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14 Cleaning Up

If we make too big of a mess, we will have to clean up after ourselves.

It's imperative to decarbonize the world economy to avoid global catastrophe. Recent developments in clean energy, storage, transmission, and clean form power have reversed the situation from a decade ago when continuing to burn carbon was cheaper than decarbonization. Nevertheless, CO_2 emissions are still rising in 2022 and the clean energy transition must happen very fast.

In this module we consider the possibility that global decarbonization will not be completed fast enough and that much more difficult and expensive "emergency measures" may have to be taken to remove CO_2 from the atmosphere or even manipulate Earth's climate itself through geoengineering.

14.1 Timing is Everything

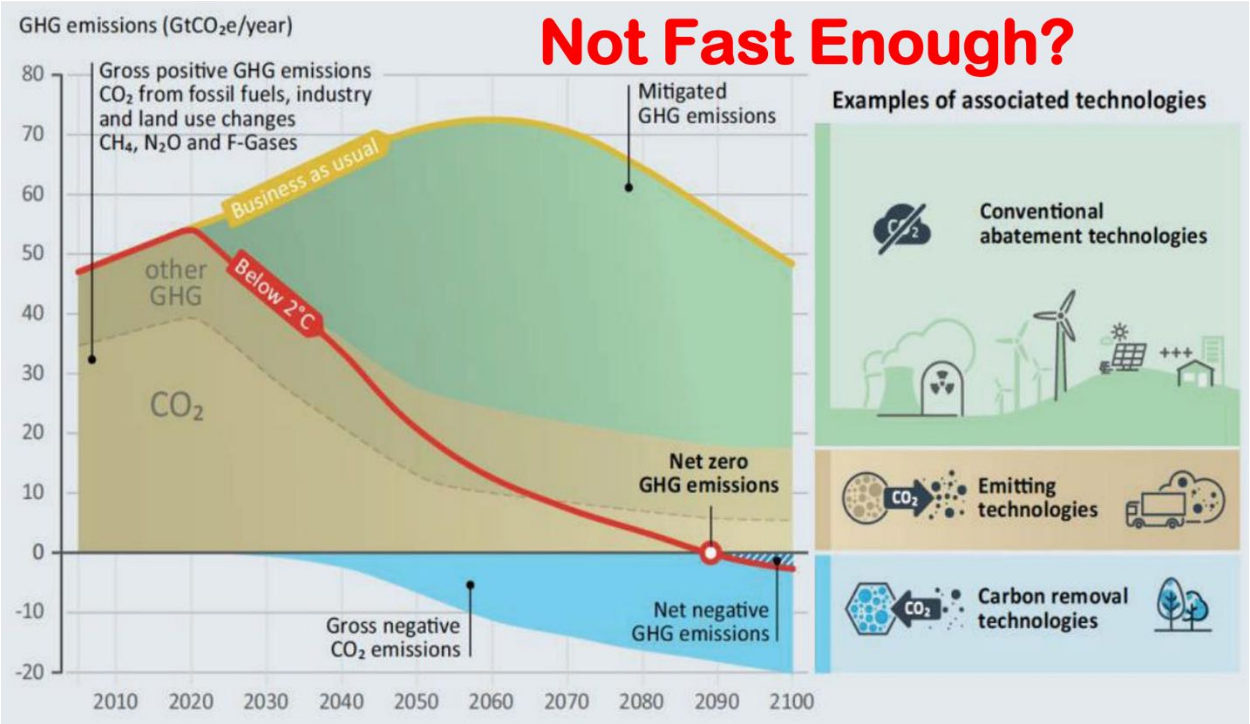


Figure 14-1: Hypothetical trajectories for positive and negative GHG emissions to avoid warming beyond the agreed 2 ºC limit

Nearly every country in the world has agreed under the UN Framework Convention on Climate Change to limit gobal warming to 2 ºC compared to preindustrial conditions, with an aspirational goal of 1.5 ºC (Module 12). Meeting these goals will require very rapid deployment of clean energy infrastruture worldwide, including huge efforts to mine the required materials and spin up new manufacturing. The massive industrial program required to save the future will likely consume a large fraction of the remaining “carbon budget” to prevent exceeding agreed warming limits.

In Fig 14-1, the yellow line shows a hypothetical future emissions trajectory in which emissions peak around 2070 and fall slowly thereafter. By contrast, emissions must follow the red line, falling by half over the next generation and then to zero in the generation after that to hold global warming to agreed limits.

The green area in Fig 14-1 represents “conventional abatement technologies:” rapid scaling of both energy efficiency and clean energy technologies discussed in Module 13. Most integrated assessment models reviewed by IPCC that successfully limit warming to 2 ºC include large amounts of negative GHG emissions (blue area in Fig 14-1) to offset both continuing CO_2 emissions (lighter brown area I Fig 14-1) that aren’t cut fast enough and also emissions of other GHGs such as CH_4 and N_2O that are harder to substitute (darker borwn in Fig 14-1).

14.1.1 Overshoot and Recovery

If emissions aren’t cut fast enough and warming continues above 2 ºC, persistent natural carbon sinks (Module 9) may or may not cool climate after emissions eventually stop. These “overshoot and recovery” scenarios may require carbon dioxide removal to bring CO_2 back down.

14.1.2 In the Long Run …

Anthropogenic CO_2 is likely to persist in the atmosphere for centuries or even millennia after emissions cease, especially if overshoot is significant. The long-term threat of excess near-term emissions requires that we develop the capability to remove CO_2 and possibly even cool the climate through radiation management.

Carbon dioxide removal (CDR) and Solar Radiation Management (SRM) are last-ditch measures. They are no substitute for rapid decarbonization of the global economy. These methods will certainly be more expensive and difficult than an all-out effort to deploy clean energy and they would cost future generations dearly.

Unfortunately, failure to solve our climate problems may cost even more.

14.2 Carbon Dioxide Reduction (CDR)

Removing CO_2 from the air isn’t as easy as it sounds!

There are two fundamental obstacles:

1. gathering dilute oxidized carbon from oxygen-rich air and storing it uses more energy than oxidizing it released in the first place; and

2. atmospheric CO_2 exchanges with two much larger reservoirs of carbon in the ocean and in land ecosystems so it's hard to ensure stored carbon stays stored.

Many CDR methods have been considered (Fig 14-2), some of which we'll look at in detail below. All require that dilute CO_2 gas be concentrated in some way from the atmosphere (upper half of Fig 14-2). This requires that a lot of energy be expended, diverted form some other use. Then the concentrated CO_2 must be stored in such as way that it can't escape back into the air (lower half of Fig 14-2).

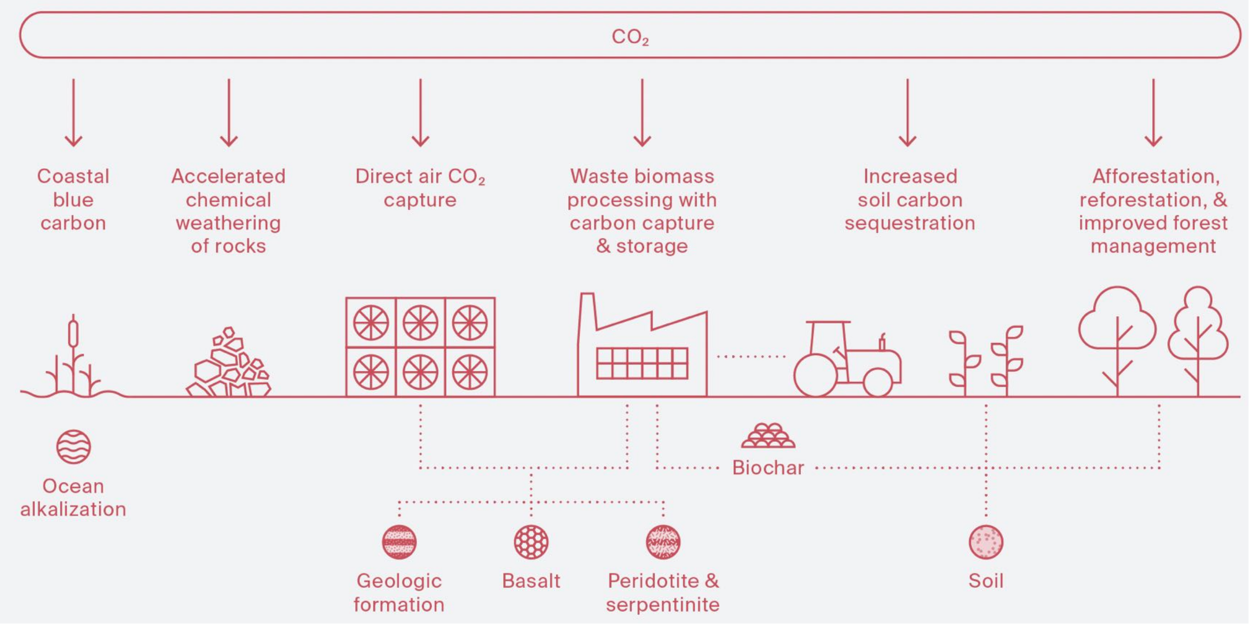


Figure 14-2: Proposed methods for carbon dioxide removal and long-term storage

The ***easiest methods for extracting CO_2 from air leverage natural photosynthesis***, which gets its energy from the Sun. Forests, grasslands, and crops are already very good at using solar energy to extract CO_2 form air – recall that they already remove about 1/7 of all CO_2 form the air each year. But organic matter formed by photosynthesis decays back to CO_2 in the presence of oxygen and microbes, producing 1/7 of all CO_2 every year as well.

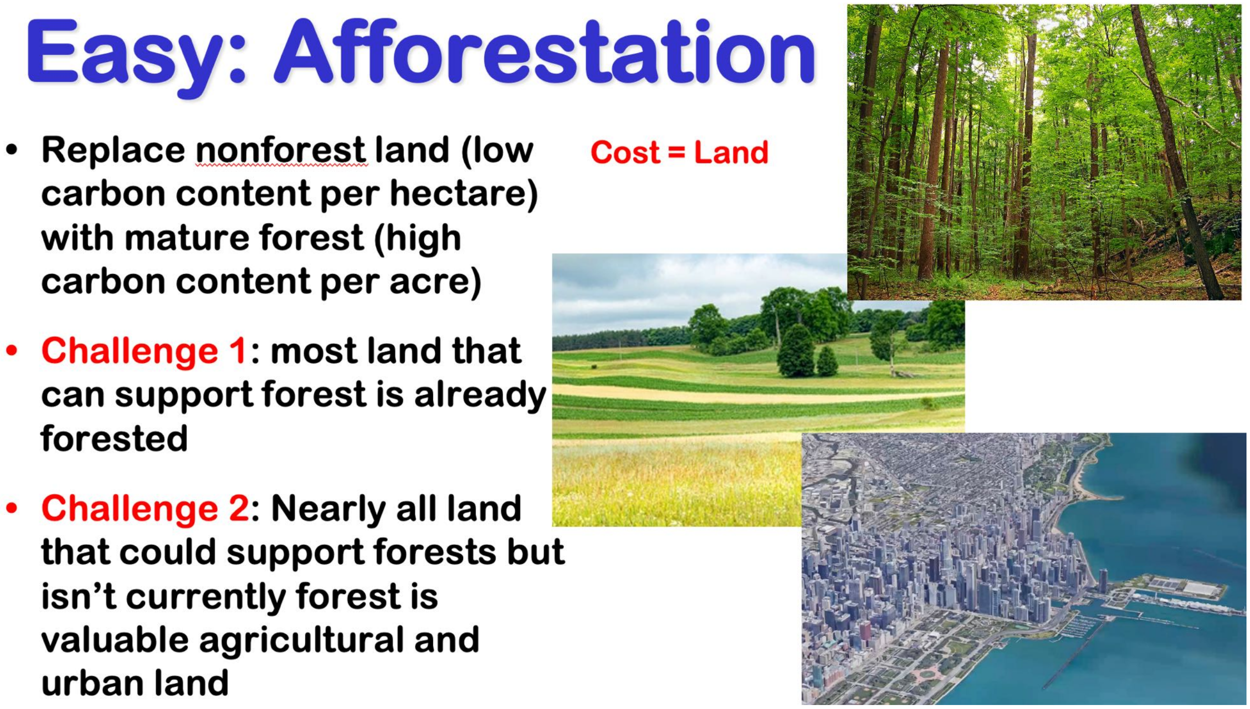
On the right side of Fig 14-2 are CDR methods that "hack biology." They are designed to interrupt the natural carbon cycle: they must ***accomplish large amounts of photosynthesis and prevent the resulting decomposition***. This might involve ***large-scale forest growth*** that stores microbe-resistant carbon in wood. Improved farm practices might sequester photosynthetic carbon in ***soil organic matter***. Partial combustion ("pyrolysis") can render organic matter unpalatable to microbes through the creation of ***biochar***.

Much more expensive and energy-intensive CDR (middle of Fig 14-2) use industrial processes to capture CO_2, either in concentrated form from waste biomass or directly from thin air. The concentrated CO_2 must then be stored somehow in a form that prevents its future escape to the air. This is also expensive and difficult. Liquified CO_2 could be transported via pipelines or tankers to be pumped deep underground. There it could be mineralized by exposure to highly reactive rocks (basalt or peridotite) or simply stored in deep porosity.

It is also possible to "hack geochemistry" by speeding up the removal of CO_2 through chemical weathering of reactive rocks (left side of Fig 14-2). This could involve mining, transporting, pulverizing, and spreading huge amounts of basalt or ultramafic rocks on high-CO_2 soils like croplands. The resulting soluble bicarbonate ions would be carried by runoff to the oceans where they would enhance the long-term solubility of fossil carbon in the deep sea. Coastal blue carbon refers to enhanced productivity of mangroves or other shallow-water marine plants whose decomposition is limited by low levels of dissolved oxygen.

14.2.1 Leveraging Forestry: Growing forests, not trees

Mature forests store enormous amounts of long-lived carbon in live and dead biomass (wood, roots, and soil organic matter). Permanently replacing low-carbon landscapes (pastures, farms, suburbs) with high-carbon landscapes (mature forests) can potentially transfer CO_2 out of the atmosphere.



Easy: Afforestation

- **Replace nonforest land (low carbon content per hectare) with mature forest (high carbon content per acre)**
- **Challenge 1: most land that can support forest is already forested**
- **Challenge 2: Nearly all land that could support forests but isn't currently forest is valuable agricultural and urban land**

Cost = Land

Note that ***forest carbon storage is NOT as simple as "planting trees."*** Each tree converts CO_2 to sugar and then wood while it's growing, but also feeds microbial decomposition when it dies. The total ***change in CO_2 over the lifecycle of a given tree is precisely zero***. Rather, forest ***carbon sequestration occurs when land is permanently changed from nonforest to forest***. This takes many decades because forests grow slowly. The idea is to compare the total carbon content of a landscape before conversion to afterward.

There are major advantages to CDR through afforestation and reforestation. Energy for CO_2 sequestration is provided naturally by sunlight through photosynthesis. Storage happens locally in wood and soil, requiring no expensive systems to gather and transport the material and no specialized reservoirs to store it. Wood is naturally long-lived, and material lost to decomposition is naturally replenished by new growth. Mature forests provide many valuable ecosystem services such as wildlife habitat, reduced air and water pollution, and recreation.

The principal limitation to forest CDR is the availability of land. Forests cannot grow on most of the planet (oceans, ice sheets, deserts, grasslands). Most land which could support forests is already forested (tropical and boreal regions). The best nonforested land for growing new mature forest is very valuable for agriculture, cities, and suburbs. In fact much of this land was converted from forest to other "productive" uses long ago, and it would be very expensive to reforest huge tracts of prime farmland and densely-populated suburbs.

Growing new forests the size of India by abandoning farms and cities might be possible, and would result in carbon uptake of perhaps 20% of today's fossil fuel emissions. Of course, this would require relocating huge numbers of people and dramatically increasing food production on the remaining farmland.

14.2.2 Hacking Agriculture

Ideally, farming is a net zero carbon activity in which annual growth is balanced by annual respiration and decomposition. In practice it is ***often a net source of CO_2 due to loss of soil organic matter***. Worse, ***overfertilization of crops releases the long-lived greenhouse gas N_2O*** and ***animal agriculture releases the shorter-lived but powerful greenhouse gas CH_4*** to the atmosphere. There is a lot of room for improvement by improving agriculture to reduce emissions. Beyond that, there is some scope for CDR through diverting CO_2 fixed by photosynthesis into longer-lived pools that keep carbon out of the atmosphere, at least for the medium term.

Soil carbon management

Top priorities for sustainable agriculture include better management of cropland and pasture to reduce carbon losses, and aggressive mitigation of powerful non-CO_2 greenhouse gases like N_2O and CH_4.

Reduced tillage crop production protects organic matter in soils by keeping it away from the air. Some soil organic matter is physically protected from contact with oxygen and microbes inside small aggregates in which the carbon is tightly bound to mineral particles, especially clay. Tilling breaks these aggregates, exposing soil organic matter to air, fungus, and bacteria which can easily transform it to CO_2. Decades or even centuries of traditional tillage have led to chronic depletion of soil organic matter and in turn require more and more fertilizer to keep land productive. Rebuilding soil carbon stocks through reduced tillage can sequester carbon.

Chemical fertilizers based on nitrogen extracted from air with fossil energy led to dramatic increases in food production and the human population explosion of the 20th Century. Chemically reactive nitrogen is a limiting nutrient for almost all biology so adding it to crops tends to increase productivity. But overuse of nitrogen fertilizers (beyond what crop plants can take up and convert to organic matter) leads to emissions of nitrous oxide (N2O) from agricultural soils. Over 100 years, each kg of N_2O warms Earth's climate as much as 273 kg of CO_2. This ratio is known as the Global Warming Potential GWP_{100}. Careful crop management to match fertilizer application to plant uptake can dramatically reduce these emissions. This is critical for reducing agricultural GHG emissions through it doesn't actually lead to CO_2 reduction.

Animal agriculture, especially the production of beef, emits a lot of methane (CH_4). Methane is another very powerful but relatively short-lived greenhouse gas with a $GWP_{100} = 28$ and an atmospheric lifetime of about 12 years. Unlike humans, cattle digest grass so they can transform the photosynthesis of highly productive grasslands into food. But their ruminant digestion produces methane during their entire grazing lifetime. Worse, the beef industry often gathers huge numbers of these animals in concentrated animal feeding operations (CAFOs, a.k.a. feedlots) to fatten them up on grain before slaughter. These CAFOs are huge emitters of CH_4 both from digestion and from the resulting manure lagoons. Improved nutrition and manure management may be able to reduce but probably never eliminate these emissions. Better animal agriculture is imperative for climate, air quality, and health but doesn't actually lead to CO_2 reduction.

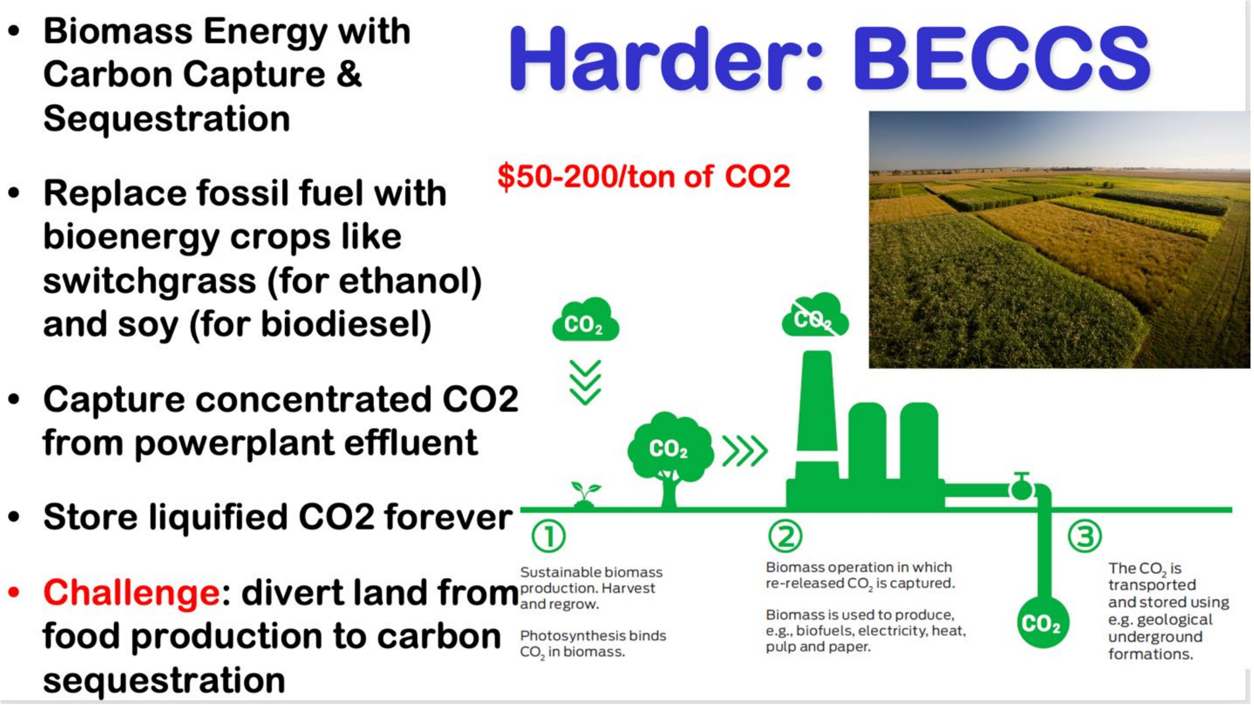
Regenerative agriculture is a broad category of improved farming practices intended to reduce GHG emissions, enhance soil nutrition and water retention, and perhaps sequester soil organic matter. It is hoped that better management of grazing animals and croplands can contribute to CDR, and that benefits for both producers and consumers are valuable in and of themselves.

Biochar

Virtually all carbon removed from the air by photosynthesis is eventually returned by oxidation (respiration, decomposition, and fire). Intentional partial combustion ("pyrolysis") can char organic waste to make it more difficult for microbes to decompose. Large amounts of plant waste (leaves, stems, stalks, stubble) could in principle be gathered and subjected to heat that drives off volatile nutrients and leaves a recalcitrant charcoal-like material that decomposes very slowly. This could then be buried or even used as an agricultural soil amendment to promote water retention. To the extent that some CO_2 fixed by crops could be diverted from microbial decomposition, large-scale production and productive use of biochar could lead to CDR and allow carbon to build up in soils.

Biomass Energy with Carbon Capture & Sequestration (BECCS)

Biomass energy includes the use of firewood for heat and cooking, and more recently the intentional production of crops for use as fuel. Corn is widely used to produce ethanol that is blended with gasoline for automobiles, and oil from soybeans is used to produce diesel. Newer biomass energy crops include *Miscanthus* and *Pennisetum*, potentially improved through genetic modification. To the extent that fuels derived from biomass energy crops displace fossil fuels,



Harder: BECCS

- **Biomass Energy with Carbon Capture & Sequestration**
- **Replace fossil fuel with bioenergy crops like switchgrass (for ethanol) and soy (for biodiesel)**
- **Capture concentrated CO2 from powerplant effluent**
- **Store liquified CO2 forever**
- **Challenge: divert land from food production to carbon sequestration**

$50-200/ton of CO2

① Sustainable biomass production. Harvest and regrow.

Photosynthesis binds CO_2 in biomass.

② Biomass operation in which re-released CO_2 is captured.

Biomass is used to produce, e.g., biofuels, electricity, heat, pulp and paper.

③ The CO_2 is transported and stored using e.g. geological underground formations.

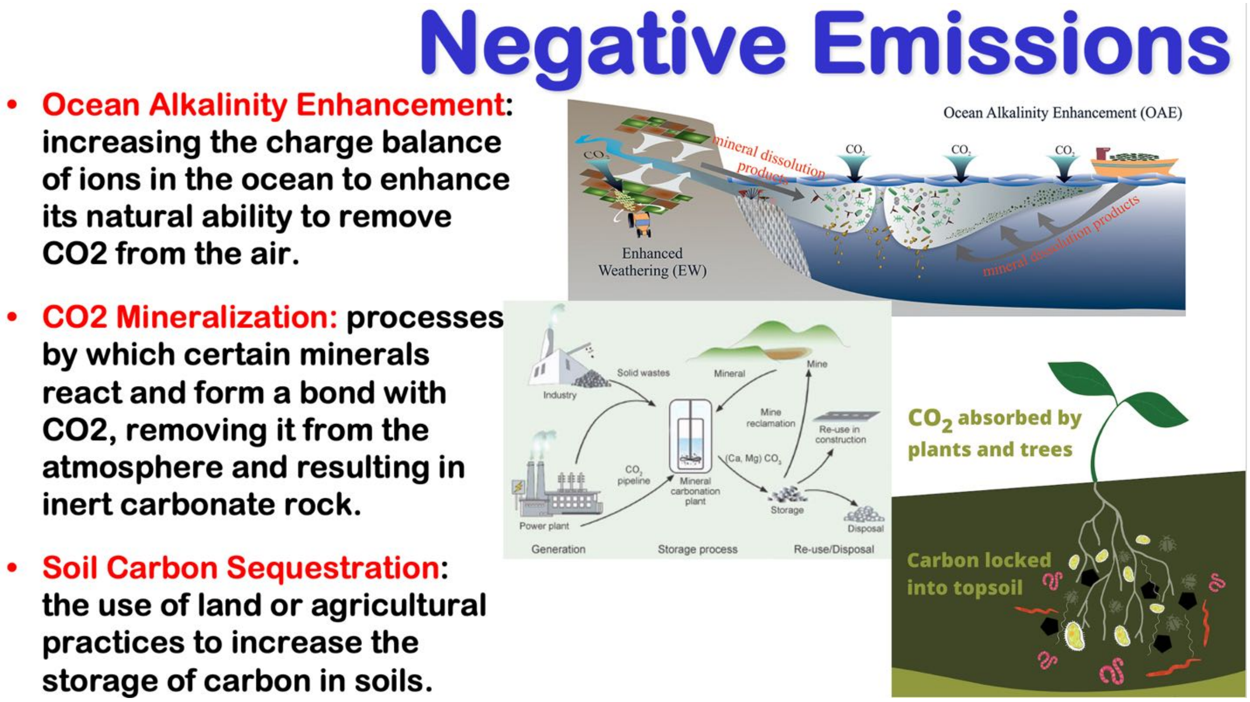
they reduce CO_2 emissions. A hypothetically carbon-neutral bioenergy lifecycle would use photosynthesis to convert CO_2 into fuel and then re-emit the same carbon atoms as CO_2 when the fuel is burned.

Biomass energy (BE) be used for CDR by combining it with carbon capture and sequestration (CCS) to extract the energy and store the carbon underground. Both BE and CCS are carbon neutral, but the combined BECCS process is carbon negative because CO_2 fixed by photosynthesis is passed into long-term storage without being re-emitted back to the atmosphere.

Both BE and CCS components have been demonstrated experimentally. A major advantage of BECCS is that chemical carbon capture from flue gas in industrial exhaust from a power plant is much more energy efficient than trying to capture CO_2 from thin air. Ambient air contains about 420 ppm of CO_2 – that is, 420 molecules of CO_2 per one million molecules of air (0.04%). Power plant exhaust can contain more than 100,000 ppm (10%) of CO_2 (assuming half of the 20% oxygen in the air is consumed by combustion with the fuel). The high concentration CO_2 in flue gas readily reacts with high-pH fluid placed in the airflow, and can then be extracted as liquid CO_2 or $CaCO_3$.

Any CCS system requires a large input of energy (usually in the form of heat) to regenerate the carbon capture reagents. Like fossil combustion with CCS, BECCS includes a ready source of heat in the form of power plant combustion. About one third of the energy generated by burning the fuel is sufficient to capture the CO_2, leaving two-thirds for power. The captured CO_2 must then be transported and stored in deep rocks or another reservoir forever.

The biggest disadvantage of BECCS is that it diverts land from food production to CDR.



Negative Emissions

- **Ocean Alkalinity Enhancement: increasing the charge balance of ions in the ocean to enhance its natural ability to remove CO2 from the air.**
- **CO2 Mineralization: processes by which certain minerals react and form a bond with CO2, removing it from the atmosphere and resulting in inert carbonate rock.**
- **Soil Carbon Sequestration: the use of land or agricultural practices to increase the storage of carbon in soils.**

14.2.3 Ocean alkalinity enhancement and carbon mineralization

When CO_2 dissolves in water, it forms carbonic acid (H2CO3) which dissociates to form free hydrogen ions (lowering the pH) and bicarbonate ions (HCO3-). The solubility of CO_2 in water depends on the acidity and conversely on the alkalinity of the water. Chemical weathering of fresh rocks on land is the main source of alkalinity in seawater, which is the basis of the long-term cycling of CO_2 that controls Earth's climate on geologic time scales (see Module 5).

It is possible to sequester CO_2 in the oceans by manipulating the large-scale alkalinity of the oceans The idea is to accelerate the natural process of chemical breakdown of rocks (which is known as "weathering"). This would involve very large-scale mining of chemically reactive rocks and subjecting them to the acidic action of concentrated carbonic acid.

Crystalline rocks from deep in the Earth range in chemical composition from light-colored granite that is high in silicon and aluminum to dark-colored basalt that is high in iron and magnesium. Basaltic rocks rich in iron (Fe) and magnesium (Mg) are known as "mafic" and are abundant in ocean crust and volcanic outflows. Mafic rocks are highly soluble at surface temperature and pressure and consume carbonic acid as they dissolve. Even more reactive are ultramafic rocks derived from Earth's mantle. These include peridotite and serpentine and are much rarer than basalt.

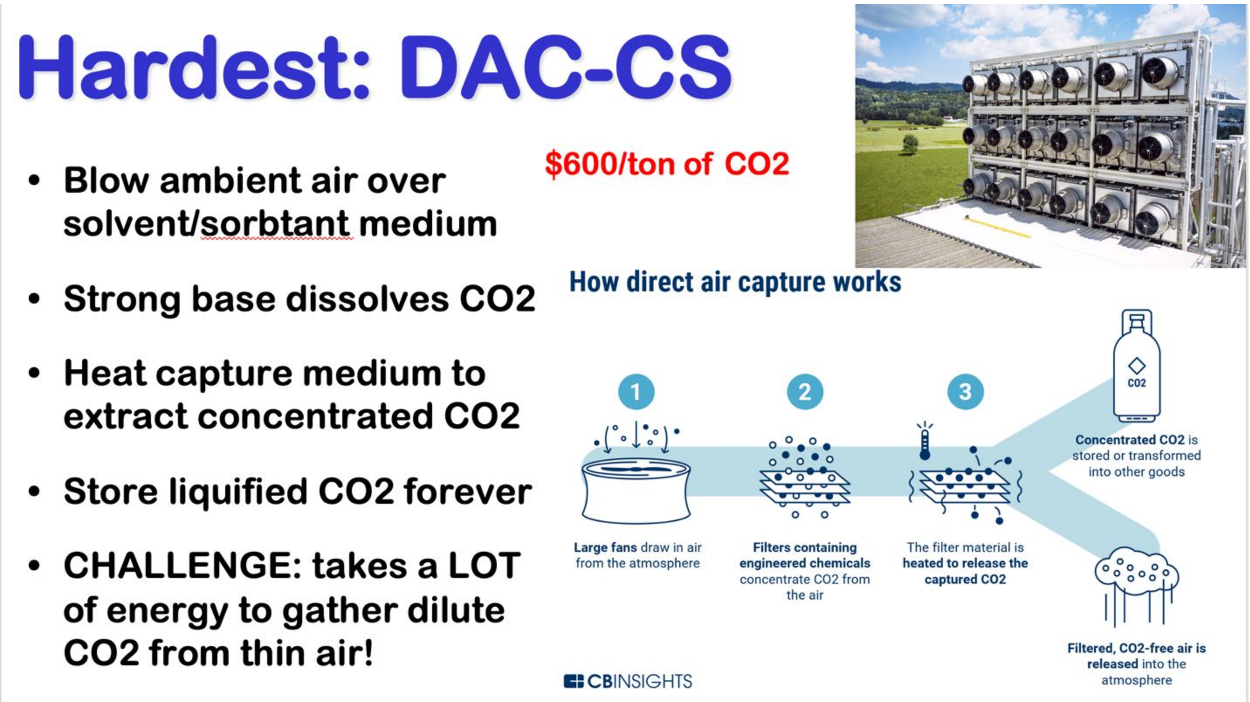
Carbon dioxide removal could be accomplished by mining huge amounts of reactive basalt or peridotite. The material would be transported to farms, pulverized and mixed with water as a slurry, then applied as a soil amendment to croplands. Dissolved CO_2 in agricultural soils would then react with the rock powder to produce alkaline runoff to streams and eventually the oceans. Besides neutralizing CO_2 in the soils, the long-term addition of alkalinity to the oceans would increase the solubility of CO_2 in seawater and eventually transfer some fossil fuel CO_2 into the deep oceans.

The big advantage of accelerated chemical weathering and ocean alkalinity enhancement is that the large energy requirement for CDR would be met chemically through highly reactive minerals rather than using heat produced by diverting energy from other uses. Mafic rocks are very abundant on Earth (pretty much the entire ocean crust is made of basalt).

The disadvantage of CDR by these methods is that it would take an enormous amount of mining and processing to sequester much CO_2. Not all crops would flourish under a steady spray of alkaline rock slurry. A lot of research and development will be required to make this work.

14.2.4 Direct Air Capture

It's intriguing to consider just "vacuuming up" CO_2 directly from the air and then stuffing it underground as either high-pressure liquid or precipitated as carbonate minerals. Unfortunately this is probably the most difficult and costly of all methods of CDR.



Hardest: DAC-CS

- **Blow ambient air over solvent/sorbtant medium**
- **Strong base dissolves CO2**
- **Heat capture medium to extract concentrated CO2**
- **Store liquified CO2 forever**
- **CHALLENGE: takes a LOT of energy to gather dilute CO2 from thin air!**

$600/ton of CO2

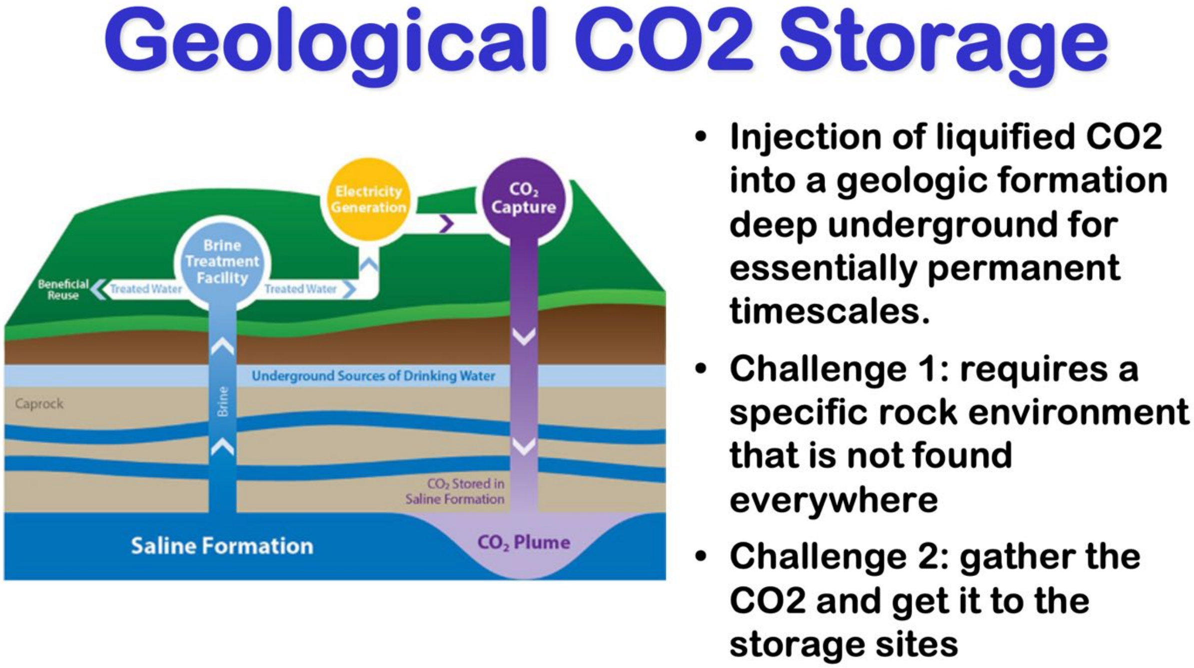
Direct air capture (DAC) of CO_2 involves blowing large volumes of ambient air (420 ppm CO_2) across glass beads or another solid medium coated with a high-pH solution into which the CO_2 gas dissolves. Once the sorbtant material becomes saturated, the CO_2 is extracted with heat to regenerate the reagents and the concentrated CO_2 must be disposed by deep burial or reaction with alkaline minerals (carbon storage, CS).

The advantage of DAC CS over BECCS is that it doesn't divert land from food production and can be done almost anywhere. The big disadvantage is that it takes much more energy than

BECCS or fossil combustion with CCS because CO_2 in ambient air is so dilute (420 ppm compared with 100,000 ppm or more in combustion effluent). Unlike BECCS or fossil fuel CCS there is no ready source of heat available to regenerate the reagent. Large amounts of energy must therefore be diverted from other uses to capture CO_2 from air. This large energy requirement also makes DAC very expensive relative to the other CDR methods considered here.

14.2.5 Geological CO_2 Storage

Other than so-called "natural solutions" like forest and farm management or accelerate chemical weathering, all forms of CDR require a geologic reservoir for permanent storage of the captured CO_2. Two experimental techniques for geological CO_2 storage have been explored: deep injection of CO_2-rich fluids into porous rocks and CO_2 mineralization in basaltic bedrock.

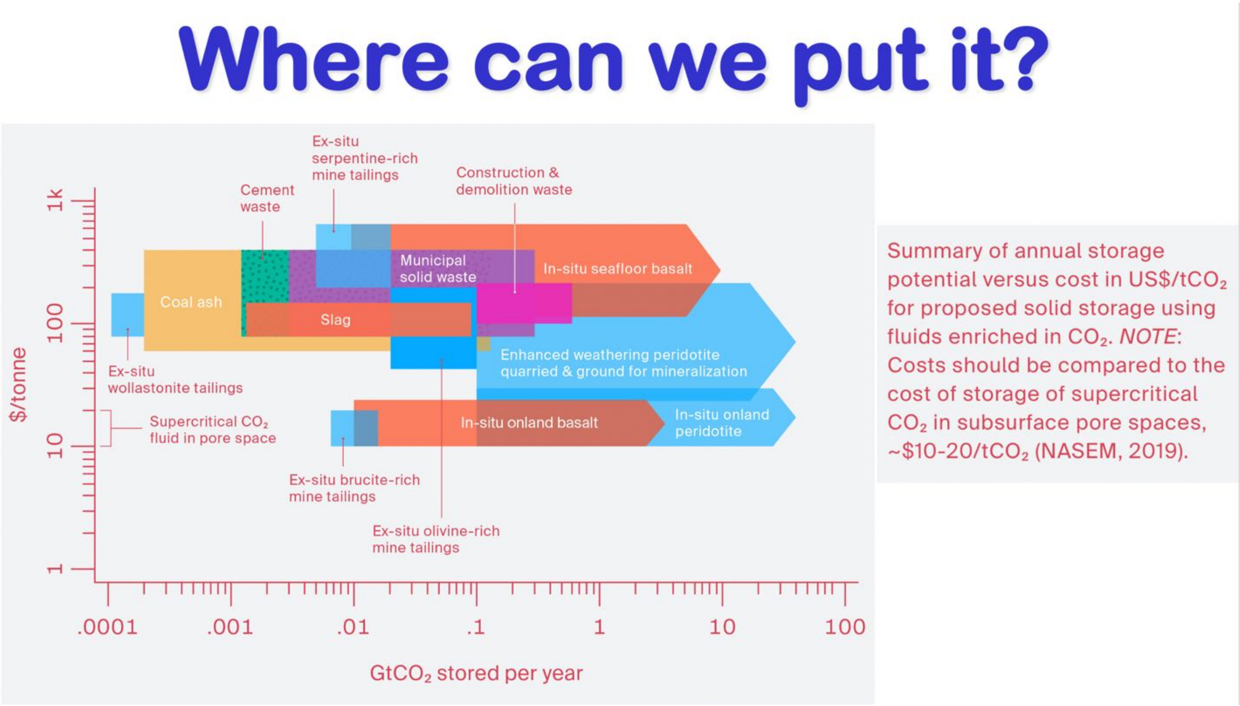


Geological CO2 Storage

- **Injection of liquified CO2 into a geologic formation deep underground for essentially permanent timescales.**
- **Challenge 1: requires a specific rock environment that is not found everywhere**
- **Challenge 2: gather the CO2 and get it to the storage sites**

Deep injection uses mature technologies already in use by the oil and gas industry. Depleted oil wells feature large volumes of pore space at great depth underground that were formerly full of petroleum but now contain salty water (brine). Oil and gas companies like this method of CO_2 storage because they hope to get paid twice: once for extracting the fuel and then again when they dispose of the combustion waste. After CO_2 is captured and pressurized into a liquid, it is pumped down into the porosity from which the oil and gas was extracted. The very high hydrostatic pressure imposed by the overlying rock keeps the CO_2 in place, and it can't migrate back to the surface due to impermeable rock layers that previously confined petroleum.

The US Department of Energy has explored the potential volumes of CO_2 that can be stored and the costs of various methods of geologic storage (Fig 14-3). The advantage of storing waste CO_2 in depleted oil and gas reservoirs is that it's relatively cheap (perhaps \$10 to \$20 per ton of



Where can we put it?

Summary of annual storage potential versus cost in US$/$tCO_2$ for proposed solid storage using fluids enriched in CO_2. *NOTE*: Costs should be compared to the cost of storage of supercritical CO_2 in subsurface pore spaces, ~$10-20/$tCO_2$ (NASEM, 2019).

Figure 14-3: Potential cost of CO_2 disposal ($/ton, y-axis) vs volume (tons/year, x-axis). Note that both axes are plotted on a logarithmic scale. US Department of Energy (2022)

CO_2, left edge of Fig 14-3). The obvious disadvantage is that there aren't enough depleted oil wells to store very much CO_2.

Other inexpensive geological storage could involve transporting concentrated CO_2 to storage wells drilled "in-situ" into reactive bedrock, perhaps basalt (Iceland?) or peridotite (Cyprus?). Moving the rock to the CO_2 for enhanced chemical weathering on farms would increase the costs many-fold but could still sequester large volumes (bottom right of Fig 14-3). There's a huge reservoir of basalt in ocean crust but drilling enough wells to store large amounts of CO_2 there would be prohibitively expensive (top-right of Fig 14-3). Much smaller amounts could be stored at higher cost in industrial waste (top-left of Fig 14-3).

14.3 Financial and Energy Costs of CDR

Let's consider the cost of carbon dioxide removal.

The mass of the global atmosphere is 5.15×10^{18} kg. The molecular weight of air is 29 kg/kMol, but the molecular weight of CO_2 is 44 kg/kMol, so ***each ppm of CO_2 in Earth's atmosphere weighs***

1 ppm of CO_2 in air

= (1 part CO_2 / 1,000,000 parts air) x 5.15×10^{18} kg x (44 kg CO2/kMol / 29 kg air/kMol)

= 7.81×10^{12} kg CO_2 = about 8 billion tons of CO_2.

So one ppm of CO_2 weighs about 8 Gt.

In this module, we considered many forms of CDR at costs from \$50/ton of CO_2 for BECCS to \$600/ton of CO_2 for DAC (not including the cost of permanent storage). Let's be generous and use a ballpark figure of \$100/ton, assuming that costs can eventually be brought down dramatically.

Using this optimistic assumption, ***removing one ppm of*** CO_2 ***form the air will cost about***

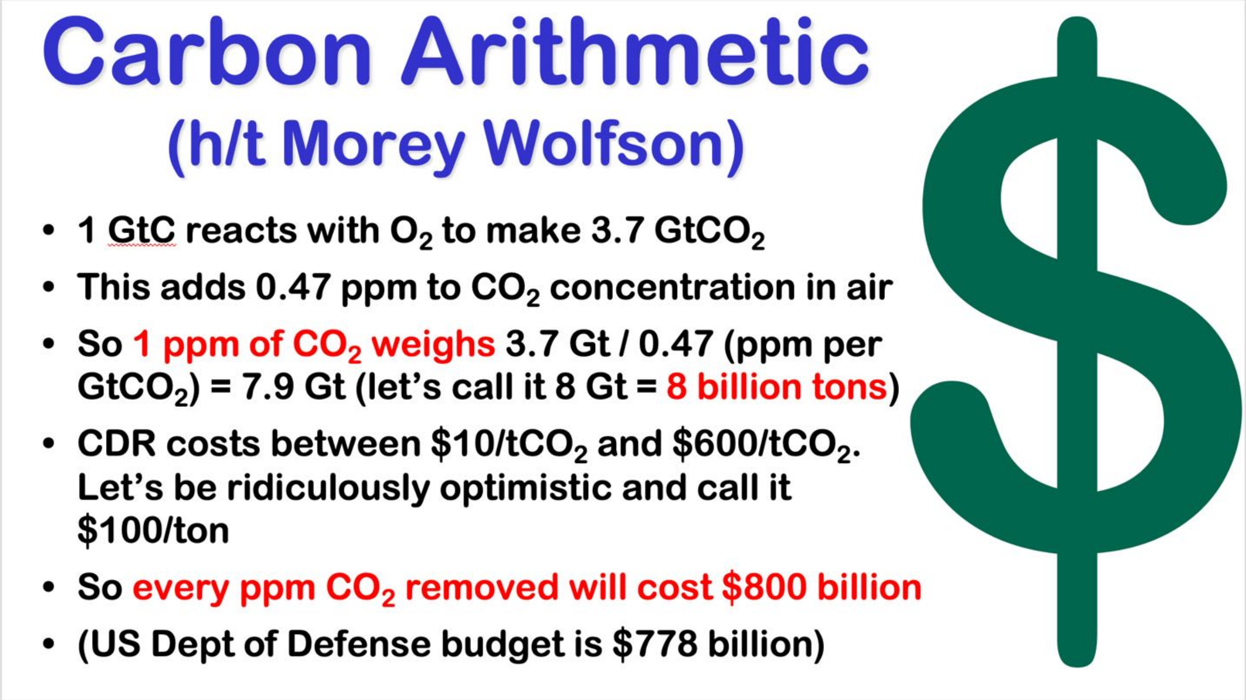
(8 billion tons of CO_2***) x (\$100/ton) = \$800 billion.***

By comparison, the US Department of Defense budget is \$778 billion.

The global economy currently creates about 5 ppm of CO_2 each year, of which only half accumulates in the atmosphere and the rest is helpfully removed by "natural sinks" in the land and oceans. Offsetting the annual accumulation of 2.5 ppm using CDR would cost about \$2000 billion per year (2% of global GDP).

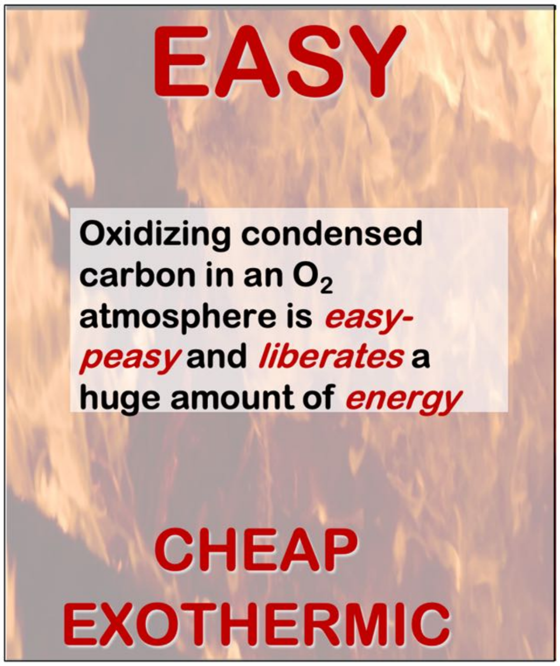
This back-of-the-envelope calculation shows how expensive "CO_2 overshoot" is likely to be. If we overshoot climate targets by 100 ppm and seek to use CDR to recover, we can expect to spend something like 100 times the US Defense budget on such a project.

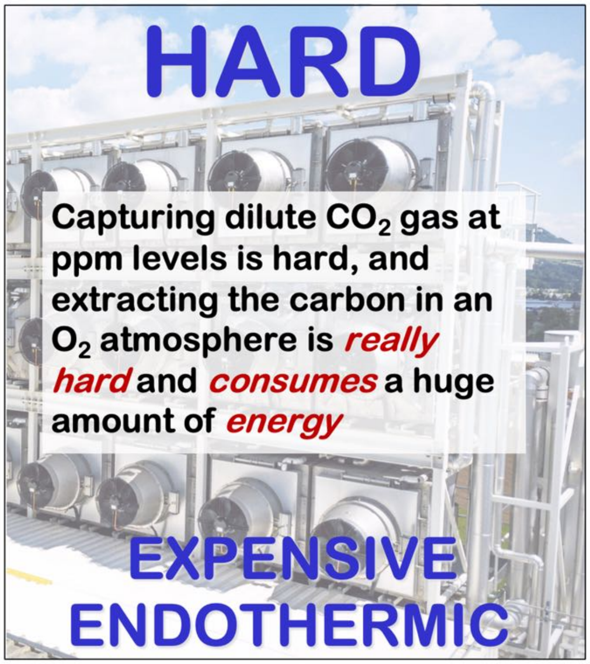
Just as land and ocean carbon sinks have provided a 50% natural offset of emissions while CO_2 rose, it is possible that changes in land and ocean carbon cycling would offset 50% of CDR as CO_2 falls. In that case the cost of 100 ppm overshoot would be 200 times the US defense budget.



Carbon Arithmetic
(h/t Morey Wolfson)

- 1 GtC reacts with O_2 to make 3.7 $GtCO_2$
- This adds 0.47 ppm to CO_2 concentration in air
- So 1 ppm of CO_2 weighs 3.7 Gt / 0.47 (ppm per $GtCO_2$) = 7.9 Gt (let's call it 8 Gt = 8 billion tons)
- CDR costs between \$10/tCO_2 and \$600/tCO_2. Let's be ridiculously optimistic and call it \$100/ton
- So every ppm CO_2 removed will cost \$800 billion
- (US Dept of Defense budget is \$778 billion)





It is certainly cheaper and easier to cut CO_2 emissions by decarbonizing the global economy as fast as possible rather than burning concentrated organic carbon now and then trying to clean up dilute oxidized CO_2 later!

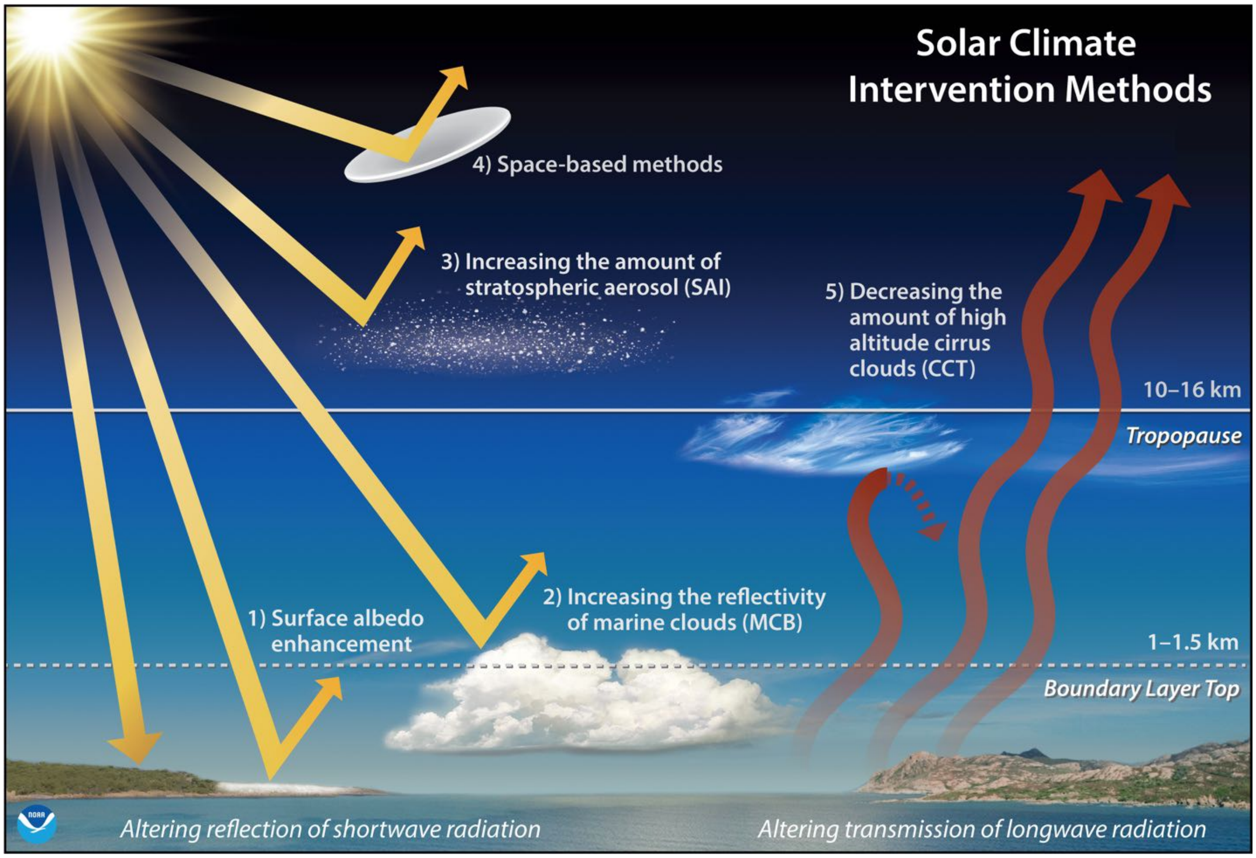
Burning concentrated reduced carbon in an O2 atmosphere is easy. It's cheap and exothermic, which is why people have been doing it for centuries. It's fun!

Capturing dilute CO_2 at ppm levels and then extracting the carbon from the oxygen, by comparison, is no fun at all. Doing so is wildly expensive and consumes huge amounts of energy which we'd really rather use for lights, heat, transportation, computing, and manufacturing.

According to the US Department of Energy, technological breakthroughs and economies of scale may eventually reduce the energy required for direct air capture of CO_2 to 5 gigaJoules per ton of CO_2. At that rate, just offsetting today's fossil fuel emissions using DAC would require 31% of today's 6×10^{20} Joules of primary energy production. That would just hold atmospheric CO_2 constant. If we also wanted to remove CO_2 from the air we would also have to expend 8% of civilization's power output for each ppm removed per year.

14.4 Solar Radiation Management (SRM)

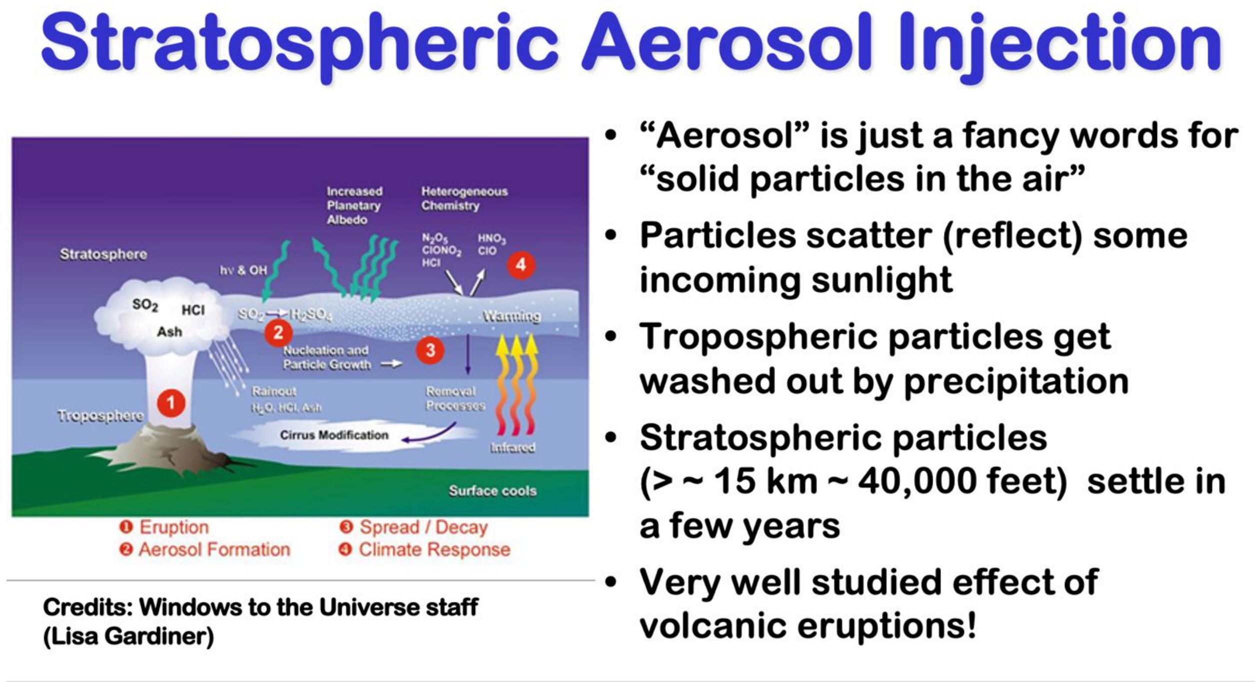
Another set of last-ditch efforts at mitigating climate change involves intentional manipulation of the Earth's radiation budget. Many methods have been considered as shown in the diagram below from NOAA.



Here we consider three classes of climate geoengineering methods using radiation management, as summarized by the US National Academies of Science:

1. Stratospheric Aerosol Injection (SAI), in which artificial particles are loftwed into the upper atmosphere where they reflect ("scatter") sunshine back to space;
2. Marine cloud brightening (MCB), in which the droplet size of low clouds over the oceans is modified to increase the reflectivity ("albedo") of marine clouds; and
3. Cirrus cloud thinning (CCT), in which cloud seeding is used to remove ice crystals from high altitude clouds to enhance their transparency to outgoing longwave radiation.

14.4.1 Stratospheric Aerosol Injection



Stratospheric Aerosol Injection

Credits: Windows to the Universe staff (Lisa Gardiner)

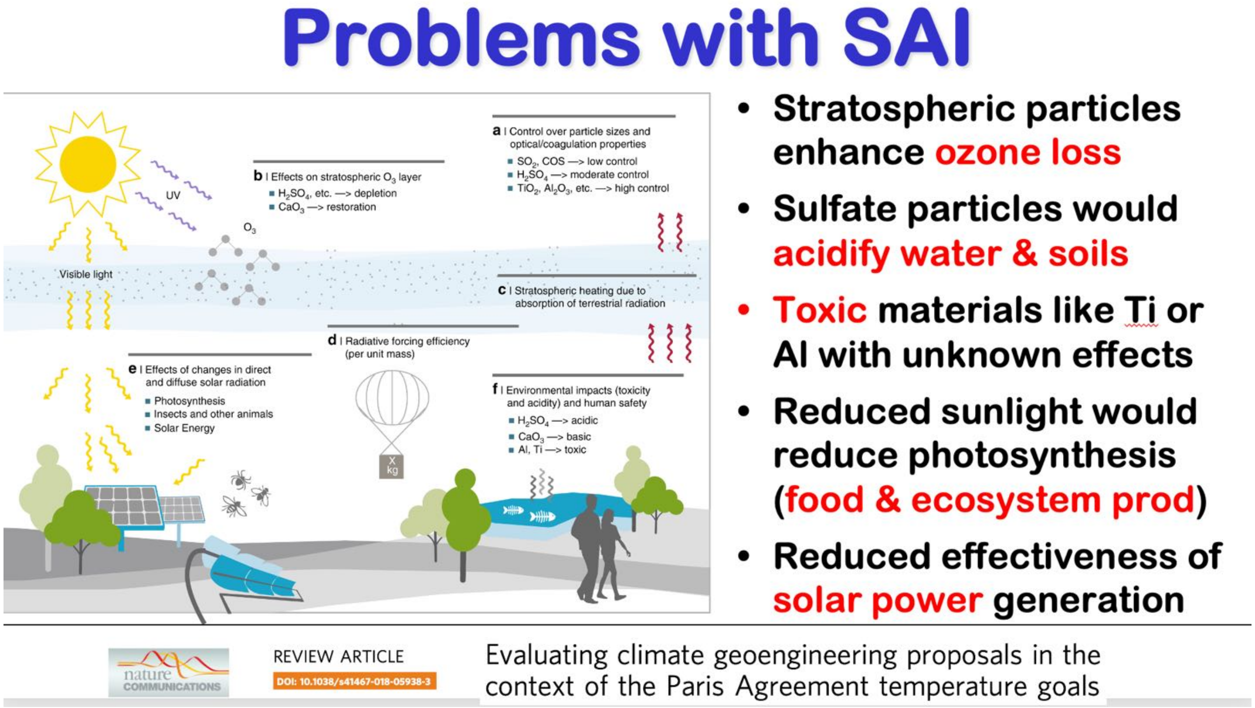
- **“Aerosol” is just a fancy words for “solid particles in the air”**
- **Particles scatter (reflect) some incoming sunlight**
- **Tropospheric particles get washed out by precipitation**
- **Stratospheric particles (> ~ 15 km ~ 40,000 feet) settle in a few years**
- **Very well studied effect of volcanic eruptions!**

Stratospheric aerosol injection (SAI) is intended to mimic the global cooling effect that follows major volcanic eruptions. “Aerosol” simply means “solids in air,” though the term often confuses people who think of spray cans.

Volcanic eruptions release huge amount of sulfur gases which condense to form microscopic droplets and solid particles of sulfate (SO_4). These particles scatter and reflect sunlight back to space, increasing Earth’s albedo and cooling climate. Particles in the troposphere are quickly washed out by rain and snow. There are virtually no clouds or precipitation in the cold stratosphere above about 15 km, so stratospheric particles persist for years. The cooling effect of stratospheric particles has been very well studied after large volcanic eruptions such as that of Mount Pinatubo in 1991.

Sulfur gases and particles could be intentionally injected into the stratosphere by high-altitude balloons or aircraft, or potentially even using inexpensive artillery. Numerical models suggest that global climate could be measurably cooled at modest cost using these methods. Cooling would fade as the particles slowly settled by gravity down into the troposphere where they would be removed by precipitation, so more sulfur would have to be injected continuously.

There are a raft of potential problems with geoengineering climate using SAI. Stratospheric particles serve as surfaces for catalytic ozone destruction, and would almost certainly harm the UV-protective ozone layer. Rainout of sulfuric particles would acidify water and soils and other ingredients such as titanium or aluminum would also pollute the environment. Any reduction of sunlight reahing the surface would reduce plant (food, ecosystem) production and degrade solar electricity.



Problems with SAI

- **Stratospheric particles enhance ozone loss**
- **Sulfate particles would acidify water & soils**
- **Toxic materials like Ti or Al with unknown effects**
- **Reduced sunlight would reduce photosynthesis (food & ecosystem prod)**
- **Reduced effectiveness of solar power generation**

nature COMMUNICATIONS

REVIEW ARTICLE

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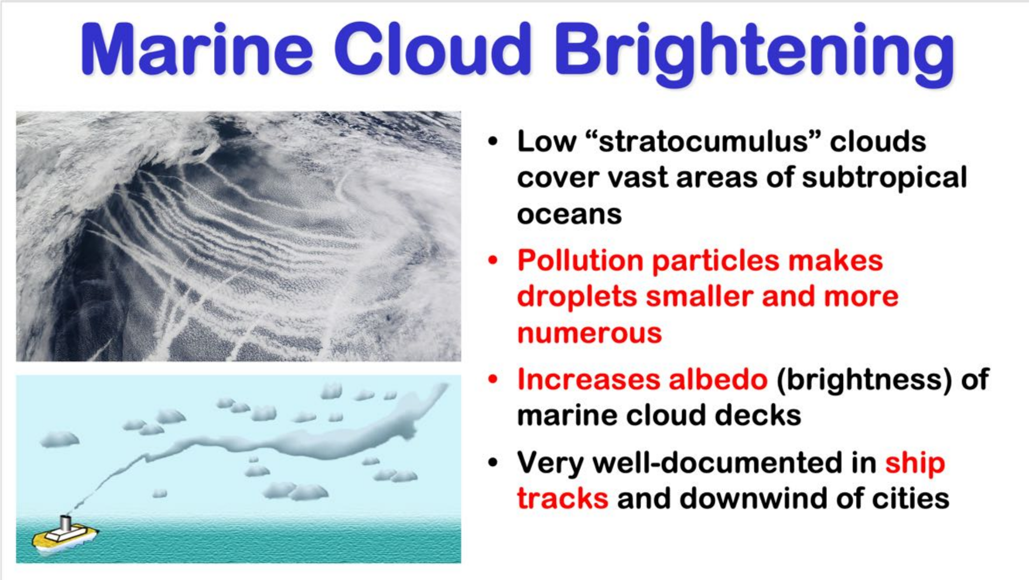
Evaluating climate geoengineering proposals in the context of the Paris Agreement temperature goals

14.4.2 Marine Cloud Brightening

Like SAI, Marine Cloud Brightening (MCB) is another albedo enhancement strategy. The idea with MCB isn't to directly reflect sunlight with particles but rather to use microscopic particles as cloud condensation nuclei in low clouds over the oceans. These particles allow microscopic droplets of liquid water to form from water vapor. Instead of fewer large droplets the idea is to make many more but smaller droplets. Low clouds with lots of tiny droplets are better at reflecting incoming sunlight – they have higher albedo.

The inspiration for MCB is the observation that low clouds over the ocean often display bright streaks where ships have passed underneath. These ship tracks are caused by pollution particles in the combustion exhaust which have nucleated tiny droplets and brightened the overlying clouds. Pollution plumes downwind of urban and industrial areas have a similar effect.

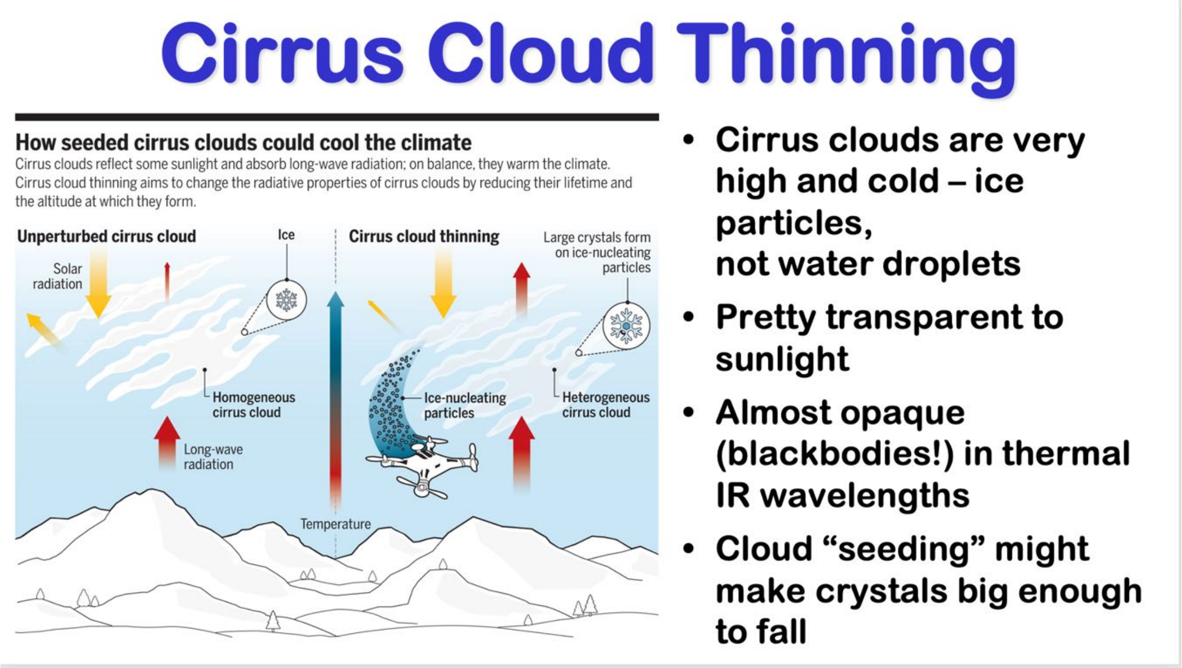
There are vast areas of persistent low clouds over Earth's cold subtropical oceans, especially along west coasts (think southern California, Peru, or Namibia). Seeding these clouds with the right mixture of particles could increase Earth's albedo and cool the climate.



Marine Cloud Brightening

- Low “stratocumulus” clouds cover vast areas of subtropical oceans
- Pollution particles makes droplets smaller and more numerous
- Increases albedo (brightness) of marine cloud decks
- Very well-documented in ship tracks and downwind of cities

14.4.3 Cirrus Cloud Thinning



Cirrus Cloud Thinning

How seeded cirrus clouds could cool the climate

Cirrus clouds reflect some sunlight and absorb long-wave radiation; on balance, they warm the climate. Cirrus cloud thinning aims to change the radiative properties of cirrus clouds by reducing their lifetime and the altitude at which they form.

- Cirrus clouds are very high and cold – ice particles, not water droplets
- Pretty transparent to sunlight
- Almost opaque (blackbodies!) in thermal IR wavelengths
- Cloud “seeding” might make crystals big enough to fall

Taking the opposite approach, intentional seeding high cirrus clouds would seek to grow ice crystals in the clouds to large enough size that they would fall as precipitation. High clouds made of ice crystals don’t block much sunlight, but they are very effective at warming Earth’s climate by absorbing outgoing longwave radiation. Removing ice crystals from cirrus clouds would theoretically allow more transmission of infrared radiation to space, offsetting some of the enhanced greenhouse effect of CO_2.

14.4.4 Cautions about SRM!

Climate intervention by radiation management does nothing about ocean acidification or other effects of CO_2 because it targets only greenhouse-induced warming. The intervention would need to be maintained indefinitely to avoid sudden warming within a few years of the particles falling out. Governance issues (who decides how much cooling to apply and for how long?) may be very difficult. Other problems and side-effects of climate geoengineering must be carefully studied before any such program is attempted.


"We're too busy mopping the floor to turn off the faucet."

It is almost certainly easier to stop making the climate problem worse by decarbonizing the global economy than to continue burning carbon and then trying to reverse engineer the more friendly climate of our past.

Using fossil fuels along with geoengineering with CDR or SRM is analogous to mopping the floor before turning off the faucet that's making the mess. It's a lot of work and it's ineffective.

Nevertheless, if we make a big enough mess by continuing to burn carbon for long enough, we may be stuck with a lot of expensive mopping.

14.5 RECOMMENDED ADDITIONAL READING

Carbon Dioxide Removal Primer. US Department of Energy, 2021. LINK

Ocean Carbon Sequestration. A Research Strategy for Ocean-based Carbon Dioxide Removal and Sequestration. National Academies Press, 2022. LINK

Reflecting Sunlight: Recommendations for Solar Geoengineering Research and Research Governance. Washington, DC: The National Academies Press. 2021. https://doi.org/10.17226/25762.