# Chapter 14

# Remediation and Geoengineering

At this point, you may be wondering whether humanity could pull greenhouse gases out of the atmosphere. The answer is yes! In fact, pulling out $CO_2$ is what the planet itself already does every year in great quantities for free. In some cases, humanity could just pay for speeding up existing natural processes.

This is called remediation. It refers to actions taken to counter the climate effects of past GHG emissions. (Climate mitigation refers to actions taken to reduce future GHG emissions.) You should not think of GHG remediation as undoing the chemical reactions, such as splitting $CO_2$ back into its carbon and oxygen constituents. This would be far too expensive. Instead, it usually means some sort of geoengineering whose purpose it is to push GHGs from the atmosphere into the ground, materials, or ocean. This goal could be accomplished, e.g., by speeding up natural rock weathering processes. Or by increasing forests. Or by compressing $CO_2$ at industrial plants into liquid $CO_2$ and storing it underground in exhausted gas wells.

An altogether different geoengineering approach would be not to tinker with the atmosphere but to reduce incoming sunlight. This goal can be accomplished (perhaps) by cloud seeding into the troposphere (lower atmosphere) or sulfur-dioxide particle seeding into the stratosphere (middle atmosphere). Nature herself is running such geoengineering experiments all the time. For example, volcanic eruptions emit reflective sulfur-dioxide particles, which have always cooled the planet – more in some years, less in others. If you are wondering whether this could ever be effective enough, the answer is “yes, easily.” Just one volcano on the other side of the globe was powerful enough to cause a year without summer in Europe in 1816.

Environmentalists often worry about the unintended consequences of solar radiation management, and for good reason. It’s dangerous. But keep perspective. Humanity has always been geoengineering. For that matter, so has the biosphere. Even the oxygen in the atmosphere is the result of indiscriminate tinkering by photosynthesizing plants. And so has the universe, blessing Earth with supervolcano eruptions and blasting it with asteroids every few ten thousand years.

A related question is *what is the optimal temperature?* — a question we first raised in Chapter 3. If the bad effects of global warming are really terrible, and if humanity for all its shortcomings fails to stop them, then maybe the bad alternative is simply less bad.

In our view, humanity should research to be prepared to intervene, regardless of whether the climate problem is natural or man-made, and whether it is cooling or warming. Interventions with fast response rates could be important to stop bad temperature feedback loops or push the planet back under a tipping point before everything gets out of hand. Meanwhile, let’s hope we will never need it.

# 1 The Social Cost of $CO_2$ (Yet Again)

In Chapter 6, we explained that climate scientists and economists universally lament the fact that today's global $CO_2$ tax policies are perverse. On average, the world is subsidizing fossil fuels. Instead, the proper tax should be somewhere between \$50/t$CO_2$ and \$100/t$CO_2$, rising over time. The main disagreement among scientists and economists is about the question of whether the tax should be high or higher, and how steeply it should rise. (Unlike most scientists and environmentalists, we think this debate is mostly irrelevant.)

Chapter 6 also explained that if the world were governed by one benevolent dictator and it cost \$100 to remove one ton of $CO_2$ from the atmosphere, then \$100 would be an upper limit to any $CO_2$ tax. That is, if everyone who emits one ton of $CO_2$ were charged \$100, the Utopian government could then spend this money to take it out again. The social problem would be solved. Our dictator's best solution would be pairing fossil fuel use with aggressive removal of $CO_2$ from the atmosphere — called <u>carbon sequestration</u> — *if* only taking out $CO_2$ from the atmosphere is cheap enough.

So what is humanity's cost of removing $CO_2$? It depends. Different $CO_2$ removal solutions have different costs in different quantities. We will explain below that the lowest-cost solution — tree farming — would already pay for itself today. Yes, in effect, the price tag to remove the first Gt$CO_2$ could be \$0/t$CO_2$! Naturally, the opportunities for such lowest-cost solutions are limited. If $CO_2$ entrepreneurs were to build more tree farms, eventually the cost of forestable land would go up and the price of lumber would go down. This creates soft limits on the capacity of tree-farming as a removal solution — but the world is a long way from bumping up against limits. Removing, say, the first 1 Gt$CO_2$ from the atmosphere (or equivalently, not emitting it in the first place) may cost under \$10/t$CO_2$. From our *moving the needle* perspective, this is *the* number environmentalists should care most about *today*. The world should implement these least costly processes to remove the first few Gt$CO_2$ as soon as possible and not argue so much about of how much all 50 Gt$CO_2$ will eventually cost.

More speculatively, it is in the realm of the possible that, with more R&D, the cost could remain under \$50/t$CO_2$ even for removing all 51 Gigatonnes of annual human $CO_2$ emissions! This \$50/t$CO_2$ is also an amount that humanity could reasonably afford in order to rid itself of its climate change problem. Over time, the costs of $CO_2$ removal processes will change. They could not only go up (as in the case of tree farms), but they could also go down (if research discovers better techniques). As with battery technology, it may be better to spend billions of dollars on R&D today than trillions of dollars on giant $CO_2$-sucking facilities that could become outdated within a few years.

Before you get too enthusiastic, the real problem is again neither technology nor cost. Instead, it is the same free-rider problem from Chapter 6 that makes assessments of the collective social cost of carbon-dioxide largely irrelevant in the real world. No country finds it in its own interest to pay for removing emissions at large scale on behalf of the world's other 200 countries. If it seems tough trying to convince countries to take responsibility for cleaning up their own emissions, wait until someone explains to voters that $CO_2$ in the air does not have country labels attached to it. How do you think American and European voters would feel about paying for sucking out $CO_2$ that India and China are emitting? Nobody wants to pay for sucking nation-less $CO_2$ out of the atmosphere. And when India and China realize that other countries will pay for removal of their emissions, would they not happily emit even more?

Attempts to set up a global system have predictably failed. Global rules under some cap-and-trade systems designed to curtail $CO_2$ (in place of an emissions tax) have created lots of funny money and shenanigans. You would not believe how inventive people can become when free money is involved!

In the end, most removal solutions stand in stark contrast to cleaner energy generation technologies in two important ways. First, $CO_2$ removal would not remove the nasty local copollution of fossil fuels to which most people truly object. The local benefits that induce local reduction in the use of fossil fuels are just not present for local removal of $CO_2$. (Removing $CO_2$ is effectively paid for domestically but mostly enjoyed abroad.) Second, if one country were to invent a clean and super-cheap electricity plant, it could sell it all over the world. Both the researching country and the deploying country would want it *in their own interests*. No country will want to pay others to suck out large amounts of $CO_2$.

# 2 $CO_2$ Removal

The cost of removing $CO_2$ is logically an upper limit to the dictatorial social cost of carbon-dioxide, whenever $CO_2$ policies, the IPCC, or the Nordhaus and Stern models are discussed. But our view has always been that the environmental focus has to shift towards promoting solutions that are in the self-interest of individual countries. If you doubt our hypothesis that the social cost of carbon-dioxide is conceptually useful but irrelevant for practical purposes, we hope that reading this chapter will convince you.

Our evidence against the cost-of-carbon view is that countries cannot even agree to solutions today that have $CO_2$ removal costs as low as \$5/t$CO_2$. They will never agree to solutions that cost as much as \$100 or \$200/t$CO_2$ — and especially while some other countries are still emitting $CO_2$.

Nevertheless, this section describes methods of removing $CO_2$. In our opinion, only the forestation-based methods are currently viable for non-trivially large amounts of removal. The others are pipe dreams, because they are and will likely remain much more expensive for a long time to come. At most, we can recommend further research. Implementation would be economically and likely also ecologically wasteful.

## Forestation

The world has been cutting forests at record rates. The global loss of tropical forests contributes about 4.8 Gt$CO_2$ per year (about 10% of annual human emissions). The most common reason to cut trees has been to make way for more agriculture to feed growing populations. The most common way of making way has been burning, often done by and for the poorest of the poor and without governmental permits. This is doubly bad: it burns carbon and it removes the trees which previously were sequestering more $CO_2$ every year.

From 2011-2015, humanity cut down about 20 million hectares of forest every year — about 50 million acres, the size of the state of New Jersey or the country of Israel. Since 2016, this amount has increased to an average of 28 million hectares per year. Brazil alone is responsible for about one-third of world deforestation (and growing). In 2021, it is at its worst level in 15 years. Nigeria, which has one of the world's highest population growth rates, has lost more than 60% of its forest cover since 1990. In Indonesia, forests are being cut for palm oil plantations. Americans and Europeans no longer cut much of their forests — not out of virtue, but because they have already cut down most of them in the past.

### ➤ Technology

The average hardwood tree absorbs about 20 kg of $CO_2$ per year, 1 tonne of $CO_2$ over 40 years of life. Fifty trees can absorb 1 tonne of $CO_2$ every year. Thus, 1 trillion trees could sequester about 20 $GtCO_2$ per year out of thin air. Even better, harping on the low cost again, estimates are that the net cost of doing so are on the order of less than \$15/$tCO_2$ for about 15 $GtCO_2$ of removal, and this includes the cost of the land! (Pushing tree planting into more expensive and harder-to-reach locales to effect the last 5 $GtCO_2$ of removal would become much more expensive.)

The way to make this work at such a low cost is to plant trees and harvest them for lumber (or higher-tech composites that can even substitute for steel) — wood keeps the carbon nicely inside. On the margin, tree-farms are already profitable today even without any subsidies, although this depends upon the price of lumber. The business case is solid.

However, forestation can only work if environmentalists understand that they must not go on the barricades to stop the harvesting of trees. The whole reason why tree planting is so efficient is that trees convert $CO_2$ into wood that can then be sold — and, after they are harvested, new trees can be planted to transform yet more $CO_2$ into yet more wood. Preventing the harvesting of trees defeats the whole purpose. (When old trees burn or die, the $CO_2$ returns to the air, which is the worst of all worlds.) Sure enough, cutting down trees does not appeal to environmentalists, but it is the right thing to do to stem climate change.

This may sound too good to be true, and indeed it may be. Trees can also emit methane and other greenhouse gases. Some evidence suggests that tree farms are not as efficient as natural forests. There is also a serious concern that if one plants trees in many deserts (which are light and thus good at reflecting sunlight), the darker color of trees can reduce the relevant albedo and actually make global warming worse! However, for now, it looks as if there are plenty of opportunities for viable tree-planting solution that are cheap and for real — and it may become better if scientists can learn how to fine-tune it. For example, it may be better to plant trees that can grow faster with a mix of other trees (and different climate zones require different kinds of trees). Scientists could also genetically engineer trees that are better at removing $CO_2$ — even in inhospitable areas. It's not for sure, but it looks very promising. Trees could viably move the needle now at extremely low cost for the first few gigatonnes of $CO_2$!

### ➤ Opportunity

Remarkably, scientists are only just beginning to understand forests. Until just a few years ago, they thought Earth had about 0.4 trillion trees. Yet we now know from satellite imaging that a better estimate is 3 trillion trees — only about eight times as many!

More importantly, how many trees could humanity potentially add to our planet? A reasonable estimate is about another 1 trillion trees. Figure 1 shows where more trees could viably be planted. In order, Russia (151 million hectares), the United States (103), Canada (79), Australia (58), Brazil (50), and China (40) have the most potential. Forests in the American West could fight desertification and protect biodiversity. And there is more good news: if there ever were to be a global treaty that pays some countries to plant trees, satellite imaging can cheaply confirm whether countries that have agreed to reforest are actually holding up their end of any bargains.

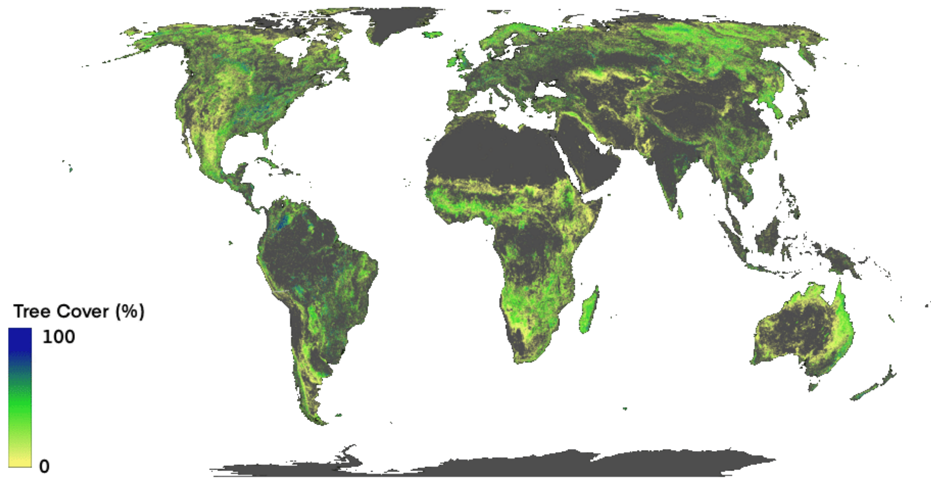
Is tree planting viable in large scale? The short answer is yes. In one state in India, Uttar Pradesh, 800,000 volunteers planted 50 million tree saplings in one day. If all the saplings grow into trees, and this process could be replicated 800 times, it would cancel out all the $CO_2$ humans pump into the atmosphere.

### ➤ Failure

The cheapest way to pull $CO_2$ out of the air, including the cost of land, is thus also the least objectionable. Better yet, trees have many local benefits, too — water filtration, flood buffering, soil health, biodiversity habitat, enhanced climate resilience, anti-desertification. This mitigates the cross-country free-rider problem. Countries benefit economically and environmentally from their own forests.

So why has humanity not managed to pursue even this low-hanging fruit? In fact, in large areas of the globe, the opposite of reforesting is happening. Brazil, Indonesia, and Africa are actively destroying their rain forests, while the rest of the world is largely watching passively.

**Figure 1.** Potentially Reforestable Areas




**Note:** Land can be unsuitable for reforestation for different reasons. The Amazon and the Congo are already forested, while the Sahara is unsuitable sand without enough rainfall.

**Source:** Crowther Lab ETH Zuerich.

The problem is that it is in the interest of individual farmers to cut down trees on public land to gain what is effectively free land. Why don't the controlling countries stop them? It depends on the locale. Farmers are powerful political constituents in many countries, where they often control large states in an upper house of Congress (the equivalent of our U.S. Senate). Moreover, even when countries decide to protect their forests, small subsistence farmers are difficult to keep in check. When their children are starving, who can blame them for cutting down trees to clear fields for grazing or planting? This is the case even if the loss to their country (and the planet) greatly dwarfs their personal gains. Drowning people often don't care whether they drag down others in their desperate attempts to survive. (And how do the police prove who started the forest fire?)

Although capitalism and industry are often claimed to be the culprits for deforestation, it is actually the opposite. In an ideal capitalist market, the owner of the forest would protect it. But when it comes to government-owned land, the enforcement costs are high and the property owner is often disorganized and conflicted. (At one point, a majority of Brazilian Congressmen were under indictment for corruption. And Indonesia and Africa typically rank below Brazil on most corruption indexes.)

We have argued that the world has no effective government that could enforce global solutions, and that country solutions are our best hopes, because countries represent the largest organizational levels with true power. Yet even this may have been too optimistic. In many circumstances, countries may not be sufficiently able and willing, either. Ironically, India's urban air quality is devastated by farmers burning off residual plant matter. One would think that India could solve this simple problem, but interstate conflicts and governmental incompetence have stymied common-sense solutions.

Nevertheless, if there is a solution, it will have to involve better governments putting restrained and managed capitalism back to work. Capitalism cannot survive without benevolent governments, just as governments cannot survive without benevolent capitalism. One reason for hope that solutions can be found is that reforestation often makes economic sense, too. Within a few years of the initial burns, former forest soil often loses its potential for productive agriculture. More efficient farming and subsidies for poor farmers in designated areas could render forest burning uneconomical, as could general reductions of poverty. A solution will require a balance between the needs of tree farmers to earn good livelihoods and the ecology of the forests. By involving local villages and providing Western environmental subsidies, incentives could be put in place to curb overly aggressive harvesting.

In sum, the current state of affairs is that reforesting solutions are both surprisingly cheap and effective, yet depressingly difficult to implement in the real world. If humanity cannot even manage reforesting, it is difficult to see how any other non-technical collective solutions will ever work.

### ➤ Biology Beyond Forestation

We discussed agricultural changes in the previous chapter. We covered trees above. However, ocean plants may be similarly important.

Trees are not the only plant capable of capturing $CO_2$. In Chapter 11, we mentioned the great potential of biological engineering. In their evolution, plants went down some clever and some not-so-clever pathways. It may be possible to engineer plant roots that can capture more $CO_2$ and fix nitrogen out of the air (thereby reducing the even more potent nitrous oxide GHGs).

Of course, if successful, we have to be careful that plants won't capture too much $CO_2$, or we may end up with another Snowball Earth. It's all about balance. Earth's oxygen is an example of how plants mutated once before to change the global environment.

As we noted before, civilization should prepare not only for temperature increases but also for decreases. As we are writing this, the 350m asteroid Apophis passed inside our geosynchronous satellites. If it had hit Earth, it would have carried more energy than all nuclear weapons combined and caused a nuclear winter-type catastrophe.

## Enhanced Rock Weathering

The next cheapest solution seems to be accelerating the process of rock chemical weathering on the surface of the earth. The principal stone that can bind $CO_2$ is Olivine. If you have never heard of it, you are not alone. However, olivine comprises about 60-80% of Earth's upper crust, mostly found (but not confined to) basalt. When olivine is weathered, it turns into magnesite and quartz. Weathering olivine is also an efficient process, not requiring extra energy, and binding the equivalent of the emissions from one liter of gasoline in one liter of stone.

If we just waited a few thousand years, olivine and some related minerals would take care of all the excess $CO_2$ in the atmosphere by themselves. But we do not have a few thousand years. If olivine is crushed into small grains, exposed, and doused with water, the weathering process can be reduced to a few years. Unfortunately, crushing and exposing are expensive. Nevertheless, in some areas (the Deccan traps in India, the Columbia river basalts in the United States, and the Siberian traps in Russia), the cost to do so may be as low as \$50/t$CO_2$. In other areas, the cost can be as high as \$150/t$CO_2$. Chances are that the costs could go down further if humanity resolved to weather olivine in large quantities and learned when, where, and how it would be least expensive.

Realistically, this is not likely to happen. Unlike tree planting, there are no local benefits to olivine conversion, so it seems unlikely that any countries will volunteer to pay for implementation at a scale large enough to remove even their own country's $CO_2$ emissions, much less those of others.

## Enhanced Ocean $CO_2$ Capture

About 70% of the planet is covered by oceans, and it is the primary destination of most atmospheric $CO_2$. Unfortunately, however bad humanity's treatment of ecosystems on land is, humanity's treatment of ecosystems in the ocean can only be described as abysmal. Out of sight, out of mind. With no country owning the oceans of the world, it is a race by fisheries to exploit them as aggressively as possible before others do so before them. It's not capitalism, but failure of shepherded capitalism that has gotten us here.

Moreover, as modest as our knowledge is about large-scale atmospheric $CO_2$ removal onto land, it is even more modest when it comes to large-scale $CO_2$ removal into the oceans.

A 2012 study in Nature suggests that seagrasses store more than twice as much $CO_2$ as forests per square mile. And like trees, seagrasses have plenty of local benefits, from cleaning water to providing habitats. But, as is the case with forests, humanity is depressingly not raising seagrasses but destroying them. Moreover, scientists don't know enough about whether seagrass planting could be made to work.

Another approach is to coopt algae. They can be up to 400 times more efficient than a tree, albeit in a bioreactor. Instead of making wood out of $CO_2$, they make more algae. It might even be possible to use algae to make plastic-type polymers or fuel out of thin air. Ironically, one of the challenges is that algae grow too fast to be easily manageable — surely a problem that can be overcome with more research.

For a while, many scientists were bullish about seeding oceans with fine particles of iron to stimulate plankton growth. Then, evidence suggested more skepticism. Seeding may not work on a large scale, because it could deplete nutrients that are needed elsewhere. Just recently, they seem to think that it could work again. In fairness, scientists do not yet know. It could work great, it may not. It's definitely worth investigating.

Ocean liming — adding a form of calcium to seawater — could also allow the oceans to absorb more $CO_2$. Cost estimates range from \$70/t$CO_2$ to \$150/t$CO_2$, with \$100/t$CO_2$ a good middle.

Other ocean research is just beginning. We are keeping our fingers crossed. Project Vesta is researching whether it is possible to use ocean wave energy to accelerate natural stone weathering. One of our UCLA colleagues wants to produce hydrogen while pushing $CO_2$ into the seawater. His cost estimates are $100/t$CO_2$, with possible long-term reductions down to $50/t$CO_2$. Unlike many other schemes, these could be nearly limitless processes.

## Industrial $CO_2$ Capture and Sequestration


I can tell you the meaning of life, but I can't explain sequestration...

Finally, there are industrial solutions to $CO_2$ removal. Humanity has become good at industrial solutions over the last century. Civilizations have built entire industries before. There are even some commercial uses for captured $CO_2$. For instance, $CO_2$ can be injected into gas wells as solvent to improve extraction. However, in this case, nature already offers so many good biological self-replicating solutions that industrial solutions will have a tough time competing—unless breakthroughs reduce costs by two orders of magnitude. This seems unlikely.

For example, Climeworks is already aggressively pursuing industrial $CO_2$ removal, though in minute amounts. They quote removal costs of about $300/t$CO_2$, with the potential to bring the cost down to $200/t$CO_2$. The U.S. Department of Energy has announced "earth shot" research to bring the cost down to $100/t$CO_2$, which may or may not be possible.

Scientists are also researching different technologies, from capture of $CO_2$ out of the thin air (which can be done anywhere, including near volcanoes to tap cheap heat) to capture at industrial plant exhaust stacks. For now, exhaust capture can only be installed in a limited set of locations (soon we hope even more limited as coal plants will hopefully be disappearing). But capturing highly concentrated $CO_2$ is three times cheaper than direct air capture. Howard Herzog from MIT estimates capture from flue gases on chimneys to be around $100-$300/t$CO_2$ by 2030, and direct air capture at $600-$1,000/t$CO_2$. Other estimates are more optimistic, going as low as $50/t$CO_2$ by 2050. None are likely to reach the $10-$30/t$CO_2$ that lumber could offer.

Right now, Climeworks and other industrial operations are funded by Stripe (a payments processor), where rich people can buy carbon offsets. Some do so out of ethical considerations, others for public relations purposes. While laudable, Climeworks is a model that will never scale to the world as a whole.

We view industrial carbon capture as an interesting research venue, although we believe it is unlikely ever to become commercially viable. Even if the costs were eventually to come down to \$100/t$CO_2$, it would still not be the lowest cost of carbon sequestration for a long time. We think that the market problems are so serious that industrial carbon capture will never be deployed on a large scale.

Nevertheless, in the 2022 Inflation Reduction Act, Congress enacted subsidies for industrial sequestration of up to \$180/t$CO_2$. Not surprisingly, there has been a rush of interest in industrial sequestration. Although our economic analysis implies that industrial sequestration makes no economic sense, our conclusion that no country would be stupid enough to undertake it was obviously incorrect. We thus need to correct it: No country would be stupid enough to undertake amounts of sequestration large enough to make a meaningful difference for global temperature. However, the subsidies can make some companies and venture capitalists very rich in the meantime — on the backs of the broader U.S. public that will eventually have to pay for the subsidies.

# 3 Solar Radiation Management

The second class of geoengineering solutions does not attack $CO_2$. Instead, solar radiation management (SRM) involves reflecting some solar energy back into space, ideally before it reaches the troposphere (Earth's lower atmosphere). Any such shield must also not block outgoing infrared radiation or it would worsen the greenhouse effect.

Not climate geoengineering again!

### Space-Based Parasol Shields

As lovely as the concept of an umbrella in space is to us Star Trek fans, this is non-sense. Launching large structures into space is too expensive. It takes a huge amount of energy to put a mass into orbit. There are even more expensive schemes — Texas Congressman Gohmert pondered whether we could move Earth to the great amusement of the press and the educated public. (Even Jean-Luc Picard could not do this sort of geoengineering.)

### Sulfur-Dioxide Particles in the Stratosphere

The most promising SRM technique is based on jetliners dispersing small reflective sulfur-dioxide particles into the stratosphere. These particles would then reflect incoming sunlight and cool the climate (as they are intended to). They circulate for a few years before falling back to Earth.

Scientists know how this type of SRM works, because volcanoes have demonstrated its efficacy many times before. However, SRM is a patch, not a solution. It does not address other harmful effects of greenhouse gases, such as ocean acidification. (In fact, sulfur-dioxide particles will make it worse.)

The big advantage of SRM is cost. The estimates are best described as ridiculously cheap, ranging from about $2 billion to $10 billion per year. This is 100-1,000 times cheaper than $CO_2$ elimination.

Furthermore, cooling the world with sulfur-dioxide may be ill-advised as long as the harm from climate change remains limited. Yet if global warming were to ever become world-threatening (although we do not see how this could happen) or just extremely harmful, sulfur-dioxide would work almost immediately. Contrast this to the many decades that it would take to start cooling the planet with $CO_2$ reductions.

### Artificial Clouds

Another interesting alternative is seeding artificial clouds. It is fairly cheap to send a few boats out onto the ocean and spray water from atomizers into the air that then form clouds. If we can do it for snow, why not for reflecting sunlight? Maybe 200-300 boats could do the job. Unlike sulfur-dioxide particles, cloud seeding can be started and stopped almost instantaneously — plus it has no negative ocean acidification consequences. Unfortunately, science is not even sure whether clouds help or hurt global warming. There could also be regions where seeding helps and other regions where it hurts.

## Be Ready For Plan C

It's important for scientists to learn more about SRM, even though it seems premature to deploy it. Hopefully, humanity will never have to. No one should be excited about solar radiation management. It shouldn't even be Plan B, but rather Plan C. Many environmentalists and scientists legitimately warn about unintended dangerous side-effects. Even the most ardent proponents only advocate for SRM as a stopgap bridge solution for a few decades, a complement to emission reductions. The second danger is that some countries may use it as a substitute. They may simply prefer to spend a little on solar radiation management rather than a lot on the underlying problem of greenhouse gas emissions.

There is an important asterisk here. Countries could disperse particles without asking other countries for permission. Countries in the Sahel may be thrilled to receive more rainfall, but what if it negatively affects rainfall in Europe? What if India suffered a heatwave killing 20 million people and decided unilaterally to deploy sulfur-dioxide particles? Would this be a good reason to start a war?

For now, we agree with many other academics interested in climate science (including Profs Dressler, Parson, Pindyck, and the National Academies) that humanity should learn more about the costs and benefits of SRM. It would be wise to understand these technologies. We advocate testing them in small-scale temporary pilot projects, where the negative effects are almost surely outweighed by the positive ones. For example, we should run a one-year experiment to find out whether a little bit of cloud seeding could increase rain in a small part of the Sahara (reducing rain over the Indian Ocean). It would be worth the learning cost. Yes, there is the possibility of unintended consequences — but they need to be weighed against the benefits of the intended consequences.

It would be foolish for humanity to count on solar radiation management as a long-term solution, if only because it may not work or the side effects may be too bad. There are good reasons to fear unintended consequences. However, it would be even more foolish not to be able to deploy a rescue if a catastrophic temperature-feedback effect were to occur.

Humanity may need to take unprecedented steps to moderate its climate. We hope use of the power to alter climate will come with far greater wisdom and forethought than what civilization has shown so far. Developing this wisdom may well be a taller order than the geoengineering itself.

# Conclusion

Large-scale expensive industrial $CO_2$ removal schemes are currently not feasible. To be economically viable, the cost of $CO_2$ removal has to be under $20/tCO2, perhaps less. Forestation in many places already has even lower costs *and* provides positive local benefits — and yet humanity is still passing it by! Environmentalists should work on moving this needle now — incentivizing entrepreneurs to plant more trees for profit. Hoping to fight climate change by simultaneously bringing down the cost of industrial $CO_2$ removal processes to $100/tCO2 and overcoming the free-rider problem seems quixotic.

We view solar radiation management as important for two reasons. First, it is cheap — so cheap perhaps that one rich philanthropist like Bill Gates could potentially stop world-wide warming. Second, its effects could be quick — unlike $CO_2$ removal, which has effects only on time spans of decades. Environmentalists should push not for deployment of solar radiation management, but for small-scale scientific research experiments — if not using sulfur-dioxide particles, then at least using ocean cloud seeding.

# Further Readings

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### Websites

- Harvard Solar Geoengineering Research Program.
- Joanne Chory, leader in reengineering plants to capture more $CO_2$ into plant roots.

### Video

- NOVA: Can We Cool The Planet?

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