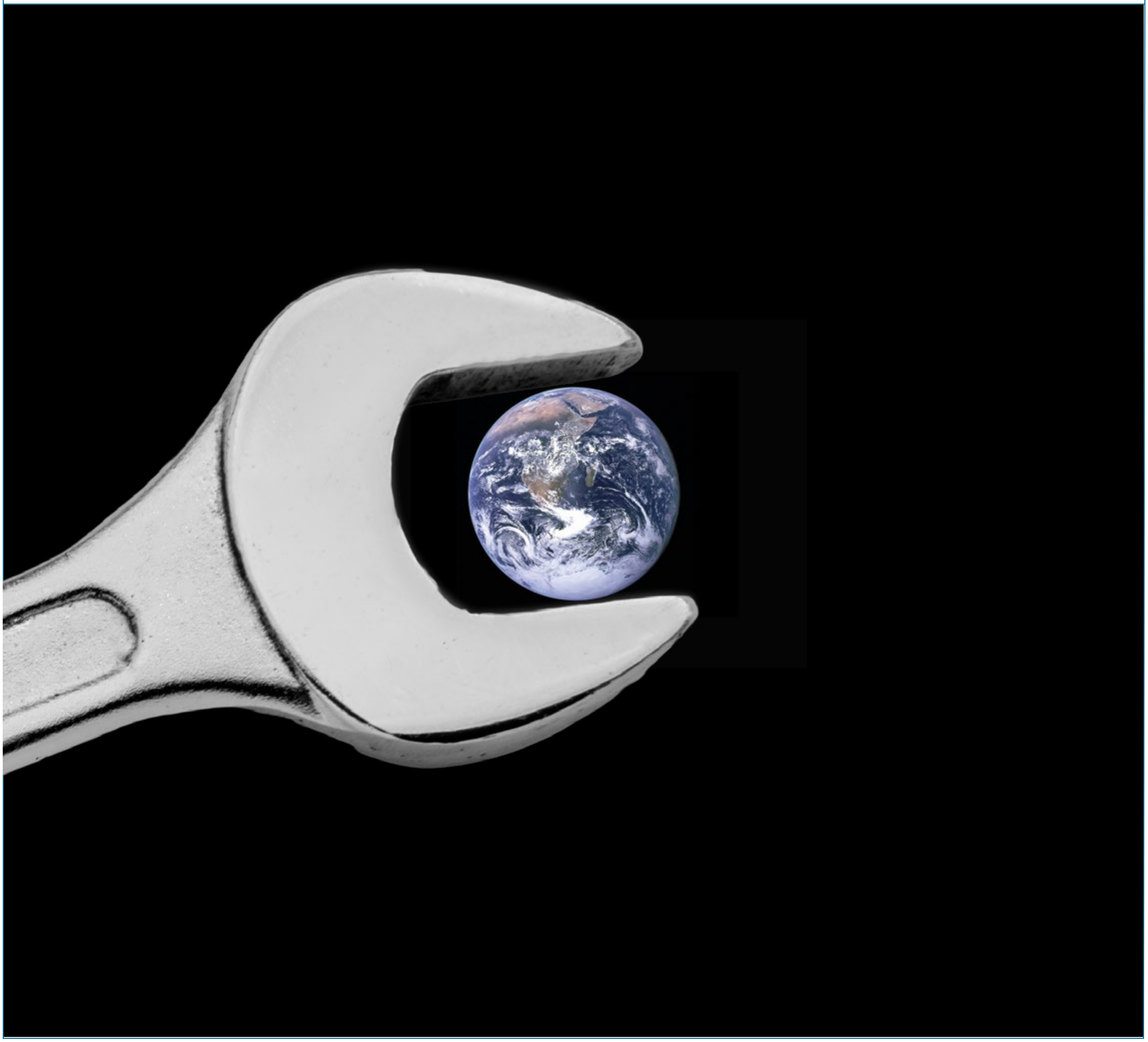
CENTER for INTERNATIONAL ENVIRONMENTAL LAW

# The Risks of Geoengineering

## Accelerating Biodiversity Loss and Compounding Planetary Crises



# Acronyms

| | |
|---|---|
| **AU** | artificial upwelling |
| **BECCS** | bioenergy carbon capture and storage |
| **CBD** | Convention on Biological Diversity |
| **CDR** | carbon dioxide removal |
| **DAC** | direct air capture |
| **EW** | enhanced weathering |
| **HGM** | hollow glass microspheres |
| **IEEFA** | Institute for Energy Economics and Financial Analysis |
| **IPCC** | Intergovernmental Panel on Climate Change |
| **MCB** | marine cloud brightening |
| **mCDR** | marine carbon dioxide |
| **OAE** | ocean alkalinity enhancement |
| **PAR** | photosynthetically active radiation |
| **PFAS** | per- and polyfluoroalkyl substances |
| **SAI** | stratospheric aerosol injection |
| **SRM** | solar radiation modification |

## Key Takeaways

**Geoengineering not only fails to address the root causes of the climate crisis but risks accelerating ecosystem collapse and species extinction. It could also severely compromise our ability to bring the biosphere back to a state where it can better regulate climate conditions and provide vital ecosystem functions.**

- Geoengineering technologies, if deployed at scale, could have **profound, unpredictable**, and **potentially irreversible effects** on biodiversity, both through their direct impacts and as a result of compounding and exacerbating existing planetary crises caused by pollution, climate change, and unsustainable land use.
- If deployed at scale, geoengineering technologies would likely cause a range of harmful impacts, including changes in precipitation, uneven cooling, and oxygen depletion, as well as degrade nutrient cycling, weaken the ozone, and disrupt food webs with **significant deleterious impacts on biodiversity and human well-being** globally.
- As it is impossible to test geoengineering technologies for their intended impact on the climate except through large-scale deployment, geoengineering proposes turning the Earth into a laboratory, with the risk of **locking in a wide range of harmful and potentially irreversible impacts**, including exacerbating climate change and its associated harms.
- **Indigenous Peoples, peasants, fisherfolks, and rural communities** are among those on the **front lines of impacts** from geoengineering experimentation and deployment, and their perspectives are under-represented in research, discourse, and decision-making.
- **Deployment of geoengineering technologies risks violating the human rights of millions of people,** ranging from the right to life to the right to a healthy and safe environment to children's rights, and threatens to perpetuate neo-colonialism by undermining transformative solutions to the climate crisis while entrenching existing unequal power relationships.

**We cannot afford to be distracted by the false promise of these highly speculative technologies. Instead, we must direct our collective efforts towards real solutions to the climate crisis: actions that tackle its drivers and safeguard the biosphere.**

Geoengineering Earth's systems would not only fail to address the root causes of the climate crisis but would severely compromise our ability to bring the biosphere back to a state where it can better regulate climate conditions and provide vital ecosystem functions. We cannot afford to be distracted by the false promise of these highly speculative technologies. Instead, we must direct our collective efforts toward real solutions to the climate crisis: actions that tackle its drivers and help safeguard the biosphere.

In this brief, we explore the biodiversity impacts of some of the most commonly discussed geoengineering approaches and how, rather than tackling the climate crisis, geoengineering could exacerbate it. We also highlight the human rights consequences of going down this path, debunk some common myths around geoengineering, and set out a series of recommendations for States.

## Introduction

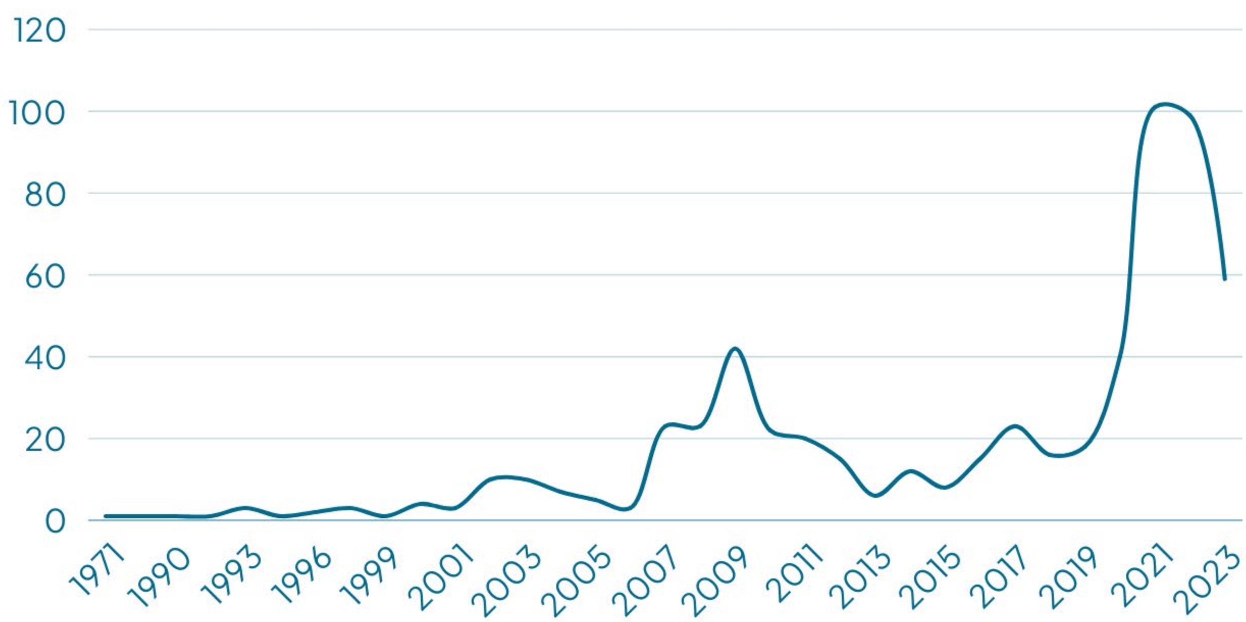
Geoengineering, once confined to the periphery of climate crisis discussions, has started to enter the mainstream discourse, creating a dangerous distraction for decision-makers from the real climate solutions that can and must be implemented today. Defined as the "deliberate intervention in the planetary environment of a nature and scale intended to counteract anthropogenic climate change and its impacts,"[1] geoengineering encompasses an array of highly speculative technical "fixes" to the climate crisis. None of these address the root causes of rising global temperatures, and all pose significant new risks to the fragile ecosystems that are our best allies in the fight to prevent climate breakdown. Untestable for their intended effect on the climate other than through large-scale deployment, the illusion of geoengineering technologies as a potential future "fix" risks prolonging reliance on fossil fuels, the key driver of the climate crisis.

### Alarming Increase in Outdoor Geoengineering Experiments

The number of outdoor geoengineering field experiments proposed or underway has grown in recent years. Based on data aggregated by the Heinrich Böll Foundation and ETC Group, since 1971, at least **598 outdoor geoengineering experiment trials** have been proposed, with over 90 percent proposed between 2004 and 2023 and more than half between 2019 and 2023 (see Figure 1).[2] Four times more geoengineering field experiments were proposed between 2019 and 2023 compared to the previous five-year period. In particular, bioenergy with carbon capture and storage (BECCS)+ biochar proposals have boomed, with 136 proposed in the past five years, **nine times more** than the preceding five years. There were also more than **four times** as many marine carbon dioxide (mCDR) removal technology (ocean alkalinkity enhancement [OAE], artificial upwelling, etc.) field experiments proposed between 2019 and 2023 compared to 2014 to 2018.

Figure 1

### Proposed Outdoor Geoengineering Field Experiements: 1971–2023




**Source:** Data analyzed from the Geoengineering Map project run by the ETC Group and Heinrich Böll Foundation, last updated September 9, 2024. Data from 2024 was excluded as it is incomplete.

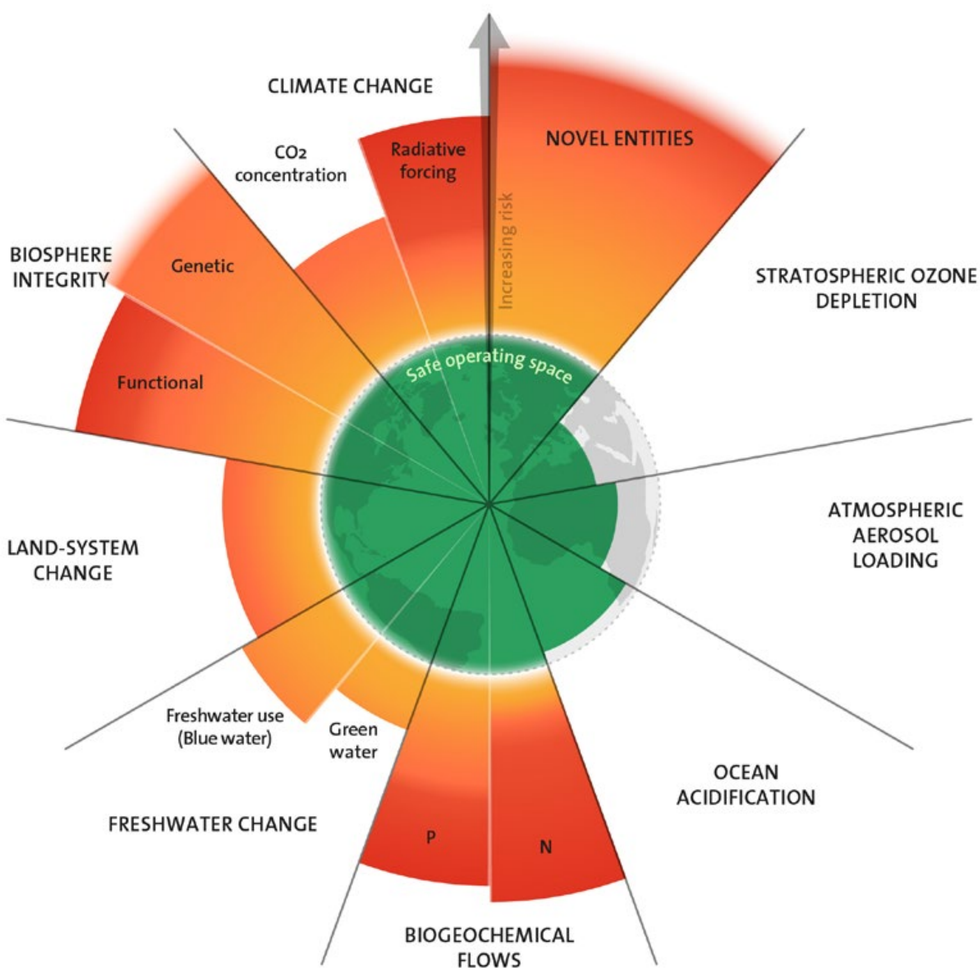
### A Major Threat to Biodiversity

Human well-being is directly dependent on the biosphere and the ecosystem functions associated with the biodiversity that underpins them in over 700 identified ways, including good health, quality of life, safety, and leisure.[3] For approximately the last 11,700 years, humanity has enjoyed the relatively stable, warm climatic conditions of the Holocene that have enabled our societies to thrive.[4] These conditions are now severely threatened due to the consequences of human activities that are driving climate change, biodiversity loss, and toxic pollution. The biosphere, one of six planetary boundaries we have already transgressed,[5] must be rehabilitated (see Figure 2).

It is highly likely that geoengineering technologies, if deployed, would have devastating and potentially irreversible effects on biodiversity, both through their direct impacts and by compounding and exacerbating existing planetary crises caused by pollution, climate change, and unsustainable land use. The deployment of various geoengineering technologies would, in all likelihood, cause direct harm to the species that are the basis of food webs — ultimately undermining the basis of life on Earth. Compromised food webs exacerbate species extinctions and can result in cascading extinctions[6] that would undermine ecosystem functions.[7] Functions that may be degraded include, but are not limited to, oxygen provision, food production, nutrient cycling, disease protection, and ecosystem resilience.

## Current Status of Control Variables for All Nine Planetary Boundaries

Figure 2




**Source:** Image reproduced with permission. © Azote for Stockholm Resilience Centre, based on analysis in Richardson et al., "Earth Beyond Six of Nine Planetary Boundaries."

## Proposed Geoengineering Technologies

This list is not exhaustive but reflects the technologies most commonly advocated for by today's proponents. Another way to categorize these technologies would be by their intended place of intervention (i.e., marine-based, land-based, atmosphere-based).

**Solar radiation modification (SRM)** aims to counteract warming associated with climate change by reducing the Earth system's absorption of incoming solar radiation. Proposed technologies include:

- ***Stratospheric aerosol injection (SAI):*** injecting sulfates or other particles into the upper atmosphere to increase the scatter of sunlight back to space
- ***Marine cloud brightening (MCB):*** whitening clouds over ocean areas by spraying a fine mist of seawater in the lower atmosphere to increase their reflectivity
- ***Increasing surface albedo:*** modifying terrestrial or marine surfaces to reflect more solar radiation
- ***Cirrus cloud thinning:*** reducing cirrus clouds to allow more heat to escape from Earth's atmosphere back to space
- ***Space-based approaches:*** positioning sun shields in space to reflect or deflect solar radiation

**Carbon dioxide removal (CDR)** seeks to remove $CO_2$ from the atmosphere and store it. Proposed technologies include:

- ***Ocean fertilization (OF):*** enriching marine nutrients to stimulate plant production, increasing $CO_2$ uptake from the atmosphere to sequester it in the deep ocean
- ***Ocean alkalinity enhancement (OAE):*** artificially increasing the rate by which the ocean uptakes $CO_2$ from the atmosphere by introducing alkaline material to marine environments or through electrochemical methods of removing acid from seawater
- ***Artificial upwelling (AU):*** transporting nutrient-rich, deep ocean water to the sea surface by pumping or other artificial means to increase plant production, increasing $CO_2$ uptake from the atmosphere to sequester it in the deep ocean
- ***Biomass storage:*** storing bales of biomass by burying them underground or by sinking them to the bottom of the ocean in an attempt to trap $CO_2$ (*biomass storage is often combined with industrial seaweed farming*)
- ***Enhanced weathering (EW):*** artificially increasing the rate by which $CO_2$ is removed from the atmosphere by breaking down carbonate and silicate rocks and spreading them in land, coastal, and marine areas
- ***Bioenergy carbon capture and storage (BECCS):*** converting biomass into heat, electricity, or fuels and capturing emitted $CO_2$ before storing it
- ***Biochar:*** the long-term storage of feedstocks (e.g., crop residues, manure, wood, sewage, etc.) over time as "pyrogenic" carbon, which is also known as charcoal
- ***Direct air capture (DAC) and carbon storage:*** using chemical processes to directly capture and store $CO_2$ from the atmosphere (e.g., storage of $CO_2$ as a liquid in geological formations or the deep ocean)

**Other approaches** include

- ***Ice-based technologies:*** using a variety of techniques, slowing or halting ice melt, including by spreading glass microbeads or pumping seawater onto its surface, causing artificial snowfall, or building a giant curtain in the ocean

## Common Geoengineering Myths

| Myth | Fact |
| --- | --- |
| **Geoengineering technologies mimic natural processes such as volcanic eruptions and the natural carbon cycle.** | Unlike volcanoes, which affect the atmosphere and other Earth systems for an average of one to three years[8] — and natural alkalizing processes that take hundreds of thousands of years[9] — SRM, EW, and biomass cultivation technologies would have to be deployed at a spatial and temporal scale never before observed in nature. For example, idealized OAE would take up approximately 10 percent of the ocean's surface,[10] and climatically significant biomass technologies would require twice the land currently cultivated,[11] creating intense land and marine use competition for ecosystems and humans. Geoengineering would introduce novel risks not observed in natural processes, such as termination shock from the abrupt discontinuation of SAI or MCB. |
| **Geoengineering is needed to buy time to address the climate crisis.** | Geoengineering does nothing to address the root drivers of the climate crisis, and no technologies have been proven effective in the long-term removal and storage of $CO_2$, while SRM will not restore the climate to its previous state. Geoengineering risks prolonging fossil fuel dependence. Relying on the promise of future speculative technologies instead of implementing real solutions today will lead to an overshoot of the critical climate threshold of 1.5°C and lock in catastrophic climate change and biodiversity loss. |
| **The known risks of climate change are so great that it is worth contending with the unknown risks posed by geoengineering.** | Geoengineering cannot put an end to the harmful impacts of climate change. It could exacerbate them. These technologies are inherently unpredictable and pose new, significant, unprecedented risks to the fragile ecosystems that sustain life on Earth, which are our best allies in the fight against the crisis. Many of the technologies proposed would also exacerbate unsustainable land and water use practices — a key driver of the climate crisis.[12] |

## Common Geoengineering Myths (Continued )

| Myth | Fact |
|---|---|
| **Geoengineering could help biodiversity.** | Geoengineering technologies could cause devastating harms to biodiversity, including potentially permanent impacts on food webs, disrupting ecosystem oxygen provision, degrading natural nutrient cycling, precipitation changes, uneven cooling, and weakening the ozone layer. The degradation of Earth subsystems will likely cause an extreme loss of ecosystem functions. Moreover, the harmful impacts on biodiversity will further exacerbate the climate crisis and compound other threats to ecosystems, such as land use and pollution. |
| **There is a vacuum of international governance on geoengineering.** | Geoengineering has been subject to a *de facto* global moratorium under the Convention on Biological Diversity (CBD) since 2010, reaffirmed in 2024, while the London Convention/London Protocol is exploring the expansion of its prohibition on ocean fertilization to include four more categories of marine geoengineering. Geoengineering deployment would also be inconsistent with a wide range of legal obligations and principles, including the precautionary principle, the obligation not to cause transboundary harm, the obligation not to pollute the marine environment, as well as the rights of Indigenous Peoples and the rights of peasants and people living in rural areas, among many other human rights. Geoengineering deployment would also be inconsistent with a wide range of legal obligations and principles, including the precautionary principle, the obligation not to cause transboundary harm, the obligation not to pollute the marine environment, as well as the rights of Indigenous Peoples and the rights of peasants and people living in rural areas, among many other human rights laws. |
| **We don't know enough about the potential impacts of geoengineering, so more research is needed.** | By their very nature, it is impossible to test geoengineering technologies for their intended impact on the climate without large-scale outdoor deployment, which would lock in any harmful and potentially irreversible impacts and turn the Earth into a risky laboratory. Research showing theoretical benefits tends to use highly idealized models underplaying harmful impacts and the likelihood that deployment would not go as planned in the real world. |

# Geoengineering's Underestimated and Potentially Devastating Effects on Biodiversity

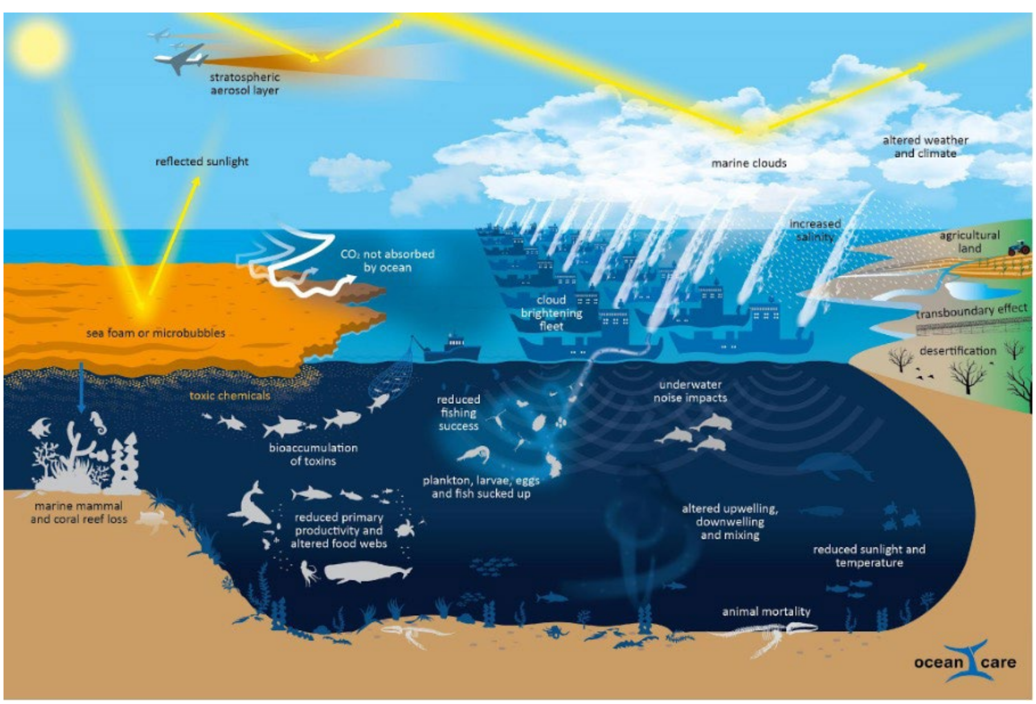
Habitat loss and degradation have long been understood to be key drivers of declining biodiversity.[13] The land- and water-use changes required to implement geoengineering technologies at a climatically significant scale would exacerbate these drivers, impacting many ecosystems and biodiversity both terrestrially and across water systems, in the name of pursuing highly speculative technologies that do nothing to tackle the root causes of the climate crisis.

This section explores the likely direct and indirect impacts of 14 geoengineering technologies on biodiversity. It is important to note that while we have categorized the technologies based on their *area of intended intervention* — marine, terrestrial, atmosphere-based geoengineering — the harms caused by various techniques frequently cross multiple ecosystems and are not confined solely to their area of deployment. The intention of geoengineering is to affect large or even planetary-scale changes to Earth's systems, which, of course, ultimately lead to transboundary ecosystem impacts.

### Atmosphere-Based Geoengineering

Atmosphere-based geoengineering technologies would have far-reaching, global impacts on biodiversity across all biomes. Deployment of solar radiation management (SRM) technologies would introduce novel risks associated with light dimming and the threat of termination shock, putting biodiversity and ecosystem functions at risk of suffering irreversible damages.[14]

Simulations show that even if light dimming — which describes the effect of Earth receiving less solar radiation — were globally perfectly uniform using ***stratospheric aerosol injection* (SAI),** surface temperatures would not uniformly fall to either preindustrial or current conditions at the regional level.[15] SAI-induced dimming would reduce the temperature gradient between the equator and the poles, resulting in excess cooling in the tropics, excess warming in the poles, or both compared to existing conditions.[16] This is significant as it signals that even if planetary cooling were achieved, ecosystems would still experience the adverse effects of regional temperature changes, decreasing their long-term resilience.




**Source:** Image reproduced with permission. © OceanCare

***Marine cloud brightening* (MCB)** is expected to also result in unevenly distributed temperature shifts, ultimately altering the land-sea temperature gradient.[17] Doing so would likely significantly impact several of Earth's subsystems, including shifts in mean annual precipitation patterns, increased warming in the Arctic and Antarctic, uneven terrestrial warming, and marine cooling.[18] These effects are likely to stress ecosystems, putting them further in danger of reaching their tipping points and undermining their ability to keep us in the Holocene. As a result of uneven cooling and physical harms caused to micro marine life during the pumping of seawater, MCB would also modify food webs through harm to primary producers and alter the vertical structure of the water column, likely making ocean stratification more pronounced, thereby leading to changes in the ocean's biogeochemical cycling with consequences for carbon sequestration and oxygen cycling that are not yet understood.[19]

***Enhancing marine microbubbles*** is a proposed albedo enhancement technology that would use surfactants — chemical substances used to reduce surface tension — to cause the bubbles left in ships' wake to linger. This could potentially result in a marine temperature decrease of up to 0.5ºC, which proponents argue could be protective of marine life.[20] However, increased ocean acidification would offset the protection of cooler temperatures. A cooler ocean is more able to absorb $CO_2$ from the atmosphere,[21] increasing ocean acidification and amplifying its negative effects on marine biodiversity, including harm to corals and shelled species like oysters.[22] Additionally, the surfactants needed to achieve enhanced marine microbubbles would inhibit the oceans' gas exchanges with the atmosphere.[23] Inhibited gas exchanges are likely to have harmful impacts on marine ecosystems due to decreased dissolved oxygen and increased dissolved $CO_2$ with not yet fully understood consequences for marine biodiversity.[24]

Idealized SRM is likely to impact the hydrologic cycle negatively.[25] SRM may offset some regional precipitation changes associated with unmitigated climate change, but overall, it is expected under a uniform dimming scenario that SAI technologies will slow the planetary hydrologic cycle, resulting in a 2 percent global decrease in mean precipitation compared to the current climate.[26] Such a decrease is expected to be most pronounced over land and/or in equatorial regions that host significant amounts of biodiversity[27] and over monsoon regions in the Southern and Northern Hemisphere.[28] One such country that would be majorly impacted is "megadiverse" Indonesia — home to approximately 10 percent of all flowering plant species, 12 percent of all mammal species, 16 percent of all reptiles, and 17 percent of all birds, as well as 40 million rural Indonesians who rely on biodiversity for subsistence needs.[29] Similarly, "megadiverse" nations that would be impacted include Colombia, the Democratic Republic of the Congo, Ecuador, Gabon, and Malaysia.

Additionally, SAI will likely have a negative impact on the ozone layer. Without robust ozone, Earth would receive more UV radiation, especially in the polar regions in their respective springs, with the greatest increases observed from March to April for the Arctic.[30] Polar species, plants, and animals are comparatively slow to adapt to environmental perturbations, meaning these ozone changes and their implications would likely affect those species least able to respond to its associated challenges. The ultimate biodiversity consequences of increased UV reaching Earth will depend on the type of UV that would increase most, which is not known and cannot be sufficiently modeled at this time.[31] Humans are also likely to suffer from increased UV exposure, given that UV damage is associated with skin cancer as well as eye damage.[32]

Furthermore, ocean acidification is likely to worsen in a world prioritizing SRM deployment over decarbonization. Since SRM does not reduce greenhouse gas emissions, $CO_2$ emissions and ocean acidification would continue under SRM deployment. The long-term consequences of unmitigated ocean acidification include direct and indirect harms to marine organisms' skeleton formation, gas exchange abilities, reproduction, growth, and neural functions.[33] These harms will have negative consequences for life at all levels of the food chain and put fisheries and those dependent upon them at risk.

### Changes in Light

Marine microbubbles, MCB, idealized SAI, and ocean fertilization may decrease photosynthetically active radiation (PAR) and increase the amount of diffuse light reaching Earth and penetrating the oceans.[34] PAR describes the range of light that photosynthetic organisms can use for photosynthesis, and diffuse light is refracted sunlight, which has spread out evenly over an area. As plant productivity is directly dependent on the ability of a plant to intercept solar radiation, net primary production is linearly related to PAR.[35] Decreases in available PAR are likely to decrease net primary production and $CO_2$ storage in plants and, in turn, decrease crop outputs, thereby negatively impacting food security. The total harm from decreased PAR will ultimately depend upon the scale and duration of SRM technologies if deployed.

In contrast, gross primary plant production may increase with higher amounts of diffuse light, providing more uniform light distribution through tree canopies.[36] However, as with the above-described hydrological changes, increased primary plant production is not a good proxy for biodiversity as not all species would benefit from these changes.[37] Less PAR and more diffuse light may be unable to penetrate the ocean as deeply as unaltered sunlight.[38] Therefore, it is likely that SRM deployment would decrease marine primary production, disrupt the food webs of the oceans, and weaken ecosystems globally.

Changes in polarized light are also anticipated to impact marine ecosystems where many species — mainly fish, mollusks, and arthropods[39] — use polarized light in ways not yet fully understood, including for navigation, prey identification, and reproduction.[40] Changes in polarized light have the capacity "to drastically increase mortality and reproductive failure in animal populations,"[41] resulting in changes to these species' communities and later ecological interactions.[42] In the marine context, these disruptions in polarized light may result in the partial loss of marine ecosystem functions such as $CO_2$ uptake, oxygen provisioning, nutrient cycling, and food availability.

### Lock-In and Termination Shock

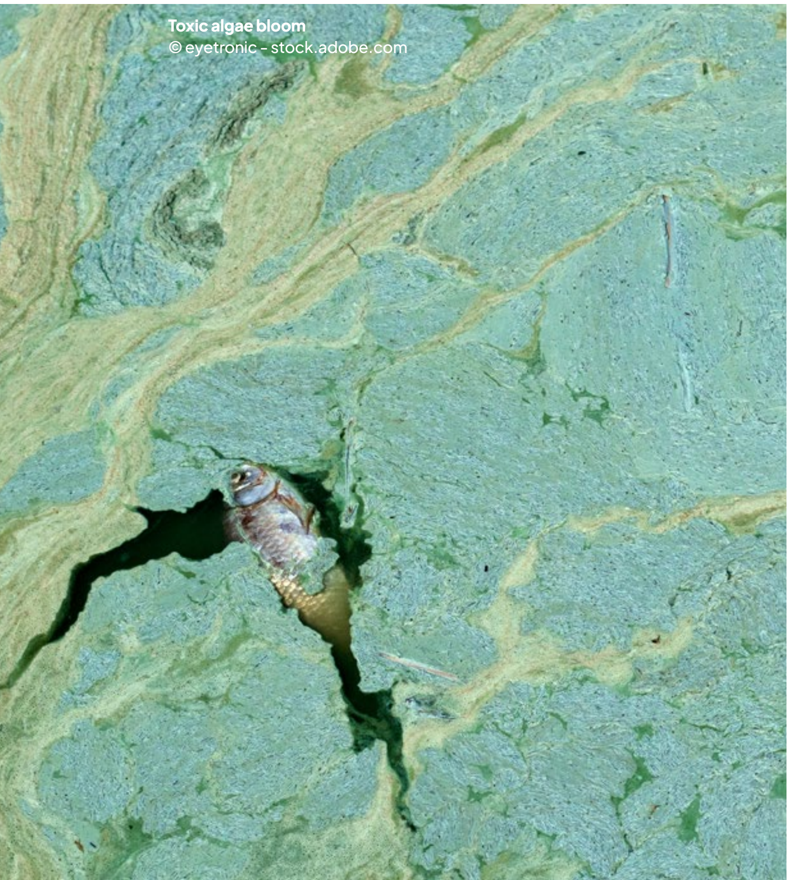
For SRM to have its intended effect, the Earth would be locked into using these risky technologies for an indeterminate amount of time while emissions were reduced by highly speculative CDR approaches, with so-called "peak-shaving" scenarios for **stratospheric aerosol injection** implying deployment on the order of 100 to 200 years.[43] The practical and geopolitical challenges of maintaining the deployment of a planetary-scale operation such as this over multiple generations are clear. Yet any abrupt pause or cessation of SRM (including SAI[44] and MCB[45]) would result in rapid temperature increases, known as termination shock. Under the temperature masking effects of these technologies, ecosystems become even less resilient to climate change, likely leading to greater species death, degradation of ecosystem functions, and severe socioeconomic consequences if they are stopped.[46] The only way to avoid termination shock once these technologies have been deployed would be through a gradual, long wind down enabled by global deployment of CDR techniques. Given that no such pathway is credible the potential deployment of SRM effectively ensures they could never be stopped.

### Marine-Based Geoengineering

Executing mineral-based ocean alkalinity enhancement and enhanced weathering at a climatically significant scale would require large-scale mining roughly equivalent to today's global coal mining industry,[47] exacerbating habitat degradation and loss. As of February 2022, 10,511 species have been found to be threatened by mining activities.[48] The biodiversity impacts associated with coal mining further illustrate the high cost of mining, showing that even when extinctions do not occur, total species richness is negatively impacted. For example, in the USA, affected streams are 32 percent less rich in species and 53 percent less abundant in total life across all taxa than unaffected streams and remain comparatively low even once mining activities have ceased.[49]

Massive infrastructure and long supply chains would have to be developed to meet the mining, processing, and transportation requirements associated with these technologies,[50] which would come with high energy and $CO_2$ emissions costs.[51] Additionally, mining is associated with other negative health and local community impacts, including noise,[52] light,[53] and particle pollution,[54] all of which negatively affect the reproduction of species and ecosystem resilience as well as human health, especially for workers. Proposals to conduct enhanced weathering (EW) and OAE without additional mining include spreading silicate and carbonate mine waste over agricultural lands and the ocean's surface.[55] As mine waste is not well characterized, it may contain major or trace elements that adversely affect terrestrial and marine biodiversity.[56] This is just one illustration of how geoengineering technologies cause harm to biodiversity outside of their intended areas of deployment.

Uncertainties about how OAE will impact marine ecosystems remain high with the potential for it to negatively affect the success of primary producers that form the base of the food chain, thereby threatening marine biodiversity, commercial fishing, as well as coastal ecosystems and their communities.[57] As acknowledged by proponents of this technology, “responses [to OAE manipulations] may be quite variable and will involve both immediate ‘shock’ response and longer-term accumulated responses.”[58] Such perturbations are expected from introducing alkaline substances that are highly caustic — such as sodium hydroxide[59] and potassium hydroxide[60] — which are associated with electrochemical and mineral alkalinity enhancement technologies.[61] In addition to potentially harming marine life through extreme pH disturbances, electrochemical OAE technologies may also harm primary producers and fish larvae caught up in the seawater extracted from the oceans. These harms may be analogous to those commonly observed during the processing of seawater for desalination.[62] In addition to physical harm from extraction, the electrochemical processing of seawater may cause additional harms to organisms in not yet understood ways.


Toxic algae bloom
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Seaweed cultivation technologies are likely to detrimentally reshape the movement of coastal waters by building up sedimentation and slowing down the flow of water due to substantial increases in biomass.[63] These hydrological changes, coupled with the physical infrastructure associated with seaweed’s cultivation, can break ecological connectivity, disrupting the flow and exchange of genes, organisms, nutrients, and energy in marine ecosystems,[64] resulting in decreased resilience to diseases and loss of food sources. It has been estimated that if ocean fertilization were to be deployed at the scale needed to limit global warming to 2°C under a high emissions scenario, this could cause an additional 5 percent decline in the biomass of fish and marine species in the tropics, especially within exclusive economic zones with substantive effect on those who make their livings from fishing.[65] Furthermore, if deployed at scale, these technologies would need to cover a suffocating 10 percent or more of the oceans’ surfaces.[66]

Ocean fertilization and industrial seaweed cultivation may also increase the risk of harmful algal blooms involving toxic diatoms,[67] a type of microalgae, which would ultimately have deleterious effects on other marine species. Harms that have already been observed from toxic algal blooms include acute and chronic poisoning of marine mammals, seabirds, and fish as a result of consuming contaminated prey such as krill, marine snails, and shellfish.[68] Seaweed cultivation and ocean fertilization would likely result in further destruction of already strained coastal ecosystems upon which many marine species and coastal communities depend.[69]

Like terrestrial fertilization, ocean fertilization would require the addition of a range of micro- and macronutrients,[70] which would result in the annual production of billions of metric tons of fertilizer to achieve its intended climatic effect.[71] Achieving idealized ocean fertilization would require a global scale-up of industrially produced fertilizers. Synthetic fertilizer production build-out would have severe adverse effects on

Deep Sea Biome


biodiversity and human health while further locking in our global dependence on fossil fuels and exacerbating human-driven climate change. Nitrogen fertilizer production and use already account for approximately 2 percent of global annual greenhouse gas emissions.[72] Scaling up fertilizer production for risky, unproven technology would ultimately increase greenhouse gas emissions, exacerbating the climate crisis and causing increased harm to biodiversity.

Artificial upwelling seeks to bring nutrients from the deep sea to the ocean's upper layers for seaweed cultivation and ocean fertilization. It would bring up nutrients quicker than natural processes and a significant amount of dissolved $CO_2$, which would then be released into the atmosphere and upper ocean waters, exacerbating ocean acidification and offsetting any positive effects on greenhouse gas emission outcomes.[73] Methane and nitrous oxide would also be brought up in large quantities, contributing to mid-water oxygen depletion events.[74] Such events can potentially cause hypoxic damage — which occurs in the absence of sufficient oxygen — which may induce mortality events in organisms that rely on dissolved oxygen, including various fish, bivalves, and corals, with the greatest impacts on larger invertebrate species.[75]

Often portrayed as devoid of life, the deep sea and sub-seafloor are home to rich and vulnerable ecosystems[76] that host a high abundance and diversity of single-celled organisms that enable the oceans' vital functions,[77] such as providing oxygen,[78] nutrient cycling, and carbon sequestration,[79] and may hold significant biotechnological potential.[80] Proposed sub-seabed and seabed storage of captured $CO_2$ puts these ecosystems at risk by introducing the possibility of bottom-up ocean acidification. This would be felt disproportionately by the most delicate marine ecosystems as the deeper ecosystems are, the smaller the range of pH perturbation they can survive.[81] If bottom-up acidification occurs, the resulting ecosystem disruptions would have devastating impacts on the entire ocean, including collapsing food webs and decreasing oxygen, likely leading to hypoxic events.

### Ice-Based Technologies

Iced-based technologies, such as spreading hollow glass microspheres (HGM) over ice or seawater spraying to artificially thicken sea ice, are speculative geoengineering technologies focused on our poles and glaciers. In the literature, only one study — by HGM proponents — claims that spreading specialized glass in the Arctic will increase the cryosphere's albedo and protect against Arctic ice melt.[82] In contrast, a recent study by independent researchers found that, rather than protecting against ice melt, HGMs deployed between March and June would increase ice melt while they would have almost no effect the remainder of the year.[83] This is because, from July to August, the snow is more reflective than HGMs, while there is little sunlight during the rest of the year.[84]

To date, limited research about the potential biodiversity impacts of HGMs has been studied.[85] In addition to unknown physical harms to Arctic species that may ingest the glass, the HGMs may leach aluminum, silicon, iron, and barium, resulting in an increased risk of ecotoxicity wherever they are spread.[86]

### Land-Based Geoengineering

As with mineral-based OAE, enhanced weathering would require large-scale mining roughly equivalent to today's global coal mining industry,[87] which would exacerbate habitat degradation and loss and have deleterious impacts on freshwater. Also, similarly to OAE, enhanced weathering without additional mining has been proposed. Using industrial and mine waste to achieve enhanced weathering on land, like with OAE, comes with uncertainties about the ecological toxicity impacts of spreading crushed uncharacterized materials over land-based ecosystems and agricultural lands.

Biomass-based CDR technologies would directly damage marine and terrestrial ecosystems. Biochar uses pyrolysis to theoretically sequester carbon from feedstocks, including crop and wood residues, manure, tires, plastics, municipal waste, and sewage. Each feedstock poses unique ecotoxicity risks through the bioaccumulation of toxins taken up by plants grown in biochar-amended soils or through the inhalation of particles associated with production and long-term breakdown.[88] A popularly cited study claims this technology could theoretically capture up to 12 percent of annual anthropogenic greenhouse gas emissions, but this would require converting over 170 million hectares of tropical grasslands into biomass plantations.[89] This is roughly the size of Libya, the sixteenth-largest nation in the world by landmass. In addition to this large-scale, unsustainable conversion of biodiverse lands, achieving idealized deployment would require realizing 100 percent of the production potential of abandoned, degraded cropland for biomass crops, as well as using 25 percent of all cattle manure and 90 percent of pig and poultry manure as feedstock.[90] Pyrolysis facilities emit pollution in the area, which may negatively impact biodiversity and human health. The permit application for a proposed facility in Saratoga, New York (USA) that would produce biochar from sewage sludge exemplifies the emission of such harmful pollutants in its request to emit the following toxins: per- and polyfluoroalkyl substances (PFAS), naphthalene, arsenic, cadmium, lead, mercury, hydrogen fluoride, and particulate matter.[91]

Implementing large-scale BECCS would have even greater land-use implications. Idealized BECCS intended to keep to the Paris Agreement's warming limits would require cultivating up to 3 billion hectares of productive land — roughly equivalent to twice the world's current total cultivated lands.[92] Biomass plantations have been shown to negatively impact biodiversity, including increased exposure to and decreased resilience to diseases, as well as habitat and food source loss. These impacts contribute to declines in the richness of plant and animal species,[93] decreasing the resilience of ecosystems due to loss of genetic diversity. The inevitable sizable carbon emissions from the large-scale conversion of land for biomass cultivation would lead to significant loss of natural areas rich in biodiversity as well as colonize productive crop and grazing lands for carbon sequestration at the risk of increased food insecurity and loss of ecosystem functions.[94]

The most efficient lands for cultivating biomass plants are tropical grasslands,[95] primarily located across the Sahel and northern Australia, in addition to being found in South and Southeast Asia, the southern United States, and northern South America.[96] Tropical grasslands have high rates of endemic species and are among Earth's areas of high biodiversity importance.[97] Converting tropical grasslands to woody forests to capture carbon has been shown to negatively impact biodiversity.[98] While degraded lands may be used for biomass cultivation, restoration would have greater net greenhouse gas reductions than those achieved through biomass cultivation while also regenerating biodiversity.[99] Ultimately, the large-scale conversion of tropical grasslands to biomass plantations risks land grabs while straining the Earth's ability to remain within the protective Holocene.

Beyond cultivation, long-term biomass storage is also likely to have negative consequences. Burying biochar may compromise the growth, nutrient cycling, and viability of ecosystems within which it is deposited.[100] One study found that plants growing on biochar-amended fields have reduced defenses against insects, pathogens, and drought, ultimately decreasing ecosystem resilience.[101] The storage of biomass on the ocean floor would cause physical damage wherever it is deposited,[102] decrease nutrient availability, and cause deoxygenation events due to the release of hydrogen sulfide, methane, and nitrous oxide during the degradation of the deposited organic matter.[103] In this way, our oceans may suffocate and starve from the bottom up.

Direct air capture (DAC) and carbon storage technologies, including the carbon storage associated with BECCS, also cause harm to biodiversity. These technologies cause changes in land use, greenhouse gas emissions related to infrastructure development, and increased demand for freshwater. For example, it is estimated that aqueous sorbent-based DAC — the technology with the largest proposed rollout at present — would consume 4.7 metric tons of water to capture one metric ton of $CO_2$.[104] In 2022, anthropogenic $CO_2$ emissions were 36,800 metric megatons.[105] Thus, capturing up to even 1 percent of emissions (368 metric megatons) with DAC would require an enormous amount of water — approximately 1,730 metric tons. This amount is greater than the annual freshwater withdrawals for domestic consumption in 144 out of 181 nations, as identified by the World Bank Group.[106] In addition to further exacerbating land and water use changes as a driver of biodiversity loss, the use of land and water for DAC will directly compete with other interests, including aqua- and agriculture, with lasting negative socioeconomic consequences due to increased food insecurity.

As a result of land use changes, idealized DAC is expected to increase toxicity to land ecosystems (by 33 to 80 percent) and metal depletion levels (by 23 to 73 percent) from 2020 to 2100.[107] In order to have a climatically significant effect, captured $CO_2$ must be sequestered for long-term storage. $CO_2$ transport and storage infrastructure development will compound DAC land-use changes, extend the areas impacted by its development, and increase risk exposure to any potential $CO_2$ leaks. Fugitive emissions of $CO_2$ can cause oxygen deprivation events, leading to loss of life or water acidification if a leak occurs in an aquatic environment.

## Accelerated Biodiversity Loss Through Exacerbated Climate Change

Far from tackling the climate crisis, geoengineering technologies risk exacerbating climate change-induced biodiversity loss — delaying action to cut emissions and potentially increasing emissions if deployed. Known as a "moral hazard" — instead of implementing known, real solutions today — reliance on highly speculative future geoengineering technologies prolongs dependence on fossil fuels. It threatens to lock in an overshoot of the critical 1.5°C threshold and the resulting irreversible impacts, as warned by the IPCC.[108] According to the Human Rights Council's Advisory Committee, "deterrence to cut emissions may be amplified in the near future by a public debate increasingly focused on the topic of carbon removal rather than carbon cuts, and research path dependencies."[109] Furthermore, deployment of different technologies could result in an increased release of greenhouse gasses due to the processes associated with the technologies' deployment and due to their impacts on biological carbon sequestration.

As previously discussed, SAI technologies may contribute to monsoon failure (when their timing and strength are not as expected) due to changes in precipitation patterns and decreased annual global precipitation levels. Not enough is known about the interplay between the Asian monsoon and the ecosystems it impacts. However, continued perturbations to the monsoon are expected to result in decreased terrestrial carbon sinks,[110] thereby exacerbating the climate crisis and its negative impacts on biodiversity through positive forcing (changes known to have warming effects).

Artificial upwelling and ocean fertilization may turn our oceans from a net carbon sink into a carbon source if deployed at scale. As illustrated above, artificial upwelling would bring up potent greenhouse gasses, including methane ($CH_4$), nitrous oxide ($N_2O$), and $CO_2$, thereby offsetting any positive effects on greenhouse gas emission outcomes.[111] Like with CDR technologies, massive infrastructure demands, including the production, installation, and maintenance of millions of pipes associated with this technology, would create additional warming compared to a no-deployment scenario.[112] Algae cultivation associated with artificial upwelling and ocean fertilization would increase biogeochemical cycling in the ocean's surface layers. This is expected to lead to the additional production of $CH_4$ and $N_2O$ due to enhanced primary production and the remineralization of sinking particles.[113]

Technologies based on biomass production assume that growing plants is either carbon neutral or results in very low greenhouse gas emissions. These approaches may increase planetary carbon debt[114] while severely impacting terrestrial biodiversity through land-use changes.[115] Capturing $CO_2$ from bioenergy production other than from ethanol fermentation has never been demonstrated at scale.[116] Furthermore, as identified in an investigative report by Carbon Brief, the amount of $CO_2$ emitted during BECCS processes is nearly four times that which is sequestered.[117]

As previously illustrated, biochar and BECCS deployment would require unsustainable land use that would turn our soils from carbon sinks to sources. If deployed, biochar application may decrease soil nitrous oxide emissions.[118] Doing so, though, would require the application of mineral nitrogen fertilizers, which have a high emissions cost to produce[119] and would lead to greater $CO_2$ soil emissions.[120] Biochar application may also increase water retention, leading to anoxic conditions that offset the benefits of nitrous oxide fixation by releasing methane — a greenhouse gas with a global warming potential 273 times greater than $CO_2$.[121] Applying biochar to lands may also "significantly increase GWP [Global Warming Potential] by 46.22%," as identified by one study.[122] Furthermore, the large-scale deposition of biochar in suitable locations will require considerable transport, burying, and processing, all of which will require substantial energy.

Any technology that requires substantial renewable energy inputs to counteract the climate crisis without addressing its root causes is a technology that is diverting energy that could otherwise be devoted to real climate solutions and access to energy. This is true of many geoengineering approaches, including mineral and electrochemical OAE, DAC, SAI, MCB, ocean fertilization, and artificial upwelling.

As illustrated by the Institute for Energy Economics and Financial Analysis (IEEFA), despite the fossil fuel industry's decades of experience in carbon capture, this technology has had a very low success rate, with high numbers of commercial failures and operational schemes capturing far less $CO_2$ than intended.[123] The large majority (73[124] to 80 percent[125]) of $CO_2$ that is being captured is used for enhanced oil recovery, leading to $CO_2$ emissions from burning fossil oil that could not otherwise be recovered.[126] Capturing and reburning $CO_2$ to use fossil fuels that would otherwise stay in the ground further entrenches harmful energy systems and exacerbates the climate crisis.

**DAC infrastructure**
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## International Law and Governance of Geoengineering Technologies

- The **Convention on Biological Diversity** has issued a series of pioneering and precautionary decisions relating to geoengineering, including a *de facto* global moratorium in 2010 because of the implications for biodiversity. Decision X/33 makes an exception for small-scale scientific research studies in controlled settings, only if justified by the need to gather specific scientific data, and after a thorough prior assessment of the potential impacts on the environment and in accordance with the obligation not to cause transboundary harm.[127] Furthermore, the *de facto* moratorium is "in line and consistent with" an earlier decision on Ocean Fertilisation which explicitly rules out a commercial purpose in such research studies.[128] **Crucially, Parties reaffirmed prior decisions of the CBD on geoengineering, including the *de facto* moratorium in 2024 at COP16, citing concern about the growth in uncontrolled outdoor experiments.**[129]
- The **London Convention/London Protocol** — which aims to prevent pollution at sea from the introduction of wastes or other matter — passed a resolution prohibiting ocean fertilization (other than except for tightly defined "legitimate scientific research") in 2008[130] and is currently considering how to address four additional categories of marine geoengineering which have been identified as having the potential to cause "deleterious effects that are widespread, long-lasting or severe."[131]
- Development and deployment of geoengineering technologies could be **inconsistent** with a wide range of **legal obligations** and **principles under international law**, including:
    - Human rights obligations, ranging from the right to life to the right to food and children's rights
    - Indigenous Peoples' rights, including Free, Prior, and Informed Consent
    - Rights of access to information, participation in decision-making, and access to justice
    - The precautionary principle
    - States' obligation to prevent transboundary environmental harm
    - States' obligations not to pollute the marine environment under the UN Convention on the Law of the Sea

## Human Rights Consequences of False "Solutions"

Geoengineering technologies pose significant, unprecedented risks to a wide range of human rights, including as a result of direct and indirect harms to biodiversity and ecosystem functions. These speculative technologies also risk perpetuating neocolonialism by undermining transformative solutions to the climate crisis while concentrating the power of potential deployment in the hands of major powers and elites.[132] Some techniques risk land and resource grabs, such as with idealized BECCS and biochar.

Geoengineering technologies risk undermining the right to a clean, healthy, and sustainable environment[133] due to their harm to biodiversity, among other environmental impacts. Further human rights that would be violated due to harms to biodiversity and ecosystem functions include the right to life,[134] health,[135] water,[136] adequate food,[137] housing,[138] an adequate standard of living,[139] and the right to culture,[140] among other human rights.[141]

Numerous international instruments lay out States' human rights obligations that would apply in the context of geoengineering technologies and their impacts on biodiversity. These include the Universal Declaration of Human Rights, the International Covenant on Civil and Political Rights, the International Covenant on Economic, Social and Cultural Rights, the Convention on the Elimination of All Forms of Discrimination against Women, the Convention on the Rights of the Child, the International Convention on the Elimination of All Forms of Racial Discrimination, the United Nations Declaration on the Rights of Indigenous Peoples,[142] the United Nations Declaration on the Rights of Peasants and Other People Working in Rural Areas,[143] and the United Nations Guiding Principles on Business and Human Rights.[144]

The Human Rights Council's Advisory Committee has warned that the deployment of geoengineering technologies has the potential to violate the human rights of "millions and perhaps billions of people," with a disproportionate impact on Indigenous Peoples, traditional communities, peasants, and fisher folks, among other groups.[145] Furthermore, the Committee notes geoengineering technologies:

"cause social risks, including for future generations ... Exposure to the effects on land is greater for frontline communities, including Indigenous Peoples, local communities, peasants, fisherfolk, rural women and other persons working in rural areas."[146] Geoengineering "would have a massive and disproportionate impact on Indigenous Peoples whose traditional lands and territories are particularly exposed and at risk of experimental uses."[147]

Due to the loss of biodiversity and ecosystem functions, these techniques may negatively impact Indigenous Peoples' cultural and spiritual values of natural areas, sacred groves, and water shades.[148] Harm to biodiversity from these speculative technologies may also lead to a loss of traditional knowledge, further decreasing Indigenous Peoples' resilience to climate and ecosystem changes.



Local communities are likely to experience similar cultural and economic losses — especially at the regional level — due to geoengineering's potential harms to biodiversity.[149] For these reasons, CBD COP10 Decision X/33 calls for integrating the views and experiences of Indigenous Peoples and local communities and stakeholders into weighing the possible impacts of geoengineering on biodiversity and related social, economic, and cultural considerations.[150] The Intergovernmental Panel on Climate Change (IPCC) has also warned of the adverse socioeconomic impacts that many geoengineering technologies could have, including hindering sustainable development.[151] The social, economic, and cultural impacts of geoengineering would likely become apparent only once deployed.[152]

Geoengineering will likely support the continuation of inequitable political and social power, entrenching neocolonialism and undermining transformative, justice-centered solutions to the climate crisis. Solar geoengineering research is primarily being advanced by a small Global North elite, funded by billionaires and billionaire philanthropy, with an emerging consensus that the likely actors for deployment would be limited to a handful of major powers. Similarly, assumptions about militarization are built into prominent deployment scenarios.[153] Meanwhile, terrestrial and marine-based geoengineering technologies would perpetuate neocolonialism through land and ocean grabs, which would violate the inherent rights of Indigenous Peoples, peasants, fisherfolks, and rural communities.[154] The potential detrimental biodiversity impacts and their human rights implications of deployed geoengineering technologies could create "sacrifice zones" that allow for the further entrenchment of the fossil economy and its harms at the expense of those most vulnerable to the climate crisis.

It is worth noting, too, that geoengineering social science analysis primarily includes perceptions from the USA and Europe, which likely creates a cultural bias about risk and the decision to use geoengineering technologies.[155] This bias is reflected in the available literature, which, to date, has widely failed to consider the specific challenges of Indigenous Peoples, fisher folks, peasants, and rural communities if geoengineering technologies were deployed.[156] Furthermore, the belief systems, traditional ways of living, cosmovision, and relationship of Indigenous Peoples to the Earth and Sky are often not included in the risk assessment of geoengineering and may be violated by these technologies.[157]

## Recommendations

As emphasized by the IPCC, “the protection of biodiversity hotspots is key to preventing a substantial global biodiversity decline from climate change.”[158] Geoengineering would do nothing to tackle the root causes of climate change, offers polluting industries a free pass, and risks further destabilizing an already destabilized climate system. If deployed at scale, geoengineering technologies would — directly and indirectly — harm biodiversity, damage food webs, disrupt ecosystem oxygen provision, degrade natural nutrient cycling, cause changes in precipitation, lead to uneven cooling, and weaken the ozone layer. The degradation of these subsystems is likely to cause an extreme loss of ecosystem functions with associated negative consequences for human well-being, including increased food and water insecurity, loss of health and culture, and, subsequently, impacting human rights. As it is impossible to test geoengineering technologies for their intended impact except through large-scale deployment, geoengineering proposes turning the Earth into a laboratory, with the risk of locking in a wide range of harmful and potentially irreversible impacts for generations to come.

We cannot afford to be distracted from real solutions to the climate crisis by the fantasy of geoengineering. Effective, human-rights-based solutions to the climate crisis, which center on equity and prioritize protecting and restoring biodiversity, exist and are achievable now, starting with a full, fair, funded phaseout of fossil fuels.

**States must take steps to protect biodiversity and prevent the normalization of geoengineering in climate discourse and policy.** To ensure States are meeting their domestic and international obligations, we recommend the following:

- Implement and enforce the Convention on Biological Diversity’s *de facto* moratorium on geoengineering at a national level and uphold decisions of the CBD on geoengineering in other international fora;
- Support the development of strong precautionary regulatory controls under the London Convention/London Protocol;
- Ban all outdoor geoengineering experiments following the Precautionary Principle enshrined in the Rio Declaration;
- Disincentive the development of geoengineering technologies by withholding public support, including funding, and by not granting patent rights for technologies or permits for experiments;
- Exclude geoengineering activities from national, regional, and international carbon market mechanisms and offsetting schemes;
- Protect biodiversity and ecosystem integrity by avoiding harmful activities in the first instance, minimize impact where it is impossible to avoid harm, and restore already damaged ecosystems while rejecting false solutions such as biodiversity offsets;

- Put in place effective procedures to implement and uphold the inherent and collective rights of Indigenous Peoples, the rights of peasants, fisherfolks, traditional communities, and all rights holders at risk from experimentation and potential deployment of geoengineering;

- Urgently prioritize real solutions to the climate crisis through a fast, fair, funded, and full phaseout of fossil fuels and by supporting the many decentralized, diverse, and readily available alternatives for socially and ecologically sustainable production and consumption patterns, including through the provision of climate finance by wealthy countries in accordance with their fair shares/equity.

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