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# Geoengineering: Assessing Risks in the Era of Planetary Security

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# Summary

The 1.5° Celsius global warming threshold that climate scientists have warned against for decades has been breached for several consecutive months over the last two years. This page-turning moment marks humanity's entry into climate overshoot. At the same time, a set of radical solutions known as geoengineering is increasingly presented as a potential emergency remedy to climate breakdown. Geoengineering technologies are intentional interventions in the Earth system that aim to lessen the impacts of climate change and even reverse increases in global temperatures. These technologies represent a significant shift in approach to both climate action and global security.

## Planetary Interventions with Long-Term Implications

Geoengineering encompasses two primary approaches: carbon dioxide removal (CDR) and solar radiation management (SRM). CDR methods aim to extract carbon dioxide ($CO_2$) from the atmosphere or the ocean, while SRM techniques seek to artificially cool the planet. Current CDR capacity is minimal, achieving approximately 2.2 billion metric tons of carbon dioxide ($GtCO_2$) per year. This is primarily through afforestation, although significant resources are now being directed toward increasing ocean-based sequestration and engineered systems, such as direct air capture. SRM proposals include controversial strategies, such as stratospheric aerosol injection, which could provide rapid temperature reductions but with the potential to cause considerable damage to regional climates.

Geoengineering approaches are often discussed simply in relation to their potential to reduce $CO_2$ emissions or shave off peak temperatures, without reference to the broader systems they take from and impact: human, ecological, international, and planetary security. As such, the inputs these approaches require and the varied categories of risk they produce are often unexplored or examined in silos.

In fact, what lies behind the potential deployment of geoengineering is a series of risks across several domains. The individual and collective impacts of these risks will change not only the logic of climate action but also, more broadly, the security paradigms in which the international community has operated for decades, if not centuries. For the first time in history, humankind is contemplating the deliberate deployment of Earth-system interventions at a planetary scale with implications that could span centuries. These interventions, intended to control the planet's climate, will, at best, reduce—or, at worst, undermine—the natural building blocks that provide ecosystem services well beyond climate regulation.

## Individual and Collective Risks

This paper is a primer for policymakers, particularly in Europe. It introduces a novel framework through which to view the risks associated with the individual and combined effects of various geoengineering approaches.

Any individual geoengineering method may carry one or more of three distinct risks:

1. **It does not work:** The method does little or nothing to stop climate change impacts or even increases emissions or temperatures.

2. **It causes harm:** The method damages and destabilizes already-fragile biophysical and social systems.

3. **It exacerbates international tensions:** The method erodes global peace, security, and cooperation, given the existing political context and the lack of any international governance framework for CDR or SRM.

Taken as a whole, meanwhile, geoengineering poses three forms of global catastrophic risk:

1. **Termination shock:** Global temperatures increase rapidly if SRM is deployed but then stopped suddenly without significant emissions reductions having taken place.

2. **Systemic destabilization:** Geoengineering compounds existing risks and vulnerabilities as cascading failures create the potential for large, possibly nonlinear, and hard-to-reverse ecosystem and societal changes.

3. **Overshoot risks:** Geoengineering leads to irreversible changes in Earth systems, as reliance on CDR and SRM delays rapid emissions reductions and undermines the effectiveness of mitigation.

The world has effectively entered the age of planetary security, albeit with no guiding analytical, governance, or legal compass to conceptualize and organize it. In this era, security considerations must increasingly guide the development of frameworks to govern the safety, boundaries, and integrity of both the biosphere and the technosphere. Such frameworks must also regulate the geostrategic competition that is taking place in both domains at the expense of human, ecological, and collective security.

# Introduction

As average global warming since the preindustrial period passes 1.5° Celsius (2.7° Fahrenheit) and the Earth's climate enters a hotter, more dangerous regime, debates about the place of geoengineering approaches—for both carbon removal and solar radiation management—are accelerating at a staggering pace. These climate interventions represent a paradigm shift in the realms of security and climate action. They introduce new forms of interference with the planet, from marine and terrestrial ecosystems to the troposphere.

Geoengineering methods do not aim to mitigate the drivers of climate change, but its effects. As such, geoengineering is often presented through a framework in which individual or combined approaches are portrayed as necessary to avoid further dangerous climate change. Geoengineering is typically described as an emergency measure that can provide vital breathing space in which the mitigation of greenhouse gas emissions can be rapidly increased.

What is not understood is that the use of geoengineering will change the paradigm in which climate action operates. Not only does geoengineering introduce a new form of moral hazard in climate action; it also creates a novel set of catastrophic and existential risks, which have the potential to lock humans into centuries of path dependence for planetary modification. This, in turn, will necessarily alter security paradigms, because the vast implications of geoengineering approaches go beyond climate interventions: They create tensions or conflicts with ecological, human, and international security. When looking at interventions in response to climate change, decisionmakers should therefore urgently consider the interactions between various forms of security. These interactions—and the fact that certain geoengineering technologies propose interventions on a planetary scale—indicate that the world has entered the era of planetary security.

Planetary security represents a more encompassing layer than international security, a human-centric concept that can be defined as the balance of interactions between the realms of military, political, economic, and environmental security. Planetary security, meanwhile, encompasses human civilizations but goes further by integrating them into the Earth's dynamic systems (the biosphere) and connecting them to techno-industrial systems (the technosphere).

In this paper, then, planetary security is defined as the resilient coexistence of human, technological, and ecological systems within the Earth's biophysical limits. Integrated planetary security would require human, ecological, economic, international, and technological security to be aligned. This is currently far from the case, indicating that the analytical frameworks needed to examine the tensions and trade-offs between the different dimensions of planetary security are lacking. By extension, current governance systems are unfit to guide the transformations and interactions that planetary security implies.

As for the governance of geoengineering techniques, the European Union (EU) has so far followed a mixed approach. On the one hand, the union has adopted a Carbon Removals and Carbon Farming (CRCF) certification framework, which aims to encourage investment in innovative carbon-removal technologies, while on the other, it has taken a precautionary stance toward SRM. In its 2023 climate security communication, the EU recognized the need to scrutinize the debate on geoengineering, understand the risks of deployment, and, ultimately, take a position on the place of these technologies in climate action.[1] Debates on the role and scope of geoengineering will only accelerate going forward, paving the way to a high risk of polarization. The new risk matrix in this paper contextualizes the cocktail of geoengineering technologies and methodologies within a holistic risk assessment.

This analysis comes at a crucial moment as humanity navigates unprecedented challenges, requiring careful consideration of the long-term implications of planetary-scale climate interventions. The decisions that societies make about geoengineering will significantly influence both human civilization and Earth systems for generations to come.

## The Era of Overshoot and Radicalism

A new world has, to a large extent, already arrived as a result of two important developments. First, 2024 was officially the first year in which average global warming exceeded 1.5°C.[2] This is the limit that climate scientists have warned against for decades and that policymakers appeared to have heeded by reaching the landmark Paris Agreement in 2015. While a couple of years above 1.5°C do not necessarily indicate that long-term warming has breached this threshold, rising greenhouse gas emissions mean it is a question of when, not if, this moment will be reached. Climate costs and risks are increasing both individually and together, tearing at the foundations of collective solidarity, and contributing to the return of realpolitik. These trends have been all too clear in debates about U.S. territorial ambitions toward Greenland against the backdrop of a warming Arctic and toward the Panama Canal against the backdrop of structural droughts.

The second development that has triggered a global reordering of social and Earth systems is a new radicalism. Crossing the 1.5°C threshold means that the world has entered a period of overshoot. The ecological, social, and economic impacts of this event are increasingly likely to be catastrophic.[3] Humanity is now heading into uncharted territory, which is motivating scientists, policymakers, corporations, and citizens to seek radical solutions to the climate and ecological emergency.

In the context of overshoot, the definition of "radical" is quite broad. At one end of the spectrum, some actors who focus on socioeconomic transformations advocate deep interventions that seek to address the root causes of the climate crisis. At the other end, some actors call for palliative measures based on technologies that are radical in scope but are increasingly presented as inevitable and therefore acceptable. These interventions largely seek to minimize the impacts of climate change with a view to allowing space and time to enact the most complex set of climate-responsive transitions on which humanity has ever embarked.[4]

Against the backdrop of climate overshoot, a new techno-solutionist set of research and lobbying interests has gained traction. This sort of technological interference is broadly termed geoengineering. It is founded on speculative and potentially risky assumptions about the habitability of the planet at higher global temperatures, the ability to temporarily hold back the worst effects of climate change, and the possibility of returning the Earth system to its pre-1.5°C state.

The United Kingdom's (UK's) Royal Society defines geoengineering as "the deliberate large-scale intervention in the Earth's climate system, in order to moderate global warming."[5] There are two broad classes of geoengineering: carbon dioxide removal, which encompasses a range of methods that attempt to extract $CO_2$ from the atmosphere or the ocean; and solar radiation management, which aims to artificially cool the planet by changing its reflectivity.

Weather-modification techniques, such as cloud seeding, despite being a form of atmospheric manipulation, are not considered to be types of geoengineering because of their short-lived and localized effects. That said, in some circumstances, when the scale of weather modification is so large that it interferes heavily with the hydrological cycle, some analysts may eventually consider weather-modification technologies to be a subcategory of geoengineering. China's Sky River project, which is designed to enhance rainfall over the country's territory, is so large in scale that its effects are already producing geopolitical concerns over shared atmospheric resources.

Geoengineering is hastily gaining traction as a technological fix for the climate emergency. The reasons for the concept's increasing popularity are varied: a growing sense of panic; climate delayism or denialism; the contention that societal, economic, and political transformation is simply impossible; the high costs of decarbonization; or a belief in the tech industry's rhetoric that continued progress and innovation are the solutions to all of humanity's ills.

However, geoengineering is a complex and fast-evolving domain with potentially far-reaching consequences. Because many of its risks are left unspoken, a path dependency is in the making. At its most extreme, solar geoengineering proposes industry-intensive, planetary-level technological interventions for a time period that may last centuries. This is unprecedented. While humans have produced technologies, such as nuclear weapons, that have enough power to annihilate human societies and produce a mass extinction in the biosphere, they have never envisaged applying technologies at a planetary level with a view to engineering, affecting, and potentially controlling the planetary environment. As such, although geoengineering approaches are currently considered through the lens of climate security, what is in fact at play is planetary security.

## A New Risk Framework

The lens of planetary security offers a fresh approach to examining the risks of geoengineering amid the rising salience of the topic and the growth in new industrial options. There is a need for a sober, up-to-date assessment of the benefits and risks of such interventions to help policymakers and publics come to informed decisions about their potential deployment.

Scientists who research geoengineering are clear that major uncertainties remain about the effectiveness, limits, and consequences of its use. Indeed, such uncertainties are a reason why it is important to conduct further research into these climate interventions. Nevertheless, these methods are receiving increasing funding and media attention. This situation opens the door to a future in which climate action could be locked into a resource-intensive technological trajectory and nature is viewed simply through the lens of carbon management.

The new typology presented in this paper categorizes and scrutinizes the risks of individual geoengineering methods and highlights how deployment of both CDR and SRM can lead to forms of global catastrophic risk.

Pursued individually, geoengineering approaches carry three distinct risks. They may:

- have little or no impact on climate change;
- damage or destabilize biophysical and social systems; or
- exacerbate international tensions.

Taken collectively, meanwhile, geoengineering may:

- cause rapid temperature rises if deployed but then stopped suddenly;
- lead to systemic destabilization by compounding existing risks; and
- result in irreversible changes to Earth systems.

This new framework was developed in response to the way in which geoengineering is often discussed through a risk-risk analysis, in which technological solutions are presented as the only possible response to climate breakdown.[6] However, relying on the potential deployment of geoengineering is a gateway to continued increases in emissions and the acceleration of other planetary crises, compounded both by climate change effects and by further, potentially desperate geoengineering attempts. It is useful to bear in mind that carbon capture and storage (CCS), which was promoted as a pivotal solution for the climate crisis and therefore delayed emissions reductions, has proved grossly ineffective while costing taxpayers billions of dollars.[7]

Policymakers will increasingly be expected to take a view on aspects of geoengineering, from the funding of theoretical research and experimentation to public engagement and international governance. In this regard, it should be noted that in the words of environmental law experts Edward Parson and Jesse Reynolds, "the strongest concerns raised by solar geoengineering are not geophysical or technical in character, but social and political. These pertain to how it might be used, under what conditions, under whose control, with what goals, and with what broad social and political consequences."[8]

While this statement relates to SRM, it is instructive for geoengineering as a whole. Humanity is at a turning point in its planetary history. In the paradigm shift to planetary security, the task ahead is to identify the forms, dimensions, and levels of security that must be reconciled; the tensions and trade-offs that arise; and the need to pursue security responses that work for the many, as opposed to the very few.

## The Motivations Behind Geoengineering

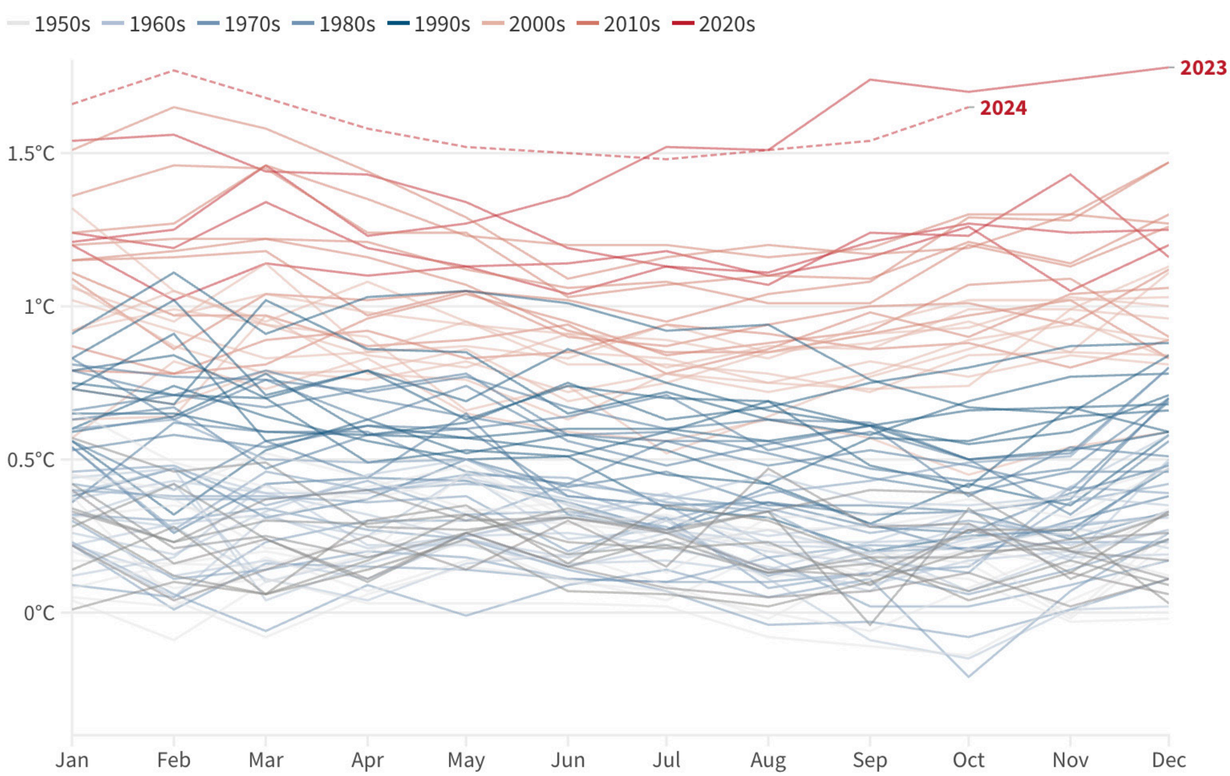
As geoengineering is framed in some quarters as a necessary response to climate breakdown, it is useful to first understand the climatic changes and policy responses that have led to this idea. Within recent climate change history, the central concepts are the emissions gap, growing energy demand, and net zero.

## Overshoot: What Lies Beyond 1.5°C?

As the world enters the second half of the 2020s, global emissions, $CO_2$ concentrations, and global temperatures are continuing to rise.[9] The year 2024 was the warmest since records began and the first year when average global warming since the preindustrial period was more than 1.5°C (see figures 1 and 2).[10] Meanwhile, global emissions from fossil-fuel use stood at an all-time high of 37.4 billion tons, and the average global atmospheric $CO_2$ concentration was above 422 parts per million (ppm)—with 350ppm considered the safe level (see figure 3).[11]

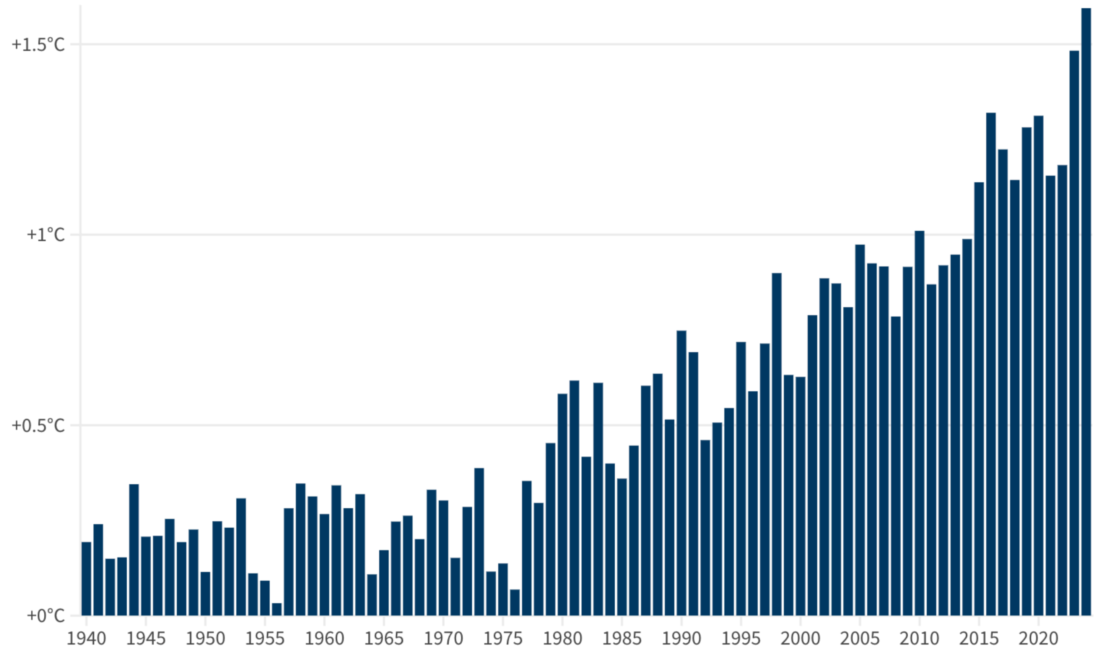
The Paris Agreement recognized that warming beyond 1.5°C would produce intolerable suffering for those most vulnerable to climate change, hence the maxim from low-lying nations of limiting warming to "1.5 to stay alive."[12] Breaching this temperature threshold is also associated with a substantial risk of triggering large, irreversible changes in the climate system, known as tipping points.

**Figure 1. Monthly Global Temperature Anomalies, 1950–2024**



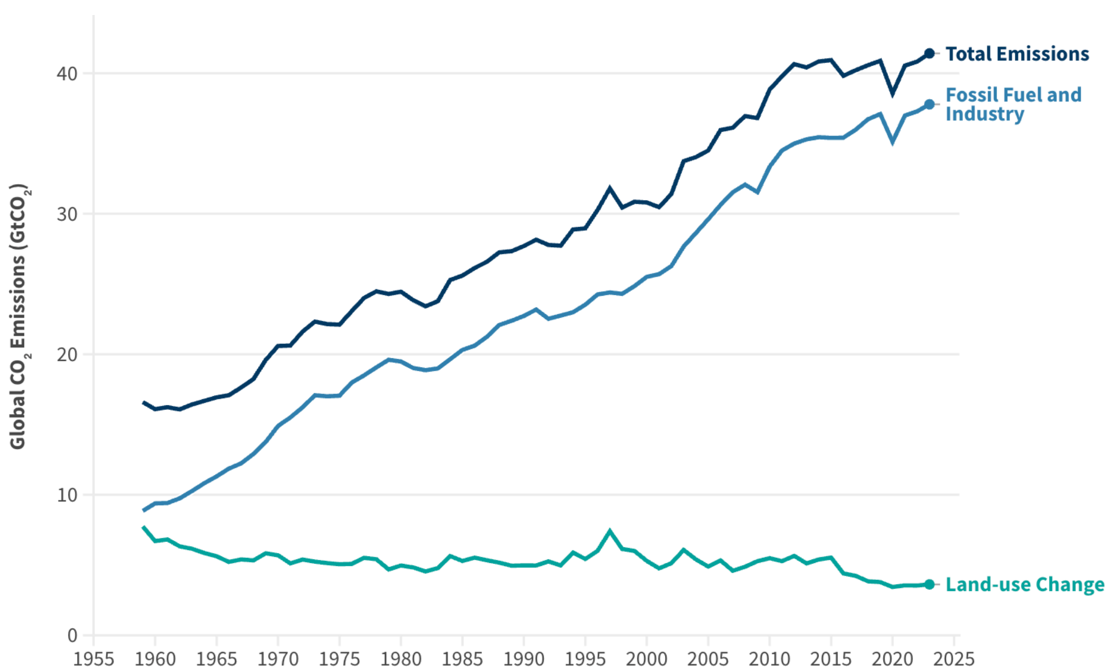

Source: "State of the Climate: 2024 Will Be First Year Above 1.5C of Global Warming," Carbon Brief, November 7, 2024, https://www.carbonbrief.org/state-of-the-climate-2024-will-be-first-year-above-1-5c-of-global-warming/.

**Figure 2. Average Global Temperatures, 1940–2024**




Source: "Copernicus: 2024 Virtually Certain to Be the Warmest Year and First Year Above 1.5°C," Copernicus Climate Change Service, November 7, 2024, https://climate.copernicus.eu/copernicus-2024-virtually-certain-be-warmest-year-and-first-year-above-15degc.

**Figure 3. Global $CO_2$ Emissions, 1959–2024**




Source: "Analysis: Global CO2 Emissions Will Reach New High in 2024 Despite Slower Growth," Carbon Brief, November 13, 2024, https://www.carbonbrief.org/analysis-global-co2-emissions-will-reach-new-high-in-2024-despite-slower-growth/.

Climate scientists have already reported increased rates of ice sheet melting, unprecedented marine heat waves, the slowing of ocean heat currents, and the collapse of some land-based carbon sinks. Further warming risks shifting Earth systems into different regimes, with consequences that are difficult to predict but could profoundly alter the distribution of natural resources and remap where long-term habitation is possible.

Alarmingly, such warming looks ever more likely. The first global stock take of the Paris Agreement, concluded at the 2023 United Nations (UN) Climate Change Conference (COP28) found an emissions gap of over 20 billion tons of carbon dioxide equivalent ($CO_{2eq}$).[13] This gap is the difference between the level of emissions reductions that nations have committed to achieve and the level at which they need to be by 2030 to keep warming to 1.5°C. These commitments, or nationally determined contributions (NDCs), are just promises; actual policies show a gap of over 24 billion tons of $CO_{2eq}$. On the basis of this trend, governments' climate plans are constructing a path toward 3°C of warming by 2100.[14] Even this is just a best estimate. Given uncertainties about how climate systems will respond to human impacts, it is possible that actual warming could be much higher—and perhaps even exceed 5°C.[15]

Beyond biophysical impacts, climate change is also leading to much greater human, economic, and societal costs. Over 80 percent of extreme weather events reported by the climate analysis website Carbon Brief can now be attributed to human-induced climate change.[16] In terms of traditional economic measures, such as damage to infrastructure, property, agriculture, and human health, the cost of extreme weather events between 2000 and 2019 has been assessed at around $16 million per hour.[17]

Hazard-related costs are not the only metric. New economic methodologies that aim to quantify the financial and economic costs of climate change point to much deeper impacts than previously thought. One study estimated that every 1°C of global warming leads to a 12 percent contraction of global gross domestic product.[18] The study's authors insisted that this may still be an underestimate compared with the systemic effects of climate change on inflationary pressures, trade and connectivity channels, productive sectors and spaces, labor, infrastructure, service provision, and welfare systems. A 2025 report assessed that at current rates, global economic growth will start contracting by at least 50 percent by 2070.[19]

These analyses stand in shocking contrast to earlier work by American economist William Nordhaus on climate and environmental impacts on the economy, which Nordhaus assumed would largely remain insulated from its planetary and ecological context.[20] While disputed, Nordhaus's estimates of climate damage and risk continue to influence both governments and industry.

Of course, economic costs are distributed neither equitably nor equally. Climate change is broadly contracting the economic capacity of less developed countries through direct and indirect shocks as well as structural scarcity effects. Inflation and the compounding costs of hazards mean that these states' national budgets are increasingly used to service debt, hollowing out their ability to invest in sovereign adaptation and economic development. Rifts between Group of Seventy-Seven (G77) and Western nations are growing every year. As the 2024 UN Climate Change Conference (COP29) demonstrated, international cooperation is fragmenting and leading to a rise in tensions.

These various data points provide a background against which to judge the progress and trajectory of climate action. In short, it is not advancing fast enough. By some measures, it is in fact going in the wrong direction.

## The Concept of Net Zero

Net zero is an elaborate carbon-accounting system that underpins the Paris Agreement. It is based on the relationship between global warming and cumulative emissions, with the central finding that warming is expected to stop once net emissions reach zero. To have a 50 percent chance of limiting warming to no more than 1.5°C, global carbon emissions will need to be reduced, captured, or offset with removals by 2050. If that is not achieved, then scaling up CDR over the rest of century is to be attempted to limit warming to well below 2°C. In other words, achieving net-zero carbon emissions does not necessarily involve committing to a phaseout of fossil fuels or a transformation of the political and socioeconomic drivers at the root of the climate crisis.

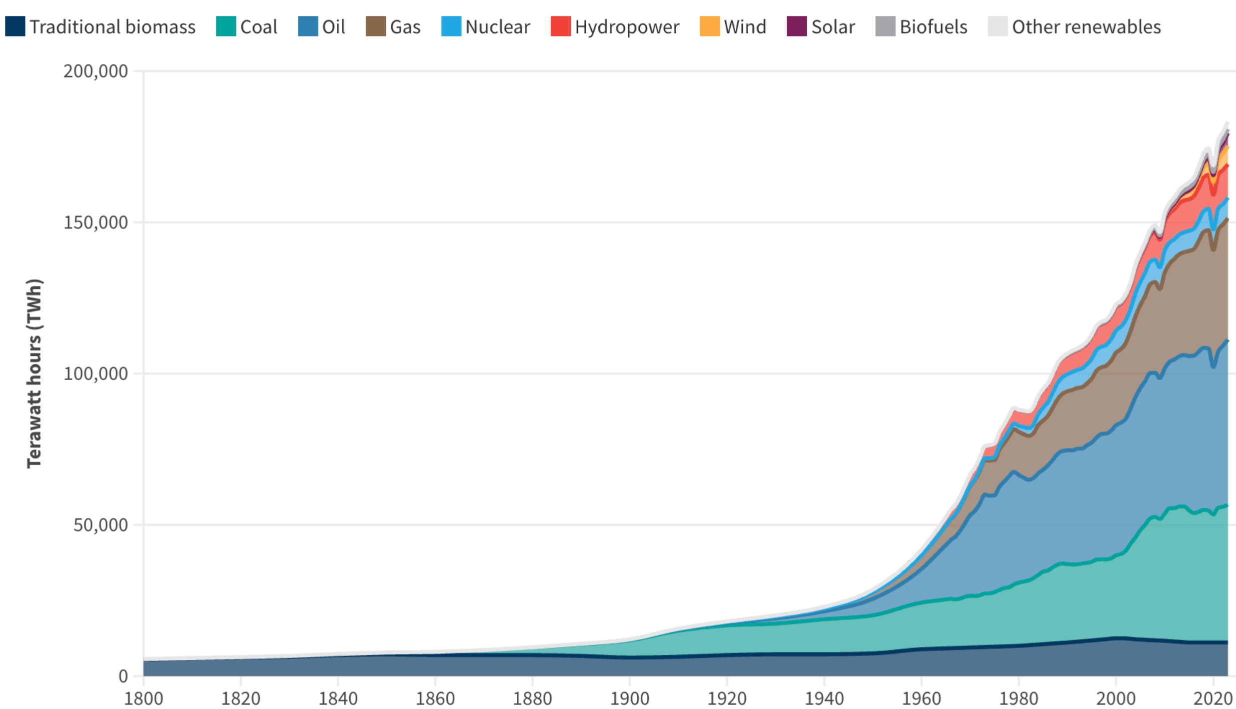
On paper, the carbon-accounting system would not be a bad idea if it were technically feasible at the scales envisaged and could be achieved without compromising other crucial goals, like preventing the collapse of biodiversity. But in practice, it introduces new social and ecological risks, and the loopholes it opens are now contributing to a hollowing out of the Paris Agreement, essentially watering down effective climate action. Indeed, because of the vast differences in countries' energy mixes and industrial capacities, the agreement allows for flexibility in meeting climate targets, including via the NDCs. It is therefore up to each country to determine how best to manage its energy transition. As such, the system for carbon removals is open to abuse, because there are no caps or limitations on deployment. Theoretically, a country could remain 100 percent dependent on fossil fuels as long as it could capture or remove its emissions.

While no country is 100 percent dependent on carbon removal or capture, some countries, such as Saudi Arabia and the United States, rely heavily on these processes in their climate policies. The lack of caps on the use of these methods and the lack of coordinated oversight of their effectiveness have created a paper tiger effect in the Paris Agreement. The loose framing of carbon removal and offsets as part of NDCs was created out of a twofold need: first, to recognize the continued use of fossil fuels in a global economy that had yet to deliver prosperity in parts of the world; and second, to allow for political-economic stability in energy-intensive economies while acknowledging the time it would take to create a renewable-energy architecture worldwide. This paradigm was also based on a false assumption that the target of net zero could be disaggregated from the global level to nations and corporations in differentiated accounting systems.

Technological innovation adds to this complex picture. The fourth industrial revolution, which relies on digitization of the world economy, is leading to the construction of new global infrastructure in the form of data centers, cable connections, and extra-terrestrial developments. This infrastructure requires large amounts of raw materials whose extraction contributes to several types of ecological damage and risk. Critically, it also requires additional energy capacity, which big tech actors are scrambling to meet. Big tech's growing energy demand partly motivated U.S. President Donald Trump's declaration on day one of his second term of an energy emergency in the United States, which is set to lead to further oil and gas exploitation, nuclear expansion, and extraction of critical raw materials.[21] The spectacular rise of technologies such as generative artificial intelligence is contributing to a surge in energy consumption that cannot be met by renewables, leading to an energy-addition scenario as opposed to an energy transition.

While the deployment of renewable energy is accelerating, the world's energy demand is growing on the back of several factors, including greater energy penetration in developing countries and the expansion of energy-intensive sectors. These trends produce a mixed picture in which additional demand for power is currently met by a growing share of renewables, while the world remains stubbornly dependent on fossil fuels for 80 percent of supply (see figure 4).[22] Worryingly, despite investments in renewable energy, clean-energy

**Figure 4. Global Primary Energy Consumption by Source, 1800–2023**




Source: "Energy Mix," Our World in Data, January 2024, https://ourworldindata.org/energy-mix.

stocks have lost 60 percent of their value since their 2021 high, while fossil-fuel portfolios have gained 50 percent of theirs.[23] This situation indicates that the fossil-fuel age may be far from peaking, including in developed economies, which had made progress toward renewables in recent years.

These numbers all tell a story of a net-zero accounting system gone wrong. Reducing the climate crisis to a carbon problem that balances sinks against emissions without capping thresholds is delivering a dauntingly risky path for the world.

This has several consequences. First, the uphill battle for phasing out fossil fuels is becoming ever more strenuous with every technological leap that drives up energy demand. Second, the energy transition is making little headway, because at a global scale, increases in renewable-energy capacity are simply adding to, rather than replacing, fossil fuels.[24] Finally, demand for carbon offsetting, capture, and removal methods is surging. These approaches can also be energy and resource intensive, for example in the process of direct air capture, which requires energy for the removal of $CO_2$ from the air.

## The Origins of Geoengineering

The geoengineering approaches of CDR and SRM have distinct backgrounds, mechanisms, and effects, and they sit differently in the public consciousness. For a long time, these two categories were considered separate from one another. While CDR was long—and wrongly—conceptualized as being more innocuous in terms of its multidimensional risks, SRM was seen as a distant and dangerous set of technologies with uncertain outcomes. As such, SRM was largely removed from policy-related conversations and was not regarded as an option for imminent deployment.

This situation is rapidly changing. In some circumstances, despite persistent uncertainties about its far-reaching risks, SRM is at times presented as a prequel to the deployment of large-scale CDR.[25] Novel carbon-removal technologies have so far proved unsuccessful at scale and supposedly require more time for effective innovation to meet the greenhouse gas removal challenge. Meanwhile, solar geoengineering technologies could be used to mitigate the effects of climate change and enable more time and space to achieve net zero. While the concept of overshoot has become central to mainstream climate narratives, as it supports the argument that the Paris Agreement targets can be met without radical socioeconomic and sociotechnological change, it is fostering a "burn now, pay later" approach—with vast dangers lurking in the background.[26]

### A History of CDR

The history of CDR is intimately linked with integrated assessment models (IAMs), numerical models that represent complex socioeconomic systems coupled to the climate. Policymakers rely on IAMs to understand different emissions scenarios, global environmental change, and questions such as how countries' climate plans may affect future global temperatures or the social cost of carbon—an estimate of the cost to society, in monetary terms, of emitting each additional ton of $CO_2$.[27] These models are integrated because they bring together different types of data, for example from climate science, energy systems, and ecology. A key assumption is that all climate policies will promote economic growth, so IAMs are required to use a cost-effective approach to "try to reach a given climate goal at minimal costs for the global economy," according to a 2023 report on CDR.[28] The shorthand for this approach is that the models have to be what the Intergovernmental Panel on Climate Change (IPCC) calls "policy-relevant."[29]

CDR and CCS have become integral parts of nearly all IAMs, as they reduce the required rate of mitigation. Promising to capture $CO_2$ at source or remove it from the atmosphere at some point in the future effectively allows fossil-fuel use to be maintained and carbon budgets extended. This approach has been widely criticized but "remains the frame of reference in climate policy," according to one paper on carbon-removal governance.[30] Yet, these models, which greatly simplify the complexities of the real world, potentially distract attention and resources away from the development of alternative pathways to a low-carbon future.[31]

Of the various CDR methods—also known as negative-emissions technologies (NETs)—the first to gain significant traction was bioenergy with carbon capture and storage (BECCS). This technology involves burning biomass, such as wood, maize, soy, or sugar cane, in thermal power plants to generate electricity. Biomass absorbs $CO_2$ as it grows; CCS technologies are then used to capture CO2 from the exhaust gases during combustion, resulting in a system that removes $CO_2$ from the atmosphere while generating electricity.

BECCS was first proposed as an NET in 1998 with mentions in peer-reviewed academic papers. It was not until 2007, however, that BECCS was recognized as having a central role in climate strategies and policies. In a highly cited paper published that year, BECCS was deployed in an IAM to limit $CO_2$ concentrations to 450ppm.[32] From that point onward, low-cost, low-emissions scenarios have used BECCS to stay below 2°C of global warming.[33] In reality, the technology's contribution has proved to be much more modest. Today, it can remove just 0.00051 GtCO2 per year.[34] As a reminder, global emissions from fossil fuels in 2024 were 37.4 $GtCO_2$.

By 2014, despite criticism from some quarters, speculative NETs, such as BECCS, were increasingly featuring in IAMs.[35] A key message that emerged at the time was that bringing down emissions was necessary but insufficient. According to the IPCC's Working Group III, which focuses on climate change mitigation, "when near-term mitigation is not sufficiently strong, future mitigation must rely heavily on CDR technologies such as BECCS, putting greater pressure on future decision makers and highlighting any uncertainties and risks surrounding these technologies."[36]

In 2018, the IPCC released a special report that assessed ninety climate change scenarios to limit global warming to no more than 1.5°C by 2100.[37] Of these, nine were able to limit warming to this level or lower, with the remaining eighty-one all overshooting 1.5°C sometime before 2100. All scenarios included varying amounts of engineered CDR.

## Carbon Budgets: From Residual to Excess Emissions

Different models have come up with different figures for the amount of carbon removal needed by 2050 to limit the average global temperature increase to 1.5°C. If there are immediate, sharp reductions in emissions and carbon removals reach 5–15 $GtCO_2$ per year by 2050, then the annual carbon removals required each year thereafter would be between 1.3 and 29 $GtCO_2$.[38] Today, the total amount of carbon removed from the atmosphere is estimated at just 2.2 $GtCO_2$ per year, almost all of which comes from afforestation or reforestation. These nature-based methods of carbon removal are temporary and susceptible to wildfires and other risks. Less than 0.1 percent of total CDR—0.0013 $GtCO_2$ a year—comes from novel methods, such as direct air capture or the charcoal-like substance known as biochar.[39] Such novel approaches are considered more durable or permanent as they sequester carbon for longer than forestation approaches.

Carbon removals were initially intended to offset the emissions of industries and activities that are technically very hard to decarbonize. For example, commercial aviation would struggle to rapidly reduce its climate impacts because there are currently no viable alternatives to burning kerosene in jet engines for large or long-range passenger aircraft. It has been proposed that the emissions from aviation and other so-called hard-to-abate industries would be offset with NETs to allow societies to reach net zero faster than by having to develop zero-carbon technologies for all industrial and food-systems activities.[40]

The large increase in proposed CDR is due in part to the growing tally of what are termed residual emissions. In general, these are emissions that are considered too expensive or technically difficult to reduce or eliminate. Their definition has become quite elastic, however, and there is little consensus on what it should include. The concept can cover different types of emissions: those that remain whenever net zero is achieved; those that occur from a specific year onward; or those from a particular range of sectors, with no time frame. There are also emissions that are optimally dealt with by NETs—in other words, by taking into account their costs and side effects. Finally, there are excess emissions, which encompass most current emissions because they are produced before net zero or any target year is reached and do not relate to hard-to-decarbonize sectors.[41]

On average, around one-fifth of countries' emissions are considered residual; this figure goes up to over a half in some cases. Agriculture, for instance, is a major hard-to-decarbonize sector that accounts for around 35 percent of residual emissions in national climate strategies.[42]

Despite the lack of clarity over the purpose of carbon removal, the wide-ranging risks involved, and the lack of real oversight of global CDR deployment, governments and nonstate actors are focusing on rapidly scaling up NETs. This is despite the fact that the upscaling of novel CDR approaches would have to grow by 40 percent a year to achieve the carbon-removal rates required for the highest level of ambition in the Paris Agreement.[43]

## A History of SRM

SRM covers a suite of proposed technologies that would effectively alter the energy balance of the Earth's climate—how much energy from the Sun enters and then leaves through the atmosphere. Some SRM approaches are intended to increase the amount of energy leaving, for example by thinning high-altitude clouds. Most methods seek to reduce the amount of energy entering by changing the albedo, or reflectivity, of the planet. These approaches range from the simple and seemingly benign—painting roofs white or attaching bubble machines to ships—to the highly controversial and speculative, such as injecting sulfur dioxide into the atmosphere or launching mirrors into space.

The history of SRM goes back over half a century. In the 1960s, the climatic impacts of a series of volcanic eruptions prompted scientists to take up the idea that global cooling could result from injecting fine reflective particles into the air. The 1991 eruption of Mount Pinatubo in the Philippines then became a central reference point for SRM. In a series of eruptions from June to August, 20 million tons of sulfur dioxide were pumped into the high atmosphere; the resulting sulfate particles reflected incoming solar radiation, and global temperatures cooled by about 0.5°C for up to two years.[44]

Weather modification was another forerunner to SRM, especially in relation to its links to the military-industrial complex and its risk of weaponization. During the Vietnam War, the U.S. Air Force carried out Operation Popeye, a cloud-seeding project that attempted to extend the monsoon season. Fifty countries, including China, Israel, Mexico, and the United Arab Emirates, now use this kind of technology.[45] However, weather-modification techniques are not considered to be geoengineering because they are not intended to impact the global climate. The difference is that geoengineering aims to constrain global temperature rises, whereas weather modification is used to alter the weather at a local scale and over short time periods.

SRM remained a niche pursuit until a highly influential 2006 essay by Dutch meteorologist Paul Crutzen on the injection of sulfate particles into the stratosphere as a possible route to reducing the impacts of greenhouse gas emissions.[46] This analysis piqued research interest around the globe, but projects have been limited to a few key institutions. The term "solar radiation management" was coined in 2006 for a joint Carnegie Institution for Science and U.S. National Aeronautics and Space Administration (NASA) workshop to avoid the controversy around the term "geoengineering."[47]

In 2024, the University of Chicago launched its Climate Systems Engineering Institute, with donors including big tech billionaires.[48] Meanwhile, the Global Systems Institute at the University of Exeter dedicates a section of its website to responsible climate interventions.[49] These developments are pivotal at a time when deregulation appears to be on the agenda in the United States and SRM is being promoted as "the only (climate intervention) that could be deployed within a single presidential term," in the words of SRM researcher Peter Irvine.[50]

An important note in the evolution of SRM from fringe idea to mainstream climate solution is that prominent climate figures have called for further research into these technologies. These figures include James Hansen, a climate scientist who provided landmark testimony to the U.S. Congress in 1988. Hansen has argued that global warming is accelerating and that a burst of global heating is "in the pipeline."[51] That is because the radiative forcing—a measure of the change in the Earth's energy balance—caused by greenhouse gas emissions has, in part, been masked by sulfur dioxide pollution from coal and heavy fuel oil, which is now falling because of tighter regulations on air pollution.

Because of the strong cooling effect of sulfur dioxide, reductions of these emissions and other pollutants are responsible for about 38 percent of the increased warming observed in the first two decades of this century, according to one study.[52] However, this study finished before the 2020 introduction of strict regulations on the sulfur content of shipping fuels, giving additional weight to the contention that global heating is accelerating.[53] Hansen has argued that humanity has inadvertently made a Faustian bargain with the climate: He is concerned that unless the Earth's energy imbalance is rectified through SRM, the 2°C warming threshold will easily be passed within the next decade. Researchers continue to explore the significance of declining sulfate pollution on global temperature increases.[54]

## Geoengineering Approaches

Geoengineering has many forms and several alternative names. Academic, industrial, and policy work in this area is increasingly referred to as climate engineering, climate modification, (responsible) climate intervention, climate repair or restoration, or new technologies for climate protection. There are also synonyms for CDR and SRM: Carbon-removal methods may be described as NETs, deep decarbonization, greenhouse gas removal, or carbon drawdown, while SRM is also used as an abbreviation for "sunlight reflection methods" or can be known as solar geoengineering. These technologies can be framed positively, for example as being restorative to nature, and in ways that portray CDR as relatively benign compared with SRM.[55]

This shift in language seems to be a way of casting geoengineering in a more favorable light. The SRM advocacy group SilverLining "conducted a public poll on the terms 'geoengineering' and 'climate intervention' and found that people were better able to comprehend what was meant by climate intervention, and also were less fearful."[56]

The following sections discuss the most common geoengineering proposals but do not cover emerging methods, such as the sinking of terrestrial biomass in the deep ocean or intentional stratospheric dehydration.

## Carbon Dioxide Removal Methods

CDR approaches include afforestation and reforestation, regenerative agriculture techniques, accelerated natural rock weathering, methods to enhance the growth of plankton or seaweed, and technologies that suck $CO_2$ directly out of the air or sea. Here, these approaches are categorized as either land-based, ocean-based, or engineered.

Descriptions of CDR approaches tend to focus on their mitigation potential (how much $CO_2$ they could remove), technical readiness level, and cost. It is important to note, however, that removal potentials and commercial readiness appraisals are based on biophysical and technological assessments that do not take into account economic, sociocultural, environmental, or institutional risk factors, such as biodiversity loss and food insecurity. Robust frameworks for environmental impact assessments of CDR approaches are only now being developed, and outdoor experiments are subject only to ad hoc appraisals by regulators.

With regard to technical readiness, several frameworks exist, but a nine-point scale is used across many assessments of geoengineering methods (see table 1).[57] However, while a technology may be ready for commercial deployment, this does not mean that it is possible or even advisable to scale it up to the levels featured in some climate policy models.

**Table 1. A Nine-Point Scale of Technology Readiness Levels**

| Level | Description |
|---|---|
| **Research and Development** | |
| 1 | Basic research |
| 2 | Applied research |
| **Applied Research and Development** | |
| 3 | Critical function or proof of concept established |
| 4 | Laboratory testing or validation of component(s) or process(es) |
| 5 | Laboratory testing of integrated or semi-integrated system |
| **Demonstration** | |
| 6 | Prototype system verified |
| 7 | Integrated pilot system demonstrated |
| **Precommercial Deployment** | |
| 8 | System incorporated in commercial design |
| 9 | System proven and ready for full commercial deployment |

Source: "Negative Emissions Technologies (NETS): Feasibility Study," Scottish Government, November 30, 2023, https://www.gov.scot/publications/negative-emissions-technologies-nets-feasibility-study/pages/6/#Table5.

Furthermore, removal potentials cannot be simply added up to assess global carbon-removal goals, because the various options would compete for resources, such as land and water, and there are uncertainties about real-world removal figures for both nature-based and engineered approaches. Mitigation potentials also vary greatly because of technological differences, methodological choices, and differing assumptions in the various studies.[58] Hence, the figures in the tables below should be treated with caution. The risk areas listed in the tables are in addition to mitigation deterrence and the production of additional greenhouse gas emissions, as these two factors apply to all geoengineering approaches in this analysis.

## Land-Based CDR

These approaches seek to augment existing Earth system processes that relate to the carbon cycle on land. This category includes land-based carbon sinks—trees, plants, and soil—as well as the sequestration of carbon through chemical reactions with rocks. There are four main methods: afforestation and reforestation, soil carbon sequestration, biochar, and enhanced weathering (see table 2).

**Table 2. An Overview of Land-Based CDR Approaches**

| Approach | Current Mitigation Potential | Cost per Ton of $CO_2$ | Technical Readiness Level | Risk Areas |
|---|---|---|---|---|
| Afforestation and reforestation | 1.86 $GtCO_2$ per year | $1–100 | 8–9 | CDR durability<br>Thermal impact<br>Land-use change<br>Food security<br>Water security<br>pH changes and nutrient flows<br>Ecosystem damage<br>Socioeconomic impacts |
| Soil carbon sequestration (SCS) | 1.8–3.8 $GtCO_2$ per year | $132 | 6–8 | CDR durability<br>Health, toxicity, and pollution |
| Biochar | 0.00079 $GtCO_2$ per year | $30–120 | 3–6 or 5–7* | CDR durability<br>Thermal impact<br>Energy security<br>Ecosystem damage<br>Health, toxicity, and pollution |
| Enhanced weathering | 0.00003 $GtCO_2$ per year | $45–472 | 3–5 | Water security<br>Land-use change<br>Energy security<br>Ecosystem damage<br>pH changes and nutrient flows<br>Health, toxicity, and pollution<br>Socioeconomic impacts |

* There are conflicting estimates because biochar production is a developed field but its commercial elements are underdeveloped.

Source: Authors' compilation.

**Afforestation and reforestation** refer to the planting of trees in places that were not previously forested and in areas that have been deforested, respectively. Efforts to reduce carbon emissions rely heavily on forests because growing trees is a cheap, recognizable, and relatively quick strategy. There are also numerous so-called co-benefits of tree planting—but only if it is carried out in appropriate locations and local communities are supported to conserve the forests over long timescales. For example, this method does not rely on future technological developments and has the potential to improve biodiversity, water purification, pollination, and local livelihoods.[59]

In terms of costs and benefits, afforestation and reforestation are more expensive than avoiding deforestation. Added to that are issues to do with the temporary storage of carbon in trees and the ineffectiveness of large-scale tree-planting projects to achieve climate change mitigation goals.[60] A 2023 investigation also revealed that more than 90 percent of rainforest carbon-offset credits, which had been bought by individuals or organizations to compensate for their emissions, did not represent genuine carbon reductions.[61]

**Soil carbon sequestration (SCS)**, also known as carbon farming, is one of two carbon-removal methods that deal directly with the land. It relates to increasing the amount of carbon in the soil through processes such as no-till farming, cover crops, the addition of manure, and agroforestry. SCS can lead to improved agricultural productivity, and cover crops can help improve the nitrogen uptake of soils, reducing the need for fertilizer.

Although soils can capture a large amount of carbon, they can also rerelease their captured $CO_2$ through warming soils or human mismanagement. The use of fertilizers to enhance carbon sequestration can produce nitrous oxide, a powerful greenhouse gas. Alternatively, rewilding with the reintroduction of large ungulates can, under certain conditions, contribute to organic carbon storage in soils, which is associated with increased water retention and improved soil structure.[62] The addition of wild animals to areas where they were not previously present could lead to a 15–250 percent increase in the amount of carbon in plants, soils, and sediments.[63]

**Biochar** is a type of charcoal that can be applied to agricultural land. It is the second carbon-removal method that can improve carbon storage in the soil, although its mitigation potential is very limited at present. Biochar can remediate contamination, increase water retention and therefore resilience to drought, and improve the availability of nutrients. However, biochar can also decrease the reflectivity of the land, leading to more warming rather than cooling, and has potentially negative impacts on health.

**Enhanced weathering**, also referred to as field weathering when used in agricultural contexts, is a technique that accelerates the geological carbon cycle through the chemical weathering of rocks, with $CO_2$ locked up in minerals in the process. This CDR approach involves the mining and grinding of minerals such as olivine, which are then spread on agricultural and other land. This technique increases the surface area over which weathering reactions take place. One benefit is that more alkaline soil and a greater supply of nutrients can enhance plant growth and SCS.[64]

The energy use of mining, grinding, and transporting the rocks is very high, however, so the reduction in $CO_2$ concentrations in the atmosphere may be less than expected when analyzed over a full life cycle. There are also significant environmental and health impacts from the process. In addition, the current mitigation potential of enhanced weathering is very low.

## Ocean-Based CDR

Like land-based carbon sinks, the ocean has naturally sequestered a vast amount of the carbon produced by human activity—around 25 percent—as well as more than 90 percent of the excess atmospheric heat trapped by greenhouse gases.[65] There are concerns that the ocean's carbon-absorbing abilities may be reduced with increased temperatures and acidification pressures. Ocean-based geoengineering technologies seek to enhance this capacity.

Ocean-based carbon-removal methods use either biological, physical, or chemical processes (see table 3). In the biological category are blue carbon, seaweed cultivation, artificial ocean fertilization, and artificial upwelling. The main physical process is artificial downwelling, while chemical methods include ocean alkalinity enhancement and electrochemical direct ocean capture.

**Blue carbon** approaches include the restoration of wetlands, such as tidal marshes, as well as mangroves and seagrass beds. Among the co-benefits are coastal adaptation to climate change through protection against floods and storm surges, protected habitats for fish and other wildlife, improved water quality, and the preservation of biodiversity.

However, it is difficult to assess carbon sequestration rates across ecosystems, and climate change–induced sea level rise and extreme weather events can mean that previously stored $CO_2$ is rereleased. There are also socioeconomic considerations related to coastal resources. In addition, it is essential to manage existing wetlands or peatlands to stop future losses, as doing so has a similar impact to efforts to stop deforestation.

**Seaweed cultivation** for carbon removal involves producing seaweed as a food or feed product; sinking it into the deep ocean, also known as ocean afforestation; or turning it into biofuel alongside CCS. Coastal seaweed farms could provide protection from coastal erosion, as they dampen wave energy and provide new marine habitats, as well as increasing fish catch and extracting excess nitrogen and phosphorus from anthropogenic activity.[66]

The problems with large-scale kelp production are the amount of farming area required, its impacts on other habitats and consequences for food production, and the energy and materials needed. The emissions from seaweed farming range between 3 and 174 kilograms (7 and 384 pounds) of $CO_2$ per ton of fresh seaweed produced, mostly from electricity consumption.[67] Currently, this is an expensive carbon-removal method with potentially low rates of carbon storage.

**Artificial ocean fertilization**, or ocean iron fertilization, is another method that would require large areas of the ocean, perhaps up to 10,000 square kilometers (3,860 square miles).[68] This approach involves adding iron or phosphorus to nutrient-depleted marine waters to enhance the growth of phytoplankton and increase $CO_2$ uptake. There is also the possibility of boosting fish catch through enhanced biological productivity in the ocean.

**Table 2. An Overview of Land-Based CDR Approaches**

| Approach | Current Mitigation Potential | Cost per Ton of $CO_2$ | Technical Readiness Level | Risk Areas |
|---|---|---|---|---|
| Blue carbon | 0.6–1.0 $GtCO_2$ per year | \$240 (mangroves)<br>\$30,000 (salt marshes)<br>\$7,800 (seagrass) | 6 | CDR durability<br>Greenhouse gas emissions<br>Socioeconomic impacts |
| Seaweed cultivation | 0.1–1.0 $GtCO_2$ per year | \$480 | 3–5<br>6 for marine BECCS | CDR durability<br>Ecosystem damage<br>Food security<br>Socioeconomic impacts<br>Ocean area<br>pH changes and nutrient flows |
| Artificial ocean fertilization | 0.1–1 $GtCO_2$ per year | \$6–554 (ship)<br>\$7–1,278 (aerial) | 1–4 (iron)<br>2–3 (nitrogen and phosphorus | CDR durability<br>Greenhouse gas emissions<br>Ecosystem damage<br>pH changes and nutrient flows<br>Socioeconomic impacts<br>Geopolitical tensions |
| Artificial upwelling | 0.05–0.1 $GtCO_2$ per year | \$100–150 | 1–3 | CDR durability<br>Thermal impact<br>Ecosystem damage<br>pH changes and nutrient flows<br>Socioeconomic impacts |
| Artificial downwelling | Zero | \$ thousands | 1–2 | As for artificial upwelling |
| Ocean alkalinity enhancement | 0.1–10 $GtCO_2$ per year | \$20–600 | 3 | CDR durability<br>Ecosystem damage<br>Health, toxicity, and pollution |
| Electrochemical direct ocean capture (eDOC) | 0.1–1.0 $GtCO_2$ per year | \$150–2,500 | 2–3 | Similar to ocean alkalinity enhancement |

Source: Authors' compilation.

This CDR approach is not considered particularly effective, however, because it has a high risk of rerelease of $CO_2$. A further issue is damage to marine ecosystems through the redistribution of nutrients and potential ocean acidification from higher concentrations of $CO_2$ at depth. These negative aspects are perhaps why this method is now presented as "ocean restoration" or "marine biomass regeneration."[69]

**Artificial upwelling** is intended to improve phytoplankton growth by pumping cold, nutrient-rich water from the depths to the surface. Fisheries or mussel farms could benefit from this approach. To achieve significant carbon sequestration, several million pumps would be needed, which would risk bringing dissolved $CO_2$ up from the deep ocean. Once the process is started, there are risks that terminating it could lead to a long-term increase in $CO_2$ and higher temperatures than if the approach had not been used at all.

**Artificial downwelling** is a physical process that accelerates existing currents to move carbon-rich surface waters down to the deep ocean. It would involve pumps, similar to those used in artificial upwelling, and would have the same kinds of risks for what is currently a very limited mitigation potential.

In addition to these biological and physical methods, there are various chemical carbon-removal proposals that would decrease the pH of ocean water. These approaches would increase the effectiveness of the ocean carbon sink and so remove more $CO_2$ from the atmosphere.

**Ocean alkalinity enhancement** is one of these proposals. It involves the addition of crushed minerals to the surface ocean, where they dissolve and form bicarbonates with $CO_2$. As well as having a reasonable carbon-removal potential, this method is promoted as a way of offsetting harmful effects of ocean acidification on organisms such as coral and plankton. However, there are significant unknowns in relation to this technique's impact on ecosystems, alongside the negative environmental impacts of mining the required minerals.

**Electrochemical direct ocean capture (eDOC)** is an emerging technology for removing $CO_2$ from seawater. It currently has high energy costs and similar risks to alkalinity enhancement. Geological storage of the captured carbon is also possible, in which case the process becomes electrochemical direct ocean carbon capture and storage (eDOCCS). Combining eDOCCS with seawater desalination could enable arid regions to build adaptive capacity.

## Engineered CDR

The engineered category of CDR blurs the definition of carbon removal because it includes CCS approaches, such as bioenergy with carbon capture and storage and direct air carbon capture and storage (see table 4). CCS processes in which $CO_2$ is captured at source from the extraction of fossil gas or the combustion of fossil fuels are outside the strict technical definition of geoengineering. However, the geological sequestration element of these approaches still relies on the infrastructure developed by fossil-fuel companies.

**Bioenergy with carbon capture and storage (BECCS)** is the use of biomass, such as wood, maize, or sugar cane, as a fuel in a thermal electricity-generating plant, with CCS technologies capturing the carbon emissions from the exhaust gases. There are currently

**Table 4. An Overview of Engineered CDR Approaches**

| Approach | Current Mitigation Potential | Cost per Ton of $CO_2$ | Technical Readiness Level | Risk Areas |
|---|---|---|---|---|
| Bioenergy with carbon capture and storage (BECCS) | 0.00051 $GtCO_2$ per year | $15–400 | Varies depending on type of tech<br><br>4–5 or 8 | CDR durability<br>Water security<br>Land-use change<br>Food security<br>pH changes and nutrient flows<br>Ecosystem damage<br>Health, toxicity, and pollution<br>Socioeconomic impacts |
| Direct air capture (DAC) | 0.000004 $GtCO_2$ per year | $600–1,000* | Varies depending on type of tech<br><br>1–2 or 7 | CDR durability<br>Health, toxicity, and pollution<br>Energy security |

* Some cost estimates are as high as $5,000 per ton.

Source: Authors' compilation.

six commercial BECCS power plants in operation around the world and fifty-six more in development.[70] Yet, BECCS has potentially significant impacts on water and food security, biodiversity, and land use change. One BECCS facility in the United States was estimated to have emitted four times as much $CO_2$ as the amount sequestered.[71]

**Direct air capture (DAC)** is the method of carbon removal that receives the most attention and funding at present. This technology uses chemical reactions to extract $CO_2$ directly from the air. The captured carbon can then be permanently stored—in the process known as direct air carbon capture and storage (DACCS)—or used in other applications, such as providing $CO_2$ for carbonated drinks. DAC is highly energy intensive and expensive, however, because ambient air has lower concentrations of $CO_2$ than at-source emissions, such as power-plant exhausts. Current carbon removals from DAC are also minimal, at just 0.000004 $GtCO_2$ per year.[72]

This technology is unproven at scale and has no ecosystem co-benefits.[73] A 2024 study found that assumptions about scaling up current DAC technologies to the gigaton scale are unrealistic because of the excessive energy use required and the estimated costs, which could exceed $5,000 per ton.[74] In light of these obstacles, achieving a cost of $100 per ton of $CO_2$ captured via DAC has become a widely shared aim. Governments, investors, and large corporations are funding this endeavor, with twenty-seven DACCS plants commissioned worldwide and another 130 planned.[75] It has been discovered, however, that DAC company Climeworks has been unable to capture enough carbon to cover even its own emissions.[76]

Some of the technologies involved in DAC have a long history, and the United States has pioneered carbon capture and utilization as a key technology in enhanced oil recovery—the process of injecting $CO_2$ into oil and gas reservoirs to extract more fossil fuels.[77] Using captured carbon during this process is typically not considered carbon removal, as any permanent storage of carbon is essentially a by-product of such operations. Where captured carbon is used in other products, such as chemicals and synthetic fuels, the method may also not provide durable storage.

## CDR Experiments and Public Opinion

Discussions of carbon removal have so far typically failed to consider public acceptance of these interventions. To date, limited research has been carried out on public perceptions of geoengineering. This is despite high-profile cases of protest against real-world geoengineering experiments. For CDR, these have tended to center on ocean-based approaches, such as artificial ocean fertilization and ocean alkalinity enhancement. This may be because the marine environment is viewed as a special natural environment that is more fragile than the land.[78]

In 2008, a U.S. businessman attempted to carry out large-scale iron fertilization in the Galápagos and Canary Islands. He failed, but later convinced a First Nations community in British Columbia to fund the dumping of 100 tons of iron sulfate in the Haida Gwaii archipelago as part of a "salmon restoration" project.[79] Critics viewed this move as a violation of both the UN Convention on Biological Diversity and the London Convention on the dumping of wastes at sea.[80]

Pilot projects by academic institutions are also experiencing opposition. The Woods Hole Oceanographic Institution's alkalinity enhancement project faced criticism from environmental groups and fishermen and had to scale back its plans.[81] The institution now has U.S. governmental approval to dump 50 tons of lye (sodium hydroxide solution) into the Atlantic Ocean off Cape Cod in 2025.[82]

In the UK, an ocean alkalinity enhancement project off the Cornwall coast was stopped because of public protests against experiments by the Canadian company Planetary Technologies.[83] This followed the firm's previous trial in Halifax, Nova Scotia, which had dyed water in the harbor pink.[84] Planetary Technologies, which plans to sell carbon credits from this type of carbon removal, is one of hundreds of companies worldwide seeking to monetize CDR.[85]

Large-scale DAC plants in Louisiana and Texas, which are due to receive $550 million and $500 million, respectively, from the U.S. government, face opposition on the ground that they will continue to afflict low-income communities and perpetuate the fossil-fuel industry.[86] The Occidental Petroleum–owned facility in Texas aims to remove 0.005 $GtCO_2$ per day, and the company has a plan for one hundred such plants. If achieved, this would account for less than 1 percent of current U.S. emissions.[87] These projects are, however, on a list of initiatives launched during the administration of former president Joe Biden to be defunded under the second Trump administration.[88]

## Solar Radiation Management Methods

SRM seeks to mitigate the consequences of human-caused climate change by altering the energy balance of the Earth's climate system. Increased concentrations of greenhouse gases are trapping more heat in the lower portions of the atmosphere, resulting in rising average global temperatures. SRM seeks to reduce this additional heat by lowering the total amount of energy that enters the atmosphere or by increasing the amount of energy that leaves.

For simplicity, the different SRM methods are categorized here with reference to their potential deployment location:

- surface-based: methods that modify the land, the ocean, or glaciers;
- atmosphere-based: methods that modify clouds or the stratosphere; or
- space-based: sunshades or mirrors in space.

As with CDR, cost is a key factor in determining SRM approaches' readiness for deployment. It has been estimated that stratospheric aerosol injection could deliver 1°C of global mean cooling for $18 billion.[89] Such costs are significantly lower than that of decarbonizing the global economy by 2050, which is estimated at $9.2 trillion per year.[90] These figures should be set against other reports that have found that unmitigated climate change could cost the global economy $178 trillion by 2070.[91] Meanwhile, global adaptation to sea level rise is estimated to cost $1.4 trillion a year by 2100.[92] A transition to a decarbonized energy system could save $12 trillion.[93]

Alongside cost, radiative forcing potential and technical readiness are among the key assessment criteria for SRM approaches. However, these methods also come with significant risks, the impacts of which could be felt in regions unconnected with their deployment. These risks include increases in temperature extremes and disruption of precipitation, with serious consequences for food security.[94]

### Surface-Based SRM

The Earth's albedo is a measurement of its reflectivity, which determines how much of the Sun's energy the planet bounces back into space. Surface-based SRM techniques aim to increase the reflectivity of the land or sea (see table 5).

**Table 5. An Overview of Surface-Based SRM Approaches**

| Approach | Current Radiative Forcing Potential | Cost | Technical Readiness Level | Risk Areas |
|---|---|---|---|---|
| **Land-based albedo modification:** | | | | |
| – urban | -0.1 $W/m^2$ | $300 billion per year for a few tenths of -1 $W/m^2$ | 9 | Thermal impact |
| – crops | -0.5 $W/m^2$ | No data | 7 | Ecosystem damage<br>Water security |
| – deserts | -2 $W/m^2$ | Several trillion dollars per year for -2 $W/m^2$ | No data | Water security<br>Ecosystem damage |
| **Ocean albedo modification** | Several -$W/m^2$ | No data | No data | Water security<br>Ecosystem damage<br>Health, toxicity, and pollution |
| **Arctic or Antarctic geoengineering** | n/a | No data | 3–4<br>9 for glacier cover systems | Thermal impact |

Source: Authors' compilation.

**Land-based albedo modification** can be achieved by painting roofs, pavements, and roads white; planting light-colored crops; or leaving crop residues on bare ground. The impact of this method on global temperatures may be small, as the expected benefits are limited to offsetting the urban heat-island effect, which in itself has the co-benefit of reducing energy demand for cooling. Proposals to cover large areas of desert with reflective material carry risks for desert ecosystems and would probably cost trillions of dollars. There is also a disconnect between this idea and the proposed large-scale deployment of technologies with the opposite aim: artificial black surfaces or solar photovoltaic panels to enhance rainfall or generate electricity.

**Ocean-based albedo modification** is focused on creating highly reflective microbubbles under the surface of the ocean, for example in the wakes of ships. The effect of this technique is similar to the white caps of breaking waves on beaches, and the aim is to create an ocean mirror to reflect more sunlight from the ocean's surface. The lifetime of the bubbles produced could be extended by adding a surfactant, a type of chemical compound, although the impacts of this method on human and natural systems are largely unresearched.

**Arctic or Antarctic geoengineering**, also referred to as glacier geoengineering or glacier stabilization, falls in the realm of climate adaptation because the aim is to conserve the frozen poles. The methods proposed range from installing reflective tarpaulins or layers of hollow glass beads to submerging enormous barriers in front of ice sheets and glaciers.

The limited effectiveness of this subcategory of geoengineering can be seen in experiments in the Svalbard archipelago that aimed to pump seawater back onto the ice sheet. These produced a 24 centimeter (9 inch) thick layer of ice that lasted only six days.[95] In addition, this method has a particular geopolitical angle, as scientific visions do not necessarily match political realities. Russia, for example, has a strong stake in a melting Arctic so as to open the Northern trade route. Moscow is also interested in the energy and mineral resources at the North Pole, which could become more readily available with thawing. Threats in early 2025 by the Trump administration to acquire Greenland—peacefully or aggressively—indicate that geostrategic competition will increasingly focus on the High North, with great implications for claims over land, sea, and resources in territories that are opening.

This competition may indicate that the world has entered an era of climate niche geopolitics, in which climate change is viewed as a geostrategic enabler for various forms of power projection and security bulwarks. Given these developments, even if refreezing were technically feasible, the key concerns with such measures are where decision making authority lies, how to deal with sovereignty claims, and how to ensure security, particularly for the Antarctic ice sheet.[96]

### Atmosphere-Based SRM

This class of SRM is the most controversial. Among the methods in this category are stratospheric aerosol injection, marine cloud brightening, and cirrus cloud thinning (see table 6). It should be noted that atmosphere-based SRM may lead to higher temperatures in the Arctic than if the global mean temperature were lowered through emissions reductions; this could have an unintended detrimental impact on the preservation of ice sheets or glaciers.[97]

**Stratospheric aerosol injection (SAI)** has received the most attention, as it is promoted as a relatively quick and cheap way to reduce global temperatures, but it carries significant risks of devastating and unequal impacts on Earth and human systems. SAI is the injection of tiny, highly reflective particles into the stratosphere, around 20 kilometers (12 miles) above the Earth's surface, to reduce the amount of energy that enters the atmosphere. Most studies have focused on particles of sulfur dioxide. Other substances, including titanium dioxide, engineered nanoparticles, and diamond dust, have also been proposed, even though the latter would cost $200 trillion over the remainder of the century.[98]

**Table 6. An Overview of Atmosphere-Based SRM Approaches**

| Approach | Current Radiative Forcing Potential | Cost | Technical Readiness Level | Risk Areas |
|---|---|---|---|---|
| Stratospheric aerosol injection | -2 to -5 $W/m^2$ | $18 billion per 1°C of global mean cooling | 3 | Thermal impact<br>Water security<br>Food security<br>Energy security<br>Ecosystem damage<br>pH changes and nutrient flows<br>Health, toxicity, and pollution<br>Termination shock<br>Geopolitical tensions |
| Marine cloud brightening | -1 to -5 $W/m^2$ | $1–2 billion per year for 1 W/m2 | 4 | Thermal impact<br>Water security<br>Ecosystem damage<br>Geopolitical tensions |
| Cirrus cloud thinning | -1 to -2 $W/m^2$ | No data | 4 | Thermal impact<br>Water security |

Source: Authors' compilation.

Among the risks of SAI are significant disruption of major weather patterns in Africa and Asia, including the monsoon; increased depletion of the ozone layer; negative impacts on terrestrial and oceanic biodiversity; potential weaponization; the centuries-long, intergenerational burden of deployment; and the risk of termination shock—a rapid and devastating increase in global temperatures if the method is stopped without significant emissions reductions and/or carbon removal.

**Marine cloud brightening** involves spraying sea salt particles into clouds above the sea to increase their reflectivity. This technique could be effective at lowering temperatures or boosting rainfall in certain regions, but it could cause negative side effects in other parts of the world because of so-called teleconnections—links in the climate system and between ecosystems in distant parts of the world. These effects may cause a rise in geopolitical tensions. Marine cloud brightening could also become less effective as the climate warms, potentially even causing a net warming rather than cooling effect.[99]

**Cirrus cloud thinning** is an SRM method that does not reflect sunlight but rather allows more long-wave energy to escape back into space and therefore increases rates of cooling. This would be done by injecting ice nuclei, dust, or pollen into cirrus clouds, which form in the upper troposphere. However, there are large uncertainties over whether cirrus cloud thinning would in fact generate cooling. The biophysical risks are similar to those of SAI.

### Space-Based SRM

Proposals to launch satellite-mounted mirrors, reflective bubbles, or giant sunshades into space are gaining attention. Such devices would be located at Lagrange point one (L1)—the point in space where the gravitational pulls of the Earth and the Sun cancel each other out. A prototype sunshade is currently being developed at the Technion–Israel Institute of Technology, which has a research focus on military technology.[100]

The cost of developing and launching such technologies is expected to be in the range of many trillions of dollars (see table 7), but the biggest concern is its weaponization, especially as space is a contested military domain.[101] Added to that is the risk of damage to the sunshade from solar storms or collisions with asteroids or parts of comets, which could result in termination shock and rapid warming. Finally, at the core of space-based solutions to terrestrial problems are existential questions about humanity's stewardship of the planet. These sit in contrast to ideas being explored by big tech billionaires of giving up on the Earth and colonizing outer space instead.[102]

### SRM Experiments and Public Opinion

SRM methods are considered to be more controversial than CDR. This distinction was highlighted in a 2024 written opinion by the chief scientific advisers to the EU, which called for an EU-wide moratorium on deploying solar geoengineering but recognized the need for future research and negotiations on a global governance framework.[103]

**Table 7. An Overview of Space-Based SRM**

| Approach | Current Radiative Forcing Potential | Cost | Technical Readiness Level | Risk Areas |
|---|---|---|---|---|
| Space-based geoengineering | -4 $W/m^2$ | $5–10 trillion for the launch | 2 | Thermal impact<br>Water security<br>Food security<br>Geopolitical tensions |

Source: Authors' compilation.

Public resistance to SRM experiments has been much greater than for CDR. A recent example is a University of Washington marine cloud brightening project off the coast of California in April 2024. The experiment did not involve actual cloud brightening but a test of sea salt particles being sprayed under different atmospheric conditions. However, City of Alameda officials halted the project, citing possible health concerns. Opponents also felt that such local testing would open the door to global deployment and distract attention from tackling rising emissions.[104]

Opposition to SRM has also come from national governments. In 2023, Mexico stated that it would ban solar geoengineering experiments in response to the unauthorized launch by start-up Make Sunsets of weather balloons that contained helium and sulfur dioxide.[105] The company sells cooling credits, a concept akin to carbon offsetting but for SRM projects. Mexico is now considering how to incorporate the ban into legislation—though it has not done so as of this writing.[106] A similar project in the UK, provocatively named SATAN (Stratospheric Aerosol Transportation and Nucleation), released a high-altitude balloon containing sulfur dioxide in September 2022.[107] The results of this test have yet to be published.

The longest-running opposition to solar geoengineering trials was a campaign by the Indigenous Sami people of northern Sweden and the Hands Off Mother Earth (HOME) Alliance against a Harvard University SAI trial. The Stratospheric Controlled Perturbation Experiment (ScoPEx) planned to release calcium carbonate particles into the upper atmosphere via a balloon and measure the ability of these aerosols to reflect sunlight. The test was abandoned in 2021, however, and the project was canceled in March 2024 because of public resistance from the Sami people, who said that "blocking out the sun with reflective particles to cool the earth is the kind of thinking that produced the climate crisis in the first place."[108]

The opinions of Indigenous peoples and those outside the geoengineering power base of the Global North are gaining prominence. In February 2024, the UN Environment Assembly failed to reach a consensus on governing, coordinating, or even collating SRM research or knowledge. A small but influential group of states led by the two biggest fossil-fuel-producing countries, Saudi Arabia and the United States, opposed governance. On the other side, there was strong resistance to further unilateral and unbalanced research and experimentation from African, Asian, Pacific, and Latin American countries.[109] Meanwhile, the EU, the UK, and others were cautiously supportive of more science but took a precautionary stance on experimentation.[110]

In 2023, the African Council of Ministers called for an international commitment to the nonuse of SRM and to limits on certain kinds of experimentation and funding.[111] A prominent African climate expert warned against the Global North treating Africa like a "giant climate laboratory."[112] As for the academic debate, an open letter from physical and biological scientists showed support for SRM research to address climate risk.[113] Which of these voices will have a long-lasting influence on SRM research and governance remains to be seen.

# The Risks of Geoengineering: A New Typology

Climate change generates multisector and multidimensional risks to the biosphere, the global economy, peace and security, and geostrategic equilibriums. Human health, ecosystems, water, food, infrastructure, and economies are already being affected. For Europe, the fastest-warming continent, many climate risks have reached critical levels and could become catastrophic.[114]

In response to climate change, various transition efforts are underway, which generate risks of their own. For example, mining associated with the energy transition has physical impacts on critical ecosystems. The global scale of mining means that it will add to the instability of ecosystem services on top of the pressures from climate breakdown. Beyond this kind of risk are the geoeconomic and geopolitical impacts of reducing or phasing out dependence on fossil fuels. In this regard, the risks of the transition away from fossil fuels focus on the potentially damaging impacts of policy, legal, regulatory, or market changes, such as financial instability, energy price rises, stranded assets, and unemployment.

In other words, climate and transition risks interact and need to be managed together to avoid derailment risks—a situation in which the consequences of climate change make it increasingly hard to deal with its drivers. For example, rebuilding after more devastating storms will suck in resources that could have been used to build out renewable energy infrastructure. More insidiously, rising climate disruption can unpick cooperation within and between countries as struggles over resources and the social and political upheaval produced by forced migration increase. These interactions already add considerable complexity to risk management in the age of climate disruption.

Geoengineering approaches, as planetary-level interventions, further complicate risk dynamics. On the one hand, CDR is promoted as a form of climate change mitigation, while on the other, SRM is advanced as a type of adaptation. However, neither category does anything to tackle the root cause of global heating. The climate responses that geoengineering provides lock humanity into path dependencies and produce cascading risks. In addition, the hazards and impacts of CDR and SRM are not limited to the locations in which they are deployed. SRM can have repercussions across time as well as space, affecting generations far into the future. Techno-solutionism is becoming an omnipresent phenomenon. This approach creates competition for resources rather than engendering a global environment of cooperation for a stable climate, ecological restoration, and equitable standards of living.

Against this background, geoengineering is often discussed using a risk-risk framework, which offers a narrow, binary worldview: whether it is better to endure the impacts of increasing climate change or risk deploying technologies that may have unintended effects.

This framing can imply that geoengineering is the only alternative to climate breakdown, with the risk assessment framed in terms of a choice between geoengineering technologies and unmitigated climate change. This kind of analysis appears to have been advanced at a solar geoengineering event at COP29 in November 2024.[115]

Geoengineering and the concept of overshoot are allowing policymakers to argue that both climate risks and transition risks can be reduced. Overshoot is a narrative that strongly promotes the idea of geoengineering, as such interventions are essential for a post-1.5°C recovery. However, what is not discussed is the set of new risks that overshoot introduces.

Overshoot represents a significant increase in the complexity of the climate crisis and begs questions such as: How is it going to work? Where are the guardrails, and who is in charge? What are the risks of not just stepping over the redline of 1.5°C but sliding far beyond it?

The broad range of risks thrown up by geoengineering encompasses almost all categories of planetary and societal hazards as well as new types of second-order risk. Overshoot, in particular, presents risks that are not only more severe than those of individual geoengineering approaches but could also lead to irreversible changes in Earth systems and terminally compromise attempts to return to a stable global climate.

## Categorizing Geoengineering Risks

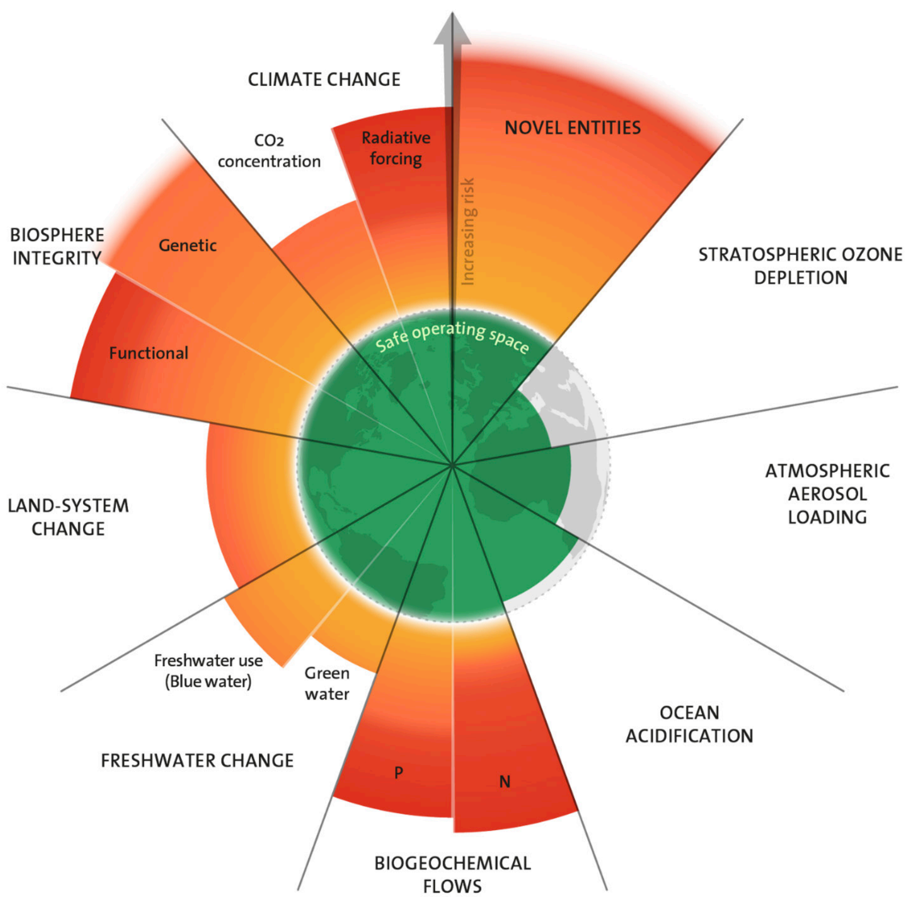
Geoengineering risks are generally evaluated from a biophysical or social perspective by looking at the impacts on both Earth and human systems. Biophysical risks include those to the climate, the land, the water cycle, and ecosystems. Social aspects encompass livelihoods, food security, energy use, and the threat of conflict. The impacts of geoengineering touch on most of the UN sustainable development goals.

In terms of purely environmental or biophysical risks, since 2009 the Stockholm Resilience Centre has carried out planetary-scale risk assessments and found in 2023 that the Earth has already transgressed six of its nine planetary boundaries (see figure 5).[116] This framework is important because climate breakdown is one of many interdependent planetary and ecological crises. The implication is that the climate crisis is simultaneously a manifestation and a driver of other ecological emergencies. By extension, any significant response to the climate crisis will necessarily affect other ecological pillars of planetary resilience and health. Depending on the type of climate intervention, negative and/or positive effects can interact with other ecological crises.

Geoengineering creates an extra layer of pressure on interconnected systems that are already under considerable strain. This is because focusing only on $CO_2$ concentrations can move humanity farther away from other safe zones for sustaining life on Earth. For example, research has found that the large-scale deployment of BECCS would have damaging impacts on freshwater use, land-system change, biosphere integrity, and biogeochemical flows, pushing humanity deeper into red zones of these planetary boundaries.[117]

It can be argued that large-scale carbon removal is therefore a form of global catastrophic risk. This is because it would affect "critical [systems] whose safety boundaries are breached by a potential threat," according to a 2024 study of global risk, and could affect large proportions of the human population, particularly with regard to food and water security.[118] Focusing on end-of-century temperature targets through a narrative of overshoot increases the likelihood of multiple failures of ecological and human systems, especially if novel methods of carbon removal cannot be scaled up and there continues to be a reliance on nature-based approaches.

**Figure 5. The 2023 Update to the Planetary Boundaries Framework**




Source: Stockholm Resilience Centre, based on analysis in Katherine Richardson et al., "Earth Beyond Six of Nine Planetary Boundaries," Science Advances 9, no. 37 (2023). Licensed under CC BY-NC-ND 3.0.

Climate risk scholars Aaron Tang and Luke Kemp have noted that solar geoengineering has various pathways to global catastrophic risk: direct impacts on ecological systems; interactions with other catastrophes, such as nuclear war or a major volcanic eruption, potentially leading to termination shock; aggravation of existing vulnerabilities in systems such as agriculture or health; or the triggering of latent risks, for example in the aftermath of societal collapse, which could also lead to termination shock.[119]

Accordingly, the following analytical framework gathers risks into two groups by viewing geoengineering approaches first in isolation from one another and then collectively as sources of global catastrophic risk.

## The Risks of Individual Geoengineering Approaches

Any individual geoengineering method may carry one or more of three distinct risks:

- **It does not work:** The method does little or nothing to stop climate change impacts or even increases emissions or temperatures.
- **It causes harm:** The method damages and destabilizes already-fragile biophysical and social systems.
- **It exacerbates international tensions:** The method erodes global peace, security, and cooperation, given the existing political context and the lack of any international governance framework for CDR or SRM.

### Minimal or Negative Impact

This is the risk that a particular geoengineering method does little or nothing to reduce climate change impacts—or actually raises temperatures or emissions. It should be noted that all geoengineering approaches produce additional greenhouse gas emissions, which must be set against their removal or radiative forcing potential. Geoengineering attempts may cause unintended changes in temperature and albedo that counteract the proposed mitigation effects. This risk of minimal or negative impact can take one of six forms.

The first relates to the **lack of equivalence between removals and avoidance**. A key risk with carbon removals is the false assumption that one ton of sequestered carbon is equivalent to, and can therefore cancel out, one ton of emitted carbon. Unfortunately, emissions are more effective at raising $CO_2$ concentrations than comparable removals are at lowering them.[120] There is a significant asymmetry: It is much more difficult to stabilize the climate than to destabilize it.

The second concern is the **reduced mitigation potential of land-based removals**. Current rates of CDR are estimated to be 2.2 $GtCO_2$ per year, most of which comes from afforestation or reforestation.[121] The onus is on such nature-based solutions not only to help reach net zero by compensating for residual emissions but also to achieve net negative emissions and so reduce atmospheric concentrations of $CO_2$. However, the actual amount of carbon removed by land-based sinks is difficult to estimate. For example, the carbon-removal benefits of forest-based methods may be one-third less than currently thought because forestation decreases surface albedo, leading to a warming effect.[122]

With higher temperatures, forests also become less able to absorb carbon, posing an increased risk of forests becoming carbon sources rather than carbon sinks. Research in 2024 found an unprecedented weakening of land carbon sinks in the previous year.[123] Other assessments of the global carbon cycle, however, found a smaller weakening.[124] Added to this is the increasing difficulty of conserving land-based sinks because of mismanagement and rising climate impacts, such as more intense and frequent wildfires, droughts, and pests.

The ability of soil to sequester carbon is also potentially overstated. For example, in the United States, SCS from cover crops is argued to be one-fifth of previous estimates and, at scale, would not be a low-cost mitigation pathway.[125] Overly optimistic figures for carbon removal can be highly misleading for policymakers, especially if the actual removals are not based on credible measurements.

A holistic approach to land management is essential if CDR, ecological restoration, and socioeconomic use are to be balanced. For instance, forest conservation has become a key mitigation option for over a quarter of countries signed up to the Paris Agreement. However, this may come at the cost of significant increased emissions from the conversion of unforested land, such as pasture, for crops.[126]

In addition, the framing of nature restoration as carbon removal is highly damaging. The EU's CRCF certification framework promotes the term "carbon farming" in relation to activities that enhance carbon sequestration in, or reduce emissions from, forests and soils, such as peatland restoration or reforestation.[127] Critics of the scheme, however, view it as an opportunity for continued carbon pollution by the agricultural sector and the fossil-fuel industry, which will use the resulting carbon credits as a way to delay essential emissions cuts.[128] Moreover, increasing the resilience of ecosystems and improving biodiversity should be the primary aims, with carbon sequestration as a co-benefit. There is also the question of who determines which areas of land are restored and for whom. Monitoring of the socioeconomic outcomes of such projects tends to lag behind assessments of their ecological impacts.

Third, **monitoring, reporting, and verification** (MRV) is a key issue across geoengineering approaches, as it is essential to know whether the interventions are working as designed. For CDR, this means measuring the amount of carbon removed through a specific project, sharing the data, and verifying them. Yet, some CDR methods, such as SCS, enhanced weathering, and ocean-based techniques, pose considerable challenges for assessing removals, not least the high costs involved, and many field trials are unable to confirm a $CO_2$ drawdown effect.[129] As solar geoengineering remains a contested concept, MRV frameworks for SRM have been little discussed and would have to form part of any international governance structure for deployment.

The fourth issue is the **temporary nature of most carbon removal**. CDR was defined in a 2023 assessment of carbon removal as “capturing CO2 from the atmosphere and storing it away for decades to millennia,” although this provides quite a broad definition of the permanence or durability of such removals.[130] How long the $CO_2$ is stored is an important consideration because the vast majority of carbon captured today is stored only temporarily through natural carbon sinks, such as trees and soils. Only geological sequestration and enhanced weathering—and, perhaps, capturing carbon in concrete—can remove carbon for 1,000 years or more.[131] This is the gold standard for permanence. However, for many carbon-offset registries, twenty-five to one hundred years is considered sufficient durability of land-based sinks for carbon removal.[132]

$CO_2$ can be rereleased into the atmosphere through natural processes, such as decomposition of organic matter in soils, climate change–induced warmer temperatures, human mismanagement, or changes in land use. For geological sequestration, rerelease can also occur via transportation to storage sites, well blowouts, or earthquakes. A project looking at artificial ocean fertilization in the Southern Ocean found that more than 66 percent of the captured carbon returned to the atmosphere within a few decades.[133] Blue-carbon ecosystems are also likely to lose their stored carbon in scenarios of higher warming.

Fifth, geoengineering technologies may in fact generate **additional greenhouse gas emissions**. The operational carbon emissions from enhanced weathering projects are a good example: Achieving a proposed annual removal of 4 $GtCO_2$ would involve mining, transporting, and crushing 13 billion tons of rock per year. The electricity requirements for this amount of rock could reach 3 percent of current global electricity consumption.[134]

One of the biggest sources of additional emissions is the use of $CO_2$ for enhanced oil recovery, rather than storage. This process has been a major recipient of funding for geological carbon sequestration projects and is the largest industrial use for $CO_2$.[135] (Enhanced oil recovery should not be confused with fracking, where high-pressure fluids are pumped underground to force open existing fissures.) The Occidental Petroleum DAC plant in Texas plans to use $CO_2$ to increase the production of crude oil, giving the oil industry “a license to continue to operate for the next 60, 70, 80 years,” according to Occidental Chief Executive Officer Vicki Hollub.[136]

Emissions of non-$CO_2$ greenhouse gases, such as methane and nitrous oxide, which are little considered in removal scenarios, are a further important factor. Both of these powerful greenhouse gases can be emitted as a result of forming new blue-carbon ecosystems or sinking marine biomass through artificial ocean fertilization, which would counterbalance these methods' climate change mitigation potential. On land, the use of mineral fertilizers, such as nitrogen, can contribute to SCS but can also produce nitrous oxide. SCS can compensate for some greenhouse gas emissions related to agriculture, but it is unlikely to balance out emissions from other sectors.

In terms of SRM, cooling due to SAI could reduce nutrient cycling and ecosystem primary production, accelerating the accumulation of $CO_2$ in the atmosphere and the ocean. There are also emissions associated with a significant use of energy. For marine cloud brightening, to achieve the proposed maximum radiative forcing of -5 watts per square meter ($W/m^2$), 1 million gallons of fuel would need to be combusted every day.[137] (Changes to the Earth's energy balance that have a cooling effect are called negative forcing and are denoted by negative values.) Aircraft and rockets are among the delivery mechanisms proposed for SAI, and space-based methods will also have considerable emissions associated with the launch of spacecraft.

Finally, geoengineering techniques can reduce albedo and thus have an **increased thermal impact**. For CDR, afforestation of global dryland areas would produce a large warming effect because of forests' lower albedo and would therefore counteract most of the carbon sequestration taking place. Higher global temperatures could also mean that tropical reforestation would be markedly less effective as a carbon sequestration tool. The application of biochar to soil can decrease albedo as well.

For SRM, albedo modification on land and in the ocean carries the risk of changes to regional precipitation and circulation patterns, including monsoons. Modeling has shown that painting roofs white over large areas could contribute to changing rainfall patterns.[138] Meanwhile, there is a risk that sea-ice geoengineering with glass microspheres could actually make the ice less reflective.[139] Marine cloud brightening could create negative impacts on temperature and precipitation over northeastern South America, exacerbating global warming, as the Amazon rainforest is a major carbon sink.

It is SAI that would have the biggest impacts, however. In some potential scenarios, 55 percent of the global population would experience rising temperatures over the decade after SAI deployment, with a high probability of extremely hot years. Depending on how SAI was conducted—for example, where sulfur compounds were injected—the most affected areas would be northern Eurasia, the Western United States, and East Antarctica.[140] Low-latitude injections of aerosols may result in large-scale changes to the weather in the tropics and increased warming in the polar regions—an impact of space-based SRM as well. In contrast, there is also a risk of excessive cooling because of uncertainties in the amount of SAI required as well as the potential impact of a major volcanic eruption.

## Harm to Biophysical and Social Systems

This risk may be framed as a trade-off: The need to remove carbon emissions means having to accept impacts in other areas. However, many geoengineering approaches affect multiple domains, eight of which stand out: water security; food security; land- and ocean-use change; energy security; damage to ecosystems; pH changes and nutrient flows; health, toxicity, and pollution; and socioeconomic impacts.

The first impact is on **water security**. To achieve end-of-century mitigation goals through afforestation and reforestation, an estimated 370 billion cubic meters (13 trillion cubic feet) of water would be required each year.[141] For context, if this CDR method were a country, it would rank fourth for national freshwater withdrawals, after India, China, and the United States.[142] Ill-advised afforestation initiatives can contribute to the depletion of freshwater resources, which can impact ecosystems' ability to survive droughts and therefore negatively affect terrestrial carbon storage.

Moreover, such programs exacerbate water scarcity for local communities. In Africa and Oceania, especially in dryland regions, afforestation would substantially increase water scarcity, as rain can provide only up to 40 percent of the trees' water requirements.[143] BECCS is another CDR approach that can raise water stress more than the climate change it is meant to mitigate. The water demand of this method could reach 10 percent of water consumption in several regions by 2050.[144]

The deployment of SAI would have particular and serious impacts on rainfall. Models indicate both more frequent droughts and greater precipitation over most regions, especially the Sahara, South America, southern Africa, and Australia, while Alaska, Greenland, Southeast Asia, and tropical Africa would face enhanced droughts.[145]

The second concern is **food security**. The mitigation potential of CDR is generally based on purely technical or economic assessments. Significantly lower figures are arrived at when the wider sustainability impacts are considered. For example, if the full technical mitigation potential of both BECCS and afforestation and reforestation were realized, they would require land three times the area of the United States and push more than 300 million people into food insecurity.[146]

Climate change is already causing grave damage to global agriculture, and SAI is not only unlikely to alleviate this but would also threaten the food supplies of billions of people.[147] This is because changes to tropical monsoons and a decrease in direct sunlight would affect crops.

Third, geoengineering techniques can cause **changes in land and ocean use**. This category of risk has crossovers with food security and biodiversity. The amount of BECCS suggested in several scenarios of 2°C warming may require between 0.5 and five times the current land area used to grow the world's entire cereal harvest—3.6 to 36.1 million square kilometers (1.4 to 19.3 million square miles). Significant ecosystem restoration would have to happen alongside any deployment of land-based CDR.[148] The needs of afforestation and reforestation would also provide competition for land. If the end-of-century mitigation potential of 4 $GtCO_2$ per year were to be achieved, 3.2 million square kilometers (1.2 million square miles) of land would be required.[149] Government pledges for land-based carbon removal in fact add up to around 10 million square kilometers (3.9 million square miles).[150] This is equivalent to two-thirds of the world's arable land and is more than the combined areas of the EU, India, South Africa, and Turkey.

The change in use of large areas of the ocean would also need to be considered if large-scale seaweed cultivation were to take place. Gigaton-scale carbon sequestration would mean farming very large areas—more than 90,000 square kilometers (35,000 square miles), over thirty times the current seaweed-farming area.[151] For example, harvesting 1 billion tons of seaweed carbon per year would mean farming more than 1 million square kilometers (0.4 million square miles) of the most productive exclusive economic zones in the equatorial Pacific. To attain an additional 1 billion tons per year, the cultivation area would need to be tripled because carbon sequestration becomes less efficient in less productive waters.[152]

The fourth impact is on **energy security**. As discussed above, enhanced weathering is particularly energy intensive. DAC also requires potentially very large amounts of energy, with estimates ranging from 180 to 500 megawatts (MW) per 0.001 $GtCO_2$.[153] Another assessment found that to achieve the Paris Agreement target of keeping well below 2°C of warming by capturing 30 $GtCO_2$ per year, DAC would require either 46–71 percent or 110–191 percent of the global energy supply, depending on the type of technology used.[154] For DAC to be viable from environmental and economic standpoints, the electricity supply would have to be fully decarbonized, but this would conflict with the global transition to clean energy. With regard to marine-based approaches, eDOC is the most energy-intensive form of $CO_2$ capture.[155]

A 2024 analysis also found that cost estimates for BECCS and DACCS could be up to $460 billion per year, based on these methods' requirements for high heat energy.[156] These figures account for nearly 50 percent of the cost of DACCS and at least 33 percent of the cost of BECCS. There are therefore risks that such costs "could become increasingly incompatible with policy imperatives that prioritize energy security and affordability" and that "the reliance on engineered carbon removals that many countries have already incorporated in their net zero planning would no longer be achievable," according to the study's authors.

SRM may affect energy security, too. Using SAI to reduce high-end to moderate global warming could decrease electricity generation from solar photovoltaics and other forms of renewable energy, making such generation more difficult and more expensive. This outcome risks continuing fossil-fuel dependence.

Fifth, geoengineering methods can cause **damage to ecosystems**. CDR and SRM can affect the abundance, diversity, and growth rates of various ecosystems. For example, across Africa, very large unforested ecosystems are being threatened by inappropriate restoration through tree planting.[157] Trees are not synonymous with biodiversity. Afforestation of grasslands has significant negative impacts on biodiversity and leads to major declines in soil quality, natural pest regulation, and the supply of pollination services. Converting land for BECCS would also require widespread loss of habitats and natural ecosystems; in some scenarios, more than 50 percent of natural forests would be lost or degraded.[158]

Marine ecosystems may also be significantly affected by CDR. Artificial ocean fertilization can lead to nutrient redistribution and depletion, reduced light, and mid-water oxygen depletion. Entire ecosystems from the upper ocean to the seafloor may be altered. There is also an increased risk of toxic algae. Seaweed farms could impact other habitats, including the deep ocean, by producing organic matter that could affect microbial production, oxygen consumption, and pH and nutrient levels. The effects of ocean alkalinity enhancement on organisms and ecosystems are largely unknown. However, introducing large amounts of metal oxides into the ocean could lead to ecosystem impacts and toxicity in marine organisms. There is also a risk of a potential shift in the composition of phytoplankton species and their growing locations, which could affect fish stocks.

Meanwhile, SAI can result in increased surface levels of ultraviolet radiation and could reduce the survival and growth of many marine and freshwater organisms across trophic levels. SAI could also cause plant communities to shift in phenology, structure, functional traits, and geographic range.

The sixth set of impacts relates to **pH changes and nutrient flows**. On land, large-scale BECCS proposals would require more than 100 million tons of nitrogen fertilizers per year to remove a total of 320 billion tons of carbon and achieve end-of-century temperature targets.[159] This would severely affect food production and the biogeochemical planetary boundary.

In relation to marine CDR, sequestering just 1 percent of global carbon emissions (at 2020 levels) via seaweed cultivation would remove between 1 and 5 million tons of phosphorus and 9–50 million tons of nitrogen from the ocean.[160] This would affect the primary productivity of other organisms. Large-scale ocean fertilization could also lead to ocean acidification in deep water from increased $CO_2$ sequestration at depth, affecting the ability of deep-ocean organisms to build shells and coral.

Seventh, geoengineering has potentially wide-ranging **impacts in terms of health, toxicity, and pollution**. For example, biochar can remain in the soil for hundreds to thousands of years, yet there are limited studies on the health effects and toxicity of both its production and application.[161] Moreover, biochar production creates particulate-matter pollution as well as greenhouse gas emissions. This is also the case for the spreading of mineral dust and mining for enhanced weathering. This approach can release chromium and nickel into the environment, which could be toxic to plants in large quantities.

For ocean albedo modification, the safety of the foam agents used would be a primary concern. While the ideal is foam that is nondispersive, nontoxic, biodegradable, and ecologically benign, there may be trade-offs with the cost and speed of implementation. Such foams have also yet to be tested outside the laboratory. The implementation of SAI could mean a potential delay of twenty-five to fifty years to the recovery of the ozone hole plus additional damage, leading to an increase in surface ultraviolet radiation and impacts on human and ecosystem health.[162]

Finally, geoengineering can have significant **socioeconomic impacts** on rural livelihoods and prosperity. Although afforestation and reforestation projects may have climate benefits, land may have a higher economic value for other uses. There is also a neocolonialist tendency for Indigenous peoples to be forcibly removed from their land because of carbon-offset projects.[163] As well as the impacts on agriculture, the large-scale expansion of crops for BECCS would mean competition with livestock grazing, housing, forest conservation, solar photovoltaics, and wind farms.

Artificial ocean fertilization can exacerbate reductions in fish catch in coastal exclusive economic zones. This is partly due to nutrient robbing, whereby nutrients in the fertilized area reduce biological productivity in adjacent regions, affecting the marine food web.

### Exacerbation of International Tensions

CDR and SRM are often viewed simply in terms of their potential to curb the global rise in temperature or their technical readiness for deployment. This means that questions of governance, geopolitical impacts, and interstate or intergenerational burden can take a back seat. In the words of political scientist Caitlin Talmadge, "overemphasis on the dangers of technology alone ignores the critical role of political and strategic choices in shaping the impact of the technology."[164]

Geoengineering approaches are presented as solutions to a climate crisis that affects humanity as a whole, but their deployment reinforces transactional and utilitarian forms of international relations. For example, many of the countries with the highest emissions—the United States, Canada, Australia, European nations, Saudi Arabia, Russia, and China—have also made large investments in various forms of carbon removal or CCS.[165] In most so-called cost-effective mitigation scenarios, however, a significant portion of the carbon removal is assumed to take place in lower-income countries.[166]

This imbalance has been bolstered by Article 6 of the Paris Agreement, which allows countries to trade carbon credits through bilateral or multilateral agreements.[167] Australia, Japan, Singapore, Sweden, and Switzerland have signed several agreements or memorandums of understanding with lower-income nations, such as Bangladesh, Paraguay, and Rwanda. These countries are more climate vulnerable, food insecure, resource stressed, and lacking in climate finance. And critics have raised red flags about how interstate emissions-trading markets are being exploited in developing nations.[168]

Over 85 percent of total land use in climate pledges is due to a few high- and upper-middle-income countries. For example, Saudi Arabia's pledge is 20 percent of the global total and depends mostly on tree planting in neighboring countries; the U.S. pledge is 12 percent of the total, and four-fifths of this is for BECCS. This is leading to situations that produce new forms of land grab, which can create further fragility for land-linked communities and Indigenous peoples, including displacement and violence.

States are not the only actors involved in these transactions: Companies are adding to the load. A 2023 research piece identified thirty-four companies that had used credits to offset 0.038 $GtCO_2$ in 2020–2022, the equivalent of Ethiopia's and Kenya's combined annual emissions.[169] Big tech's demand for carbon credits is surging particularly fast, as illustrated by the Symbiosis Coalition, which Google, Meta, Microsoft, and Salesforce created to develop 20 million tons of carbon credits by 2030.[170] The coalition was established against the backdrop of soaring energy demand and resulting carbon emissions, for which big tech actors are seeking diversified offsetting and removal strategies.

All of this leads to the key point: As yet, geoengineering is not properly regulated or governed. Article 6 of the Paris Agreement provides a framework for countries to meet their climate targets through carbon markets and, by extension, the implementation of CDR projects. But geoengineering approaches are generally being tested and deployed without rules of engagement, potential prohibitions, or limitations on use.

This lack of regulation has produced a market for experimentation, which creates several issues. One is that private-sector actors, including many start-ups, are using the lack of regulation to test out different products under the guise of climate action. Another issue is that at the state level, there are increasing concerns about security dilemmas and the potential for a technological arms race to deploy geoengineering, or counter-geoengineering, particularly SRM.[171] Or a climate-vulnerable country may feel that it has no option but to try a particular technology as an emergency measure. If one country engages in research on planetary-level technologies, others with the necessary resources could follow suit. It is important to be able to anticipate the potential threats from unilateral research and deployment, especially as SRM has long been viewed as having a dual-use potential—in other words, both civilian and military or preemptive defense research applications.[172]

Solar geoengineering methods come with large challenges in terms of verifying their effects on local precipitation and temperature. Against the background of increasing droughts in various parts of the world, this could produce maladaptation loops, in which shocks increase societal brittleness and push governments to resort to short-term fixes that compound drivers of ecological fragility, leading some populations and countries to become ever more enticed by unsuitable remedies. For example, disruptions of precipitation may lead more countries to resort to weather modification. This type of technology is already being deployed at scale in countries like China with no governance or monitoring frameworks to mitigate its second-hand effects. Indeed, water security is an important issue in the larger set of tensions between China and India. The latter is concerned about the large-scale deployment of rainfall-altering technologies that might take rain away from other regions or, on the contrary, increase rainfall patterns and lead to droughts in some areas and flood risks in others. The problem is that these concerns cannot be proved without robust attribution science. Tensions over perception, disinformation, and opinion manipulation could readily occur here as well.

In this context, it is clear that geoengineering must be regulated and governed. But what should be the aims of such governance? Who should be accountable for dramatic, multidimensional, planetary-level security risks, and how can risk attribution be verified? Will geoengineering play out in favor of or against the notion of climate justice?

These questions are all currently unanswered. In the UN Environment Assembly debates in Nairobi in February 2024, the failure to reach an agreement on SRM research shed light on the obstacles that divergent interests and political differences are placing in the way of necessary global rules. In the meantime, testing, experimentation, and various domestic research programs in the United States and China highlight the risk that technological proliferation may colonize the future through actions on the ground or in the air.

The EU, for its part, adopted a precautionary measure on SRM in late 2024. The union's scientific advice mechanism recommended that the EU push for a global moratorium on the use of SRM while advocating more research on the technologies themselves and their implications.[173] This position illustrates the EU's will to remain at the helm of climate leadership. A risk looms, however. While the union's approach reflects a science-based stance on climate matters, the EU's embrace of competitiveness when it comes to technological innovation and reindustrialization risks enhancing the bloc's material and energy footprint in the next decade.[174] Since the EU's competitiveness trajectory ignores ecology and climate change, the union has failed to design innovation that reconciles climate, ecological, geoeconomic, and technological objectives. Only by doing so will the EU generate true leadership and create alliances with third countries that also seek de-escalation of planetary security risks.

This is even more crucial since governance frameworks have not just reached a legal and normative limit; they are at a point of radical reorganization. Geoengineering developments are the latest sign that humanity has entered the age of planetary security without an institutional and ethical framework to offer guidance and protections. This new age potentially repeats patterns of the past: Countries are locked into security dilemmas that produce technological arms races with ever-expanding energy bases, while inputs are sought from countries that will suffer the brunt of geostrategic competition and climate impacts but have limited ability to shape the competition and its outcomes. Yet, the age of planetary security also opens humanity up to the complete permeation of the living world by technology, all the way from the exosphere to the ecosystems and geochemical processes that underpin life and civilization.

## Global Catastrophic Risk

Taken as a whole, geoengineering poses three forms of global catastrophic risk:

1. **Termination shock:** Global temperatures increase rapidly if SRM is deployed but then stopped suddenly without significant emissions reductions having taken place.

2. **Systemic destabilization:** Geoengineering compounds existing risks and vulnerabilities, as cascading failures create the potential for large, possibly nonlinear and hard-to-reverse ecosystem and societal changes.

3. **Overshoot risks:** Geoengineering leads to irreversible changes in Earth systems, with reliance on CDR and SRM delaying rapid emissions reductions and undermining the effectiveness of mitigation.

### Termination Shock

The possibility of termination shock from the deployment of solar geoengineering, specifically SAI, is classified as a novel global catastrophic risk.[175] Termination shock is the situation in which SAI is used to mask a high level of global warming and is then suddenly stopped, leading to a rapid and damaging rise in temperatures. Under different scenarios, this could produce up to 5°C of average global warming in a few decades.[176] For this reason, Tang and Kemp have described the effects of SAI as a "planetary Sword of Damocles."[177]

The deployment of SAI would come with a multicentury commitment, as it would be based on the assumption that novel methods of carbon removal, such as DAC, could be scaled up sufficiently to enable SAI to be stopped. One 2023 assessment, based on current climate policy, was that SAI would need to be deployed for 245–315 years.[178] Termination shock is therefore deeply linked with a heavy intergenerational burden and the requirement of near-perfect global governance for several generations alongside "heroic assumptions about state rationality," in the words of political scientist Olaf Corry.[179]

A further type of intergenerational burden comes from the long-term geological sequestration of $CO_2$. The issues are similar in some respects to the storage of nuclear waste, for example the labeling of sequestration sites so they remain undisturbed over millennia. More pressing, though, is the lack of legal or regulatory frameworks and, therefore, accountability for long-term storage of $CO_2$. There are questions over whether there would be the necessary technical and financial stability to maintain monitoring and deal with potential leaks over the long term.

Alongside issues of governance are more basic questions about the technological development and energy use of SAI. For example, it is unclear where the fuel for the necessary fleet of high-altitude airplanes would come from. At present, there is no realistic or scalable alternative to kerosene-based jet fuels. Sustainable aviation fuels are unlikely to become a viable option in the near future, so SAI risks, on the one hand, perpetuating fossil-fuel use even as it is deployed to counteract this very issue and, on the other, diverting fossil bases toward the maintenance of geoengineering, potentially subtracting from a just use of fossil fuels.

Added to that, implementing SAI would create long-term path dependencies that could entirely change the paradigm of climate action, not only further entrenching fossil-fuel and technological interests but also presenting the threat of massively accelerated and catastrophic global warming. Seen this way, SRM should be assessed not in terms of the risk of unmitigated climate impacts but in terms of the plausibility of the extinction of the human race.

## Systemic Destabilization

There is a category of second-order or systemic risks that does not feature in many discussions of geoengineering. These risks relate to how geoengineering approaches would join with an already highly interconnected system. According to a 2024 assessment of global risk,

> Some geoengineering technologies . . . may enable society to mitigate and adapt to climate change; however, they may also increase vulnerability to termination shocks. . . . In this highly interconnected landscape, "synchronous" and "cascading" failures create the potential for mechanisms and outcomes of societal collapse, once contained to a single localised civilisation, to rapidly spread across multiple nations and impact humanity on a global scale.[180]

Policymakers are having to wrestle not only with current climate impacts but also with future adaptation needs alongside financing the energy transition and compensating for loss and damage; geoengineering applications add an extra dimension to already complex systems. This raises several questions about how the various approaches would interact. For example, it is unclear whether SRM would adversely impact nature-based carbon removal, especially given its potential to disrupt the hydrological cycle.

Nor is it certain what would happen if multiple geoengineering approaches were deployed at the same time or in competing locations. Simultaneous deployment could happen either deliberately or unintentionally. Examples include BECCS and DAC, land-based enhanced weathering and ocean alkalinity enhancement, artificial black surfaces to stimulate rainfall and reflective materials to increase albedo, and seaweed cultivation and artificial upwelling. These methods have not been designed to produce harmonized effects. They act like a game of Tetris whose pieces have not been made to fit together. They compete for resources and produce compound crises for other ecological pillars of planetary stability, which, in turn, may accelerate damaging environmental change.

SRM simulations often consider only a single scenario, based on scientific rather than policy-related factors, which limits decisionmakers' ability to compare risks between SRM and non-SRM scenarios and between different SRM approaches. Scenarios that include both SRM and CDR and their potential interactions are only now being considered, which is surprising because one of the arguments for SRM deployment is to give time for novel CDR methods to be scaled up. There is a significant lack of modeling or analysis of the ways in which multisector systems shape risk, especially given large uncertainties about rapidly changing human and Earth systems. This includes the potential for SRM to both mitigate and create derailment risks.[181]

### Overshoot Risks

**Moral hazard** is the situation in which people engage in risky behavior because there is no incentive to act responsibly and they are protected against the consequences of their actions. In relation to geoengineering, this translates to organizations not making stringent cuts to their emissions because they believe that technological and nature-based solutions to climate change will make this unnecessary. Both the concept of net zero, in which real-world emissions reductions are replaced by market trading of permits, and the tacit agreement to enter a period of temperature overshoot have enabled this worldview. Consequently, a "burn now, pay later" approach has allowed carbon emissions to soar and is diverting essential financial and intellectual resources—and attention—away from decarbonization.[182]

Meanwhile, the history of SRM research has been bound up with the concept of **mitigation deterrence** since Crutzen's influential 2006 paper on the subject.[183] When climate goals are narrowly defined—that is, simply to limit global temperatures—it can be easy for SRM to appear as a credible substitute for climate change mitigation. Yet, solar geoengineering would only ever be a stop gap, deployed on the premise that novel carbon-removal technologies could be scaled up quickly enough. Moreover, as has been discussed at length, SRM comes with several environmental and social risks, in particular concerns over equity in deployment decisions and governance.

Researchers have argued that EU climate policy making has already missed critical opportunities to avoid mitigation deterrence.[184] For example, the EU's CRCF certification framework has been criticized for framing CDR as a part of natural carbon cycles, blurring the distinction between short- and long-term storage, and permitting carbon removals to replace, rather than complement, emissions reductions.[185] If CDR were to be scaled up in a responsible way, there would need to be separate targets and timetables for emissions reductions and carbon removals. In the United States, providing funding for CDR, rather than developing a regulatory framework for carbon removal, has been the priority. The lack of standards for robust, high-quality removals has already resulted in carbon-market fraud and is likely to encourage free-riding efforts by corporations and countries.[186]

Big oil and big tech are now joining forces to determine the pace, shape, and outcomes of the energy transition as well as planetary and human futures.[187] The moral hazards that geoengineering methods produce are at the level not only of climate action but also of political transparency and legitimacy. It is increasingly apparent that a small elite is determining the types of risk to which it is acceptable to expose humanity. And since the members of this elite provide goods and technologies that foster the growth of economies, the pace of innovation, and thus the international balance of power, their influence on political institutions and deliberation processes is outsize.

Because many of the risks of geoengineering are left unspoken, there is a path dependency in the making. The consequences of opting in to geoengineered futures are wide reaching and dynamic, and they permeate the fabrics of communities, societies, and economies. At a minimum, geoengineering would produce intergenerational burdens that force future generations to deal with climate impacts, adaptation investments, and loss-and-damage payments.

Climate change obviously does this, too. But combining climate change and geoengineering interventions locks in delayed action. In addition, the deployment of geoengineering would mean the release of $CO_2$ from temporary and ineffective forms of CDR; competition over natural resources for long-term, large-scale CDR; risks of termination shock from long-term SRM that are higher than current estimates; and continued energy dependencies that may include fossil fuels because of the multiplication of climate technologies. Climate justice would cease to function in these circumstances, instead raising the specter of heightened competition for habitable spaces and the fragmentation of governance systems between technologically rich and poor countries and societies. In such a world, no credible form of governance anchored in the concepts of dignity and humanity could emerge.

Finally, geoengineering rests on a core assumption—leading to overconfidence—that humans can deliberately interfere in Earth systems to reduce climate change impacts. The expectation is that by the middle to the end of this century, carbon removals could return the climate to a safe state and reverse decades of high $CO_2$ concentrations. This may prove to be a reckless assumption because of climate tipping points and the risk of **irreversible damage** to Earth systems. Only rapid and immediate reductions in emissions will be effective in lessening climate change impacts, which will look very different in pre- and post-overshoot worlds.

The delay in reducing emissions means that issues such as ocean acidification, biodiversity loss, ecosystem destruction, extreme weather, and human reliance on adaptation infrastructure all become more serious. Geoengineering would not prevent the fundamental drivers of climate breakdown, but it would add complexity to an Earth system that is already struggling to adapt to a new reality. Even if the amount of time spent above 1.5°C of average global warming were limited, marine and terrestrial biodiversity would likely be affected for over a century; some ecological communities would never return to pre-overshoot levels.[188]

High-latitude ecosystems, permafrost-affected soils, global mean ocean temperatures, and oxygen levels would take several centuries to adjust to the atmospheric conditions that arise at the 1.5°C target in overshoot scenarios.[189] The climate system would also continue to change as a consequence of increases in $CO_2$ concentrations, irrespective of future emissions and the size of the overshoot. For example, sea levels would continue to rise for hundreds or thousands of years even if global temperatures were reduced.[190]

Research has questioned whether human and biophysical systems will survive climate overshoot.[191] Even a temporary increase in average global temperatures beyond the safe level of 1.5°C would mean that climate change impacts will accumulate over the next several decades. Carbon removals are not an easy answer to the climate change question. Up to 400 billion tons of $CO_2$ would need to be extracted from the atmosphere by the end of the century to get back to a relatively stable climate. According to the journal *Nature*, "in emissions terms, that is equivalent to running the US energy industry in reverse for around 80 years."[192]

## Conclusion

In the face of accelerating climate breakdown and the continued overshoot of temperatures and planetary boundaries, geoengineering is an attractive and easily marketable prospect for scientists, policymakers, and investors. Presented as solutions to the climate crisis, carbon removal and solar geoengineering are often described through the lens of their potential to turn down planetary temperatures or balance out carbon-accounting sheets. They are therefore technical means employed for a greater end: preserving human societies and allowing more time to deliver the clean-energy transition and climate justice.

This is a misleading and narrow frame with which to discuss geoengineering applications. In reality, they create several first- and second-order risks by compounding climate instability, derailing the energy transition, and reducing the potential for more radical and direct forms of climate action to take root. At present, while some novel carbon-removal methods may have a level of technical viability, none is ready to be deployed at scale. The carbon emissions removal gap is simply too large. Policymakers also do not seem to have learned from past carbon-market failures, as current governance frameworks do little to discourage corporate reliance on intangible permits for real-world emissions.

There is a disquieting notion that carbon removal is the more benign partner to solar geoengineering, because in many cases, it uses or enhances natural processes. However, with technological solutions still at the speculative stage of development, the onus is on land-based carbon sinks to take the strain. This approach conflicts with several other ecological and socioeconomic goals and risks overburdening already-fragile ecosystems. For engineered CDR applications, such as DAC, the additional demand for energy and materials is producing various negative impacts. In countries like Iceland, where geothermal energy is plentiful, the risks of deployment may be limited. In other locations, where energy supply remains dependent on fossil fuels and natural resources are under increasing pressure, both novel and nature-based CDR approaches should be deeply scrutinized.

A further layer of risk comes with the co-evolution of geoengineering and the digitization of economies and societies. The ever-increasing incentives for technological innovation and market competition produce an accelerating demand for energy and materials, which is mirrored by the resource demand of carbon-removal techniques.

As technological innovation is a part of the race for geoeconomic and geopolitical power as well as national security, geoengineering is both a product of this technological arms race and a source of geopolitical tension. Concerns about the international security implications of geoengineering are therefore warranted, especially in the absence of any governance framework to limit its use.

This situation is compounded by a shift in attitudes toward solar geoengineering. Such technologies, particularly SAI, were long considered a last resort within the scenario of runaway climate change—a concept that had yet to be defined. However, the alarming increases in global temperatures and human impacts of climate disasters over recent years are providing proponents of SRM with further motivation for its research and potential deployment. The economic toll of these events is also being calculated, providing greater rationale for advocates of SRM; for example, the United States has put the cost of weather and climate disasters since 1980 at almost $3 trillion.[193]

As engineered carbon-removal methods are still at a nascent stage of development, proponents of solar geoengineering argue that its implementation and the resulting cooling of the planet would buy time for such technologies to be sufficiently scaled up. Yet, while planetary-scale SRM offers the potential to shave off some part of the temperature increase, it does nothing to avert the collapse of biodiversity or prevent certain climate tipping points from being crossed. In addition, SRM may weaken climatic processes that are essential for renewable-energy generation, thus perpetuating reliance on fossil fuels. Analysts are also only beginning to understand the impacts of individual CDR and SRM approaches, not to mention the interactions between and within these two classes of geoengineering.

Techno-solutionism not only creates path dependencies but also embeds technologies ever more deeply into societal, ecological, geochemical, and Earth systems, which were once organically attuned to each other. These technological means of ensuring planetary stability and geopolitical security are becoming an end in and of themselves. Geoengineering is producing a paradigm shift in which technology becomes a necessary tool for a habitable planet rather than a climate risk-management approach. It is producing dependence on technology as a means of survival, changing the logic of technological use, which was originally confined to enhancing efficiency, productivity, and economic performance. By contrast, technology is increasingly posited as a means to control complex Earth systems while diminishing the place of natural and organic processes that go beyond climate regulation.

And indeed, this trend has another consequence: In relying on these innovations, humanity may commodify nature to the point of losing track of its vital importance beyond acting as a carbon sink. Ecosystems are not just climate mechanisms. They are the repository of planetary evolution and the providers of ecological and cultural services that enable complex human civilizations. The more humans rely on technological fixes to solve the externalities they produce via unsustainable economics and geostrategic competition, the more they risk engineering their way out of their natural environment, producing ever more demand for technologies in return. The outcomes of such technological perpetuation leave little room for organic planetary regulation. Behind this path dependence lurks the threat of artificializing complex living fabrics—at humanity's collective peril.

There is an absolute and urgent need to arrest the acceleration of global heating and climate change. Deploying geoengineering is not the path to greater systemic security, however. With the current level of information, it is clear that geoengineering methods generate too many risks, trade-offs, and paradigm shifts that go beyond what humanity is capable of managing, governing, and mitigating.

It is therefore important not only to advocate more research into the risks of geoengineering to help lessen its impacts; equally necessary is to limit deployment in the first place and model deployment effects in different scenarios, taking inputs and coordination dynamics into account. IAMs cannot focus only on mitigation trajectories and the mitigation potential of solutions. An effective, just, and successful transition must be based on implementation modeling that helps decisionmakers to understand the interactions between transition solutions and wider Earth systems. On the ten-year anniversary of the Paris Agreement, these are key policy areas that should be at the top of the agenda for climate action, particularly for the EU.

Advocates of geoengineering are pushing planetary-level interventions without due consideration of their planetary-scale risks; their interplay with international, human, ecological, and national security; or path dependencies that may lock human and planetary futures into uncertainty at best, or extinction at worst. This trend indicates that a new field—planetary security—is now needed to comprehend, analyze, and respond appropriately to the fundamental shifts underway in climatic, ecological, technological, and civilizational systems.

As part of this effort, future research by Carnegie on the geopolitics of geoengineering will investigate the tensions and trade-offs between international and planetary security. Analysis will focus on the security dilemmas that are driving ever-greater extraction- and energy-intensive growth models in international systems. Understanding these dynamics is crucial to navigate the implementation of effective, climate-responsive transitions that avoid perpetual techno-solutionism.

# Glossary

**Afforestation:** The process of growing trees in a location where a forest did not previously exist.

**Albedo modification:** The process of altering the Earth's albedo, or reflectivity, to change how much of the Sun's energy bounces back into space.

**Arctic or Antarctic geoengineering:** Various geoengineering methods aimed at conserving the frozen poles—in particular, glaciers and ice sheets.

**Artificial downwelling:** The process of accelerating existing currents to move carbon-rich surface waters down to the deep ocean.

**Artificial ocean fertilization:** The process of adding iron or phosphorus to nutrient-depleted marine waters to enhance the growth of phytoplankton and increase $CO_2$ uptake.

**Artificial upwelling:** The process of pumping cold, nutrient-rich water from the depths to the surface of the ocean to improve phytoplankton growth.

**BECCS:** Bioenergy with carbon capture and storage. The capture of carbon dioxide emissions from the burning of biomass; these emissions are then sequestered underground.

**Biochar:** Biomass that is heated to high temperatures to create a charcoal-like substance, which is applied to soil to sequester its carbon.

**Blue carbon:** The carbon captured by ocean and coastal ecosystems, including wetlands, such as tidal marshes, as well as mangroves and seagrass beds.

**Carbon credit:** A unit that represents the reduction, removal, or avoidance of one ton of carbon dioxide equivalent.

**Carbon offsetting:** Compensating for carbon emissions by purchasing and retiring carbon credits.

**Carbon sink:** A natural or artificial system that absorbs more carbon from the atmosphere than it releases. Examples are forests, oceans, and soils. The opposite is a carbon source, for instance the burning of fossil fuels.

**CC(U)S:** Carbon capture (utilization) and storage. A means of capturing carbon dioxide from industrial processes at source and then either using the carbon dioxide or storing it underground.

**CDR:** Carbon dioxide removal. A range of techniques aimed at removing carbon dioxide from the atmosphere.

**Cirrus cloud thinning:** The injection of particles into cirrus clouds in the troposphere to allow more long-wave energy to escape back into space and therefore increase cooling.

**$CO_2$:** Carbon dioxide. A long-lived greenhouse gas that is accumulating in the atmosphere and is the biggest driver of anthropogenic climate change.

**$CO_{2eq}$:** Carbon dioxide equivalent. The global warming potential of a greenhouse gas compared with carbon dioxide.

**COP:** Conference of the Parties. An annual gathering, organized by the United Nations, at which representatives of different countries discuss climate change and associated issues.

**DAC:** Direct air capture. The industrial process of capturing carbon dioxide from ambient air using chemicals.

**DACCS:** Direct air carbon capture and storage. The process of direct air capture but with geological storage of the captured carbon.

**Durability:** The length of time that carbon is sequestered, or locked away from the carbon cycle. Also referred to as permanence.

**eDOC:** Electrochemical direct ocean capture. A marine carbon-removal method that relies on changing the pH of seawater to remove dissolved carbon.

**eDOCCS:** Electrochemical direct ocean carbon capture and storage. The process of electrochemical direct ocean capture but with geological storage of the captured carbon.

**Enhanced weathering:** A carbon-removal method that accelerates the natural weathering of rocks.

**Geoengineering:** The umbrella term for carbon dioxide removal and solar radiation management.

**Greenhouse gases:** Gases such as carbon dioxide, methane, and nitrous oxide that trap heat in the atmosphere and create global warming.

**Greenhouse gas removal:** Another way of referring to negative-emissions technologies but with the inclusion of all greenhouse gases, not just carbon dioxide.

**$GtCO_2$:** Gigatons (billions of tons) of carbon dioxide.

**Hard to abate:** A term used to describe emissions from industries such as steel, aviation, and cement that are considered too costly to reduce. See also: Residual emissions.

**IAMs:** Integrated assessment models. Simplified numerical models that represent complex biophysical and social systems.

**IPCC:** Intergovernmental Panel on Climate Change. The body that is tasked to write reviews on climate change and report to the United Nations Framework Convention on Climate Change.

**Marine cloud brightening:** The process of spraying sea salt particles into clouds above the sea to increase their reflectivity.

**MRV:** Monitoring, reporting, and verification. The process through which carbon dioxide removals are measured, published, and checked to ensure that they have taken place.

**Nature-based solutions:** Ways of managing natural ecosystems with the purpose of sequestering carbon.

**NDCs:** Nationally determined contributions. Climate commitments made by countries that have signed up to the Paris Agreement.

**NETs:** Negative-emissions technologies. Another way of referring to carbon dioxide removal.

**Net zero:** The point at which greenhouse gas emissions are balanced by an equal amount of greenhouse gas removals.

**Ocean alkalinity enhancement:** The introduction of alkaline substances to seawater to improve the natural process of carbon sequestration.

**Paris Agreement:** An international treaty on climate change adopted by 196 countries at the United Nations Climate Change Conference in Paris on December 12, 2015 (COP21).

**Radiative forcing:** A measurement of the imbalance in the Earth's energy budget caused by changes in the climate system, such as increased concentrations of greenhouse gases.

**Reforestation:** The process of growing trees in an area where they were previously removed.

**Residual emissions:** Emissions that are considered to be difficult to avoid or eliminate for financial or technical reasons. See also: Hard to abate.

**SAI:** Stratospheric aerosol injection. A type of solar geoengineering that involves the injection of particles into the stratosphere to produce a global cooling effect.

**SCS:** Soil carbon sequestration. Management of the land so that soil can absorb and store more carbon dioxide.

**Seaweed cultivation:** The process of producing seaweed as a food or feed product, sinking it into the deep ocean, or turning it into biofuel.

**SRM:** Solar radiation management. A range of methods of reflecting sunlight away from the Earth or allowing long-wave radiation to escape the atmosphere to cool the planet. Also called solar geoengineering

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