in which vested interests push for implementation. International research coordination as described above should support and clarify these principles of research governance.

03 **Third, in parallel with strengthening SRM governance, SRM research should also be strengthened; and the two should co-evolve.** Given the risks posed by overshoot and early evidence that some forms of SRM might substantially reduce them, more research on SRM should be conducted.

Critical needs include a better understanding of the effects of SRM on the climate system, greater knowledge of the environmental and societal impacts of SRM, and deeper insight into public views regarding the technology. SRM governance, including possible future global frameworks, should also be researched.

Expanded research, for instance through joint North-South research projects and research led by scientists in the South, should boost the participation and build the capacity of researchers from developing countries. Expanded research should encompass natural science, social science, and interdisciplinary work. Additional research on SRM would represent a tiny fraction of research on climate change: current SRM research funding worldwide is only in the tens of millions of dollars annually while global climate change research funding is in the billions of dollars.[105]

Crucially, given the broad impacts and need for SRM research to be perceived as unbiased and trustworthy, research funding should be transparent. Expanding research does not imply any decision on future use. Results may indicate specific approaches or conditions under which policymakers may judge it advisable to use or may show limitations or risks that suggest it should not be deployed.

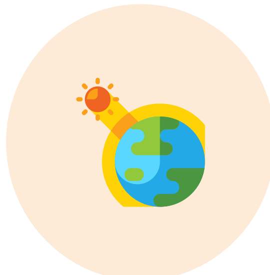
In addition, international coordination of SRM research based on shared priorities shaped by policymakers with equitable North-South representation should be significantly strengthened. Appropriate venues for setting SRM research priorities might include WMO and/or UNEP. Research coordination (including through aligned funding mechanisms) in pursuit of shared priorities might be carried out by the Global Research Council or the Future

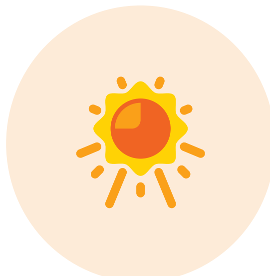
Earth program. International collaboration, involving researchers from different countries working jointly on shared projects, should also be pursued.

04 **Fourth, an international, independent scientific review and assessment of the best available evidence from SRM research should take place every few years.** Assessments should incorporate new research and respond to any gaps or limitations in knowledge identified in earlier assessments. Potential assessment bodies include the IPCC, WMO, and UNEP. (The last of these may be particularly appropriate due to its broader environmental remit.) An assessment of SRM should evaluate the potentials, limitations, and risks of the technology, in the context of the risks posed by elevated atmospheric greenhouse gas concentrations.

05 **Fifth, because the potential use of SRM raises multiple concerns, including novel and severe governance challenges, broad consultations and dialogues on these issues are needed.** The gravity of SRM-related concerns and their high stakes and global impact require that consultations involve a broad range of participants and forums worldwide, including governments, international organizations and a wide range of civil society organizations and other interested parties. Intergovernmental dialogues could take place in various settings, such as the UN General Assembly or UNEA, as well as informal and multi-party settings.

In view of the deep uncertainties about SRM and its governance, these consultations should not initially pursue formal legal or policy action but should instead aim to build shared knowledge and capacity, explore issues and potential responses, and build norms and trust. When issues have ripened enough that intergovernmental decisions about SRM governance are judged appropriate or necessary, these should be based on robust science and assessment, and broadly shared views about acceptable risk tradeoffs, precaution, and just and legitimate global decision-making.





Endnotes

68 IPCC AR6 WG3, p. 114.

69 Values for status, cost, and removal potential are from IPCC AR6 WG3, pp. 115-116.

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71 Based on United Nations Convention to Combat Desertification. 2022. "Africa's Great Green Wall: Close to 18 Million Hectares of Land Restored." https://www.un.org/africarenewal/web-features/africa-great-green-wall-close-18-million-hectares-land-restored-back-health.

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74 IPCC AR6 WG3, p. 25.

75 IPCC AR6 WG3, p. 1270-1271.

76 IPCC AR6 WG3, pp.107-110.

77 The failure to pay for cheaper emissions cuts today challenges any assumption that countries would be willing to pay for costlier CDR as an alternative in the future.

78 UNFCCC, art. 4.1(d); Paris Agreement, art. 4.1.

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80 European Commission. 2022. "Proposal for a Regulation of the European Parliament and of the Council Establishing a Union Certification Framework for Carbon Removals," COM(2022) 672 final.

81 US Office of Fossil Energy and Carbon Management. n.d. "Carbon Dioxide Removal" https://www.energy.gov/fecm/carbon-dioxide-removal.

82 There is no commonly accepted definition of "higher-quality CDR." The European Commission, however, is currently attempting to craft one in the context of its CDR Certification Framework development process, in which it has set forth the following "QU.A.L.ITY" criteria: QUantification, Additionality, Long-term storage, and sustainabi-ITY. European Commission. 2022.

83 Paris Agreement, art. 6.2.

84 UNEP. 2023. *One Atmosphere: An Independent Expert Review on Solar Radiation Modification Research and Deployment.* United Nations Environment Programme, Nairobi.

85 European Commission. 2023. *A New Outlook on the Climate and Security Nexus: Addressing the Impact of Climate Change and Environmental Degradation on Peace, Security and Defence.* JOIN(2023) 19 final, pp. 20, 22.

86 US Office of Science and Technology Policy. 2023. *Congressionally Mandated Research Plan and an Initial Research Governance: Framework Related to Solar Radiation Modification.* Office of Science and Technology Policy, Washington.

87 IPCC AR6 WG1, p. 629.

88 UNEP, 2023, p. 11.

89 UNEP, 2023, p. 12.

90 IPCC AR6 WG1 p. 628.

91 IPCC AR6 WG1 p. 625.

92 UNEP, 2023, p. 17.

93 IPCC AR6 WG3, p. 424.

94 IPCC AR6 WG3, p. 424.

95 IPCC AR6 WG3, p. 424.

96 Jebari, Joseph et al. 2021. "From Moral Hazard to Risk-Response Feedback." *Climate Risk Management* 33: 100324. DOI:10.1016/j.crm.2021.100324.

97 UNEP, 2023, p. 20. See also IPCC AR6 WG1, p. 629.

98 Felgenhauer, Tyler et al. 2022. *Solar Radiation Modification: A Risk-Risk Analysis.* Carnegie Climate Governance Initiative, New York.

99 IPCC AR6 WG3, pp. 1494-1495.

100 National Academies of Sciences, Engineering, and Medicine 2021 *Reflecting Sunlight: Recommendations for Solar Geoengineering Research and Research Governance.* The National Academies Press, Washington; UNEP 2023.

101 As established under customary international law, 'significant transboundary harm' encompasses harm to other states' environments and areas beyond national jurisdiction, which include the high seas, Antarctica, and outer space, regardless of where the activities take place. See Stockholm Declaration Principle 21 (1972), Rio Declaration on Environment and Development, Principle 2 (1992), and International Law Commission. 2001. "Draft Articles on Prevention of Transboundary Harm from Hazardous Activities, with Commentaries." In *Report of the International Law Commission on the Work of Its Fifty-Third Session*. UN Doc A/56/10, pp. 148-170. United Nations, New York. Also, refer to the ICJ decision, 'Legality of the use or threat of nuclear weapons,' (1996, Paragraph 29). This proposal is consistent with the customary international law of the prevention of transboundary harm and the 2010 decision of the Convention on Biological Diversity COP Convention on Biological Diversity COP. 2010. X/33. "Biodiversity and Climate Change." UNEP/CBD/COP/DEC/X/33.

102 SRM experiments proposed thus far are thousands to billions of times smaller than the smallest intervention that might have a minimally detectable climate effect. For example, proposed MCB experiments might spray 10-100 kg of sea salt into the lower marine atmosphere, while one SAI experiment proposed to introduce about 1 kg of material into the stratosphere. As a reference, a Pacific ship crossing introduces more than 20,000 kg and a typical intercontinental airline flight introduces 10's of kg of sulfur to the atmosphere. In contrast, model studies suggest that roughly 10 billion kg of sulfur would need to be injected into the stratosphere over 10 years to have a measurable impact on global average surface temperature.

103 Comparable experiments include Free-Air Carbon Dioxide Enrichment; Dispersion of Air Pollution and its Penetration into the Local Environment.

104 The parties to the London Convention and London Protocol developed an assessment framework for determining whether ocean fertilization activities are legitimate scientific research. International Maritime Organization. 2010. "Assessment Framework for Scientific Research

Involving Ocean Fertilization," *Report of the Thirty-Fifth Consultative Meeting and the Eighth Meeting of Contracting Parties*, LC 32/15, Annex 6.

105 The most recent published figures for SRM put its total research funding at 8 million USD in 2018. Necheles, Ella et al. 2018. "Funding for Solar Geoengineering from 2008 to 2018" Harvard's Solar Geoengineering Research Program. https://geoengineering.environment.harvard.edu/blog/funding-solar-geoengineering. Although there is no clear global summation, the US federal government spends about 5 billion USD annually on of climate change research, while the EU allocates about 6 billion USD to climate research and developments through its Horizon Europe program. US Global Change Research Program. n.d. "Budget." https://www.globalchange.gov/about/budget; European Commission. 2022. "EU to invest €13.5 billion in research and innovation for 2023-2024." (December 6) https://ec.europa.eu/commission/presscorner/detail/en/IP_22_7404. Philanthropies are allocating 6 to 10 billion USD to emissions reduction. Desanlis, Helene et al. 2022. *Funding Trends 2022: Climate Change Mitigation Philanthropy*. ClimateWorks, San Francisco.

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Image credit: USGS, Unsplash