SFS
GEORGETOWN UNIVERSITY

STIA 4102

CLEAN ENERGY INNOVATION

Lecture 10:

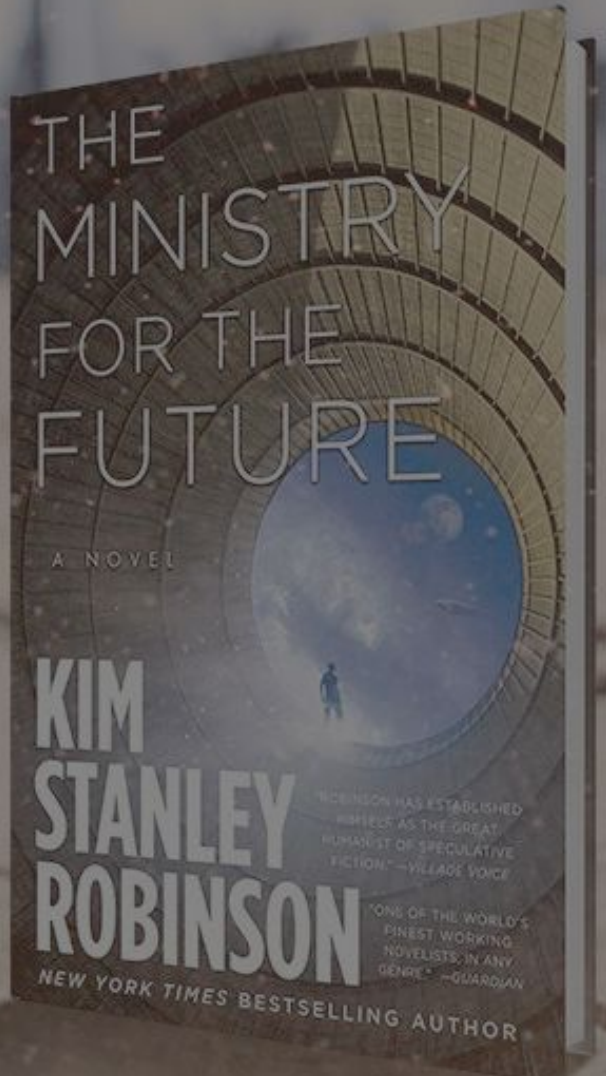
Carbon Removal & Geoengineering

What to Expect When You're Expecting

a Worst-Case Scenario

Thursdays 3:30-6:00 PM
133 Reynolds Hall
Fall 2023 Semester

November 2nd, 2023
Prof. Jonathan "Jo" Melville

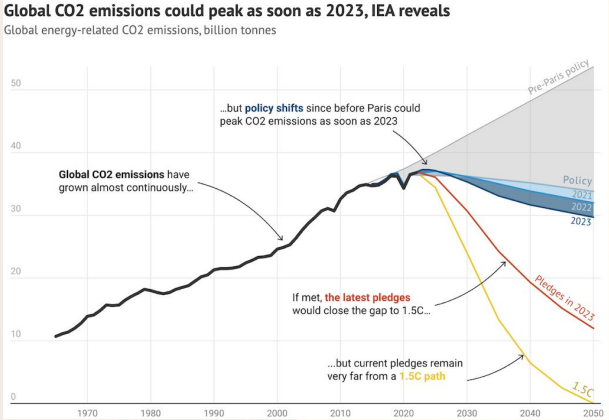


We flew to sixty thousand feet, as high as the planes could get. Higher would have been better but we couldn't do it. […]

Once up there we deployed the fuel lines and pumped the aerosols into the air. The plumes looked like dumped fuel at first, but they were really aerosol particulates, we were told mostly sulfur dioxide and then some other chemicals, like from a volcano, but there wasn't ash like in a volcanic explosion, it was a mix made to stay up there and reflect sunlight.

[…] soon enough what we released would get carried by the winds all over the stratosphere, mostly in the northern hemisphere but eventually everywhere. There it would be deflecting some sunlight. […] Our operation only made things a little whiter by day, and the sunsets were sometimes more red than before. Quite beautiful on certain days. But mostly things looked the same. The sunlight we deflected to space was said to be about a fifth of one percent of the total incoming. Very important crucial stuff, but it's not really possible to see a difference that small. Global effect was said to be like Pinatubo's eruption in 1991, or some said a double Pinatubo. The total release was taken to the stratosphere in several thousand individual missions. We had a fleet of only two hundred planes, so we went up scores of times, spread out over seven months.

Global CO_2 emissions will peak in 2023

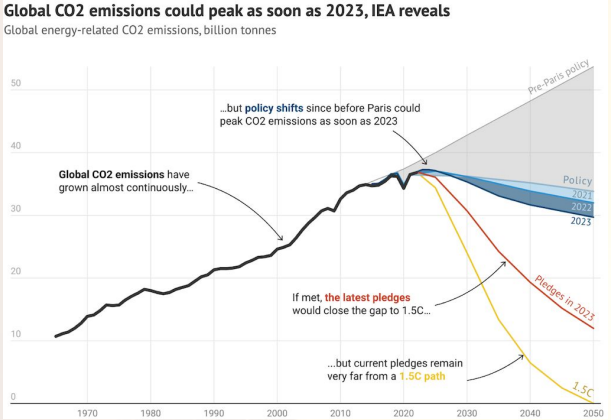


← 2023 IEA* NZE report**

* International Energy Agency
** Net-Zero Emissions by 2050 Scenario

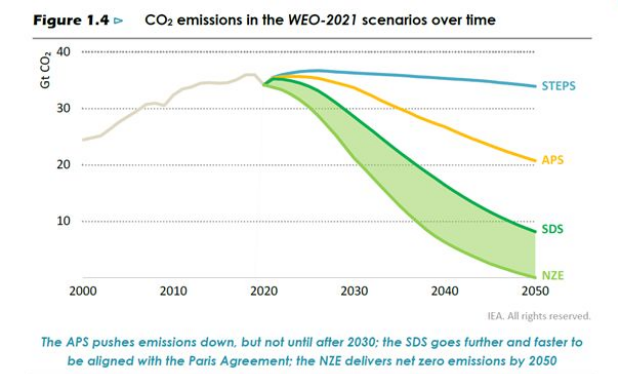
Global CO_2 emissions will peak in 2023

~~2022~~ ~~2021~~



← 2023 IEA* NZE** report

2021 IEA NZE/APS† report →



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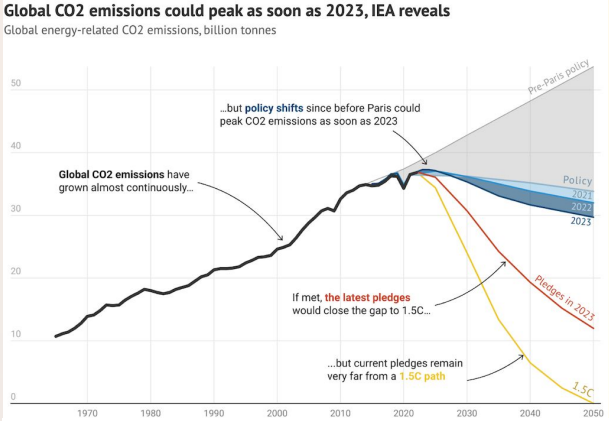
Global CO_2 emissions will peak in 2023

~~2022 2021 2020 2019~~



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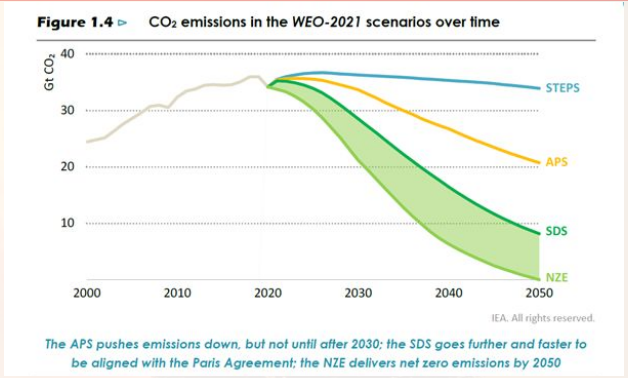
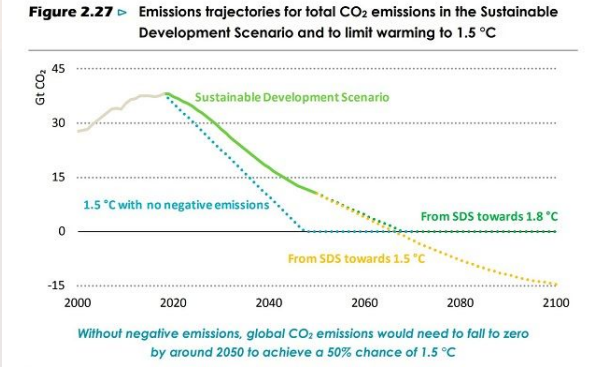


2021 IEA NZE/APS† report →



← 2019 IEA SDS‡ report

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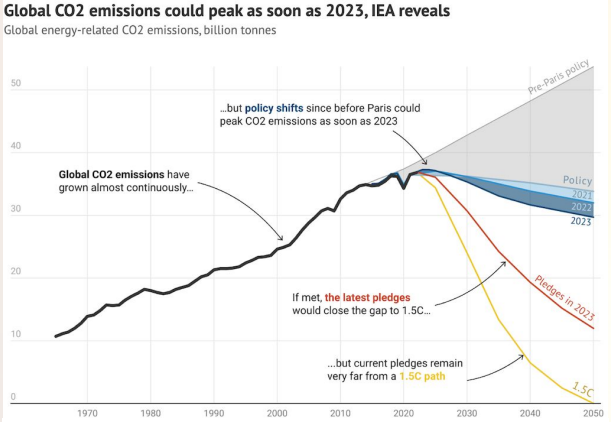
‡ Sustainable Development Scenario

Global CO_2 emissions will peak in 2023

~~2022~~ ~~2021~~ ~~2020~~ ~~2019~~ ~~2018~~ ~~2017~~ ~~2016~~



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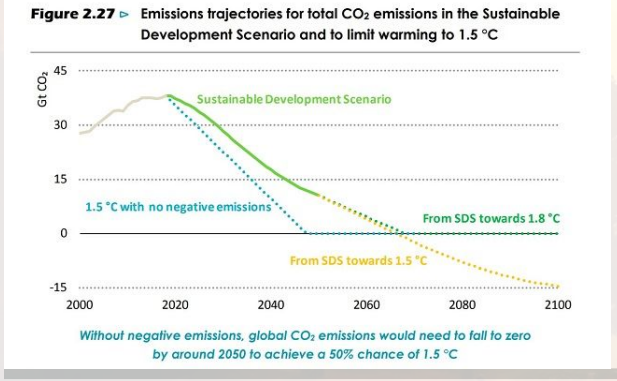

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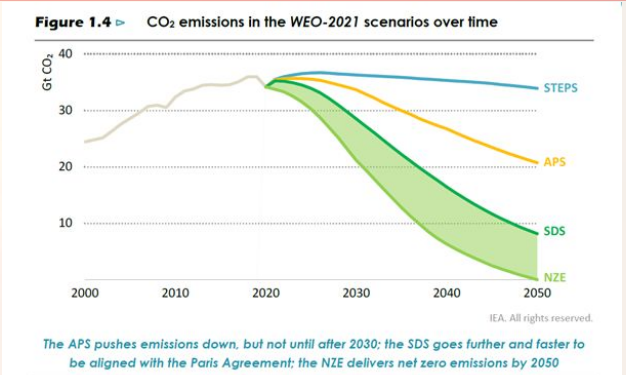
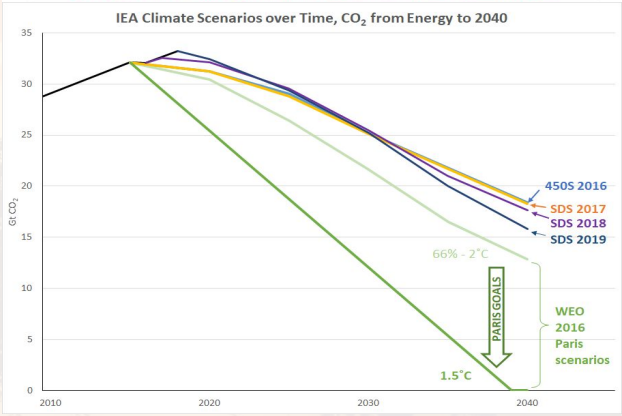


2016-2019 IEA SDS reports →



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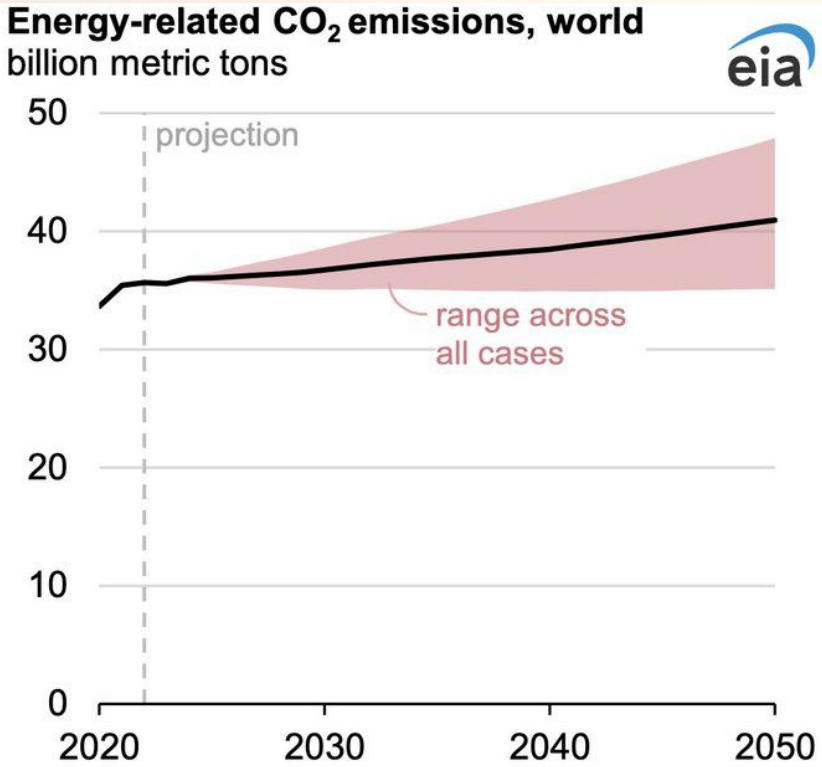
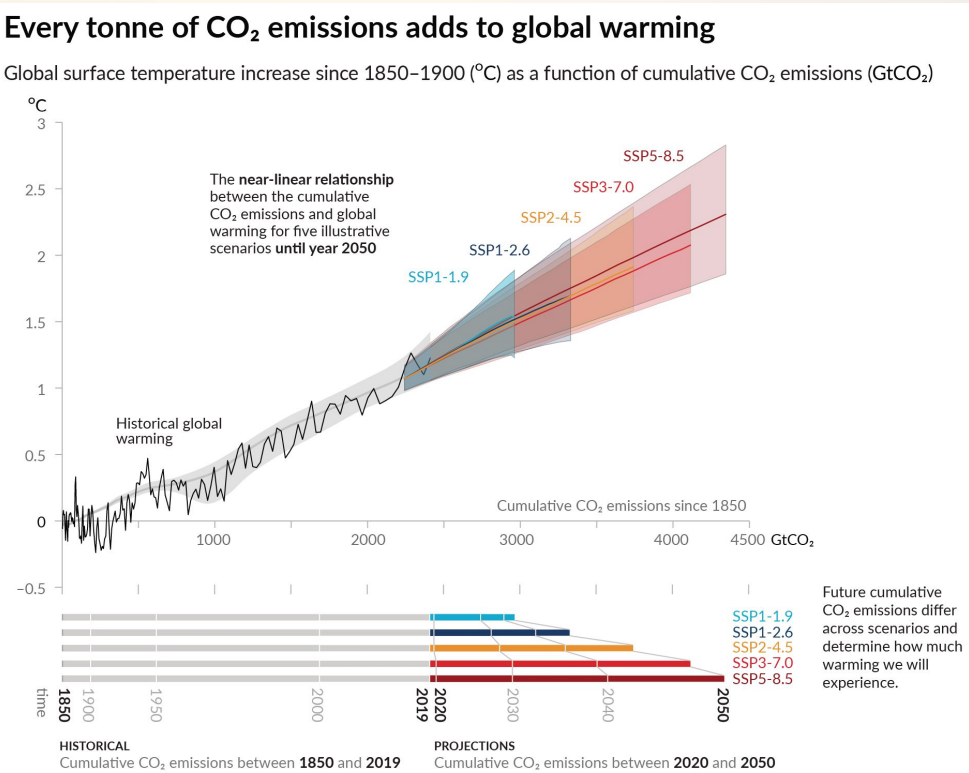
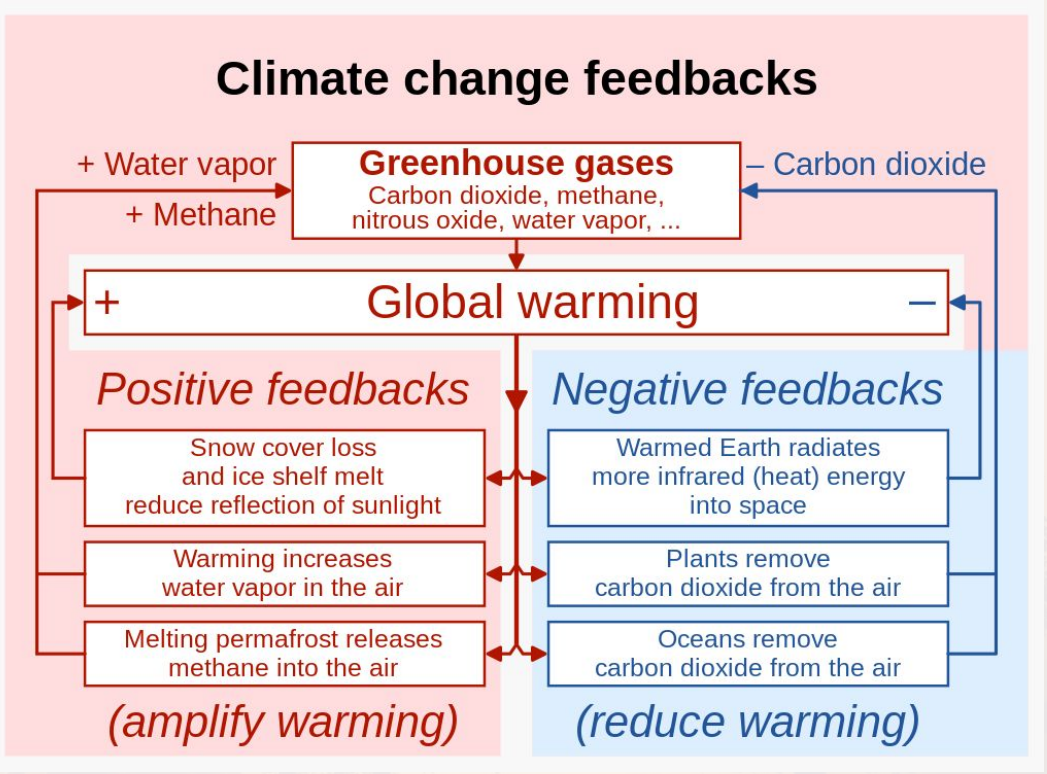
…maybe things don't get better



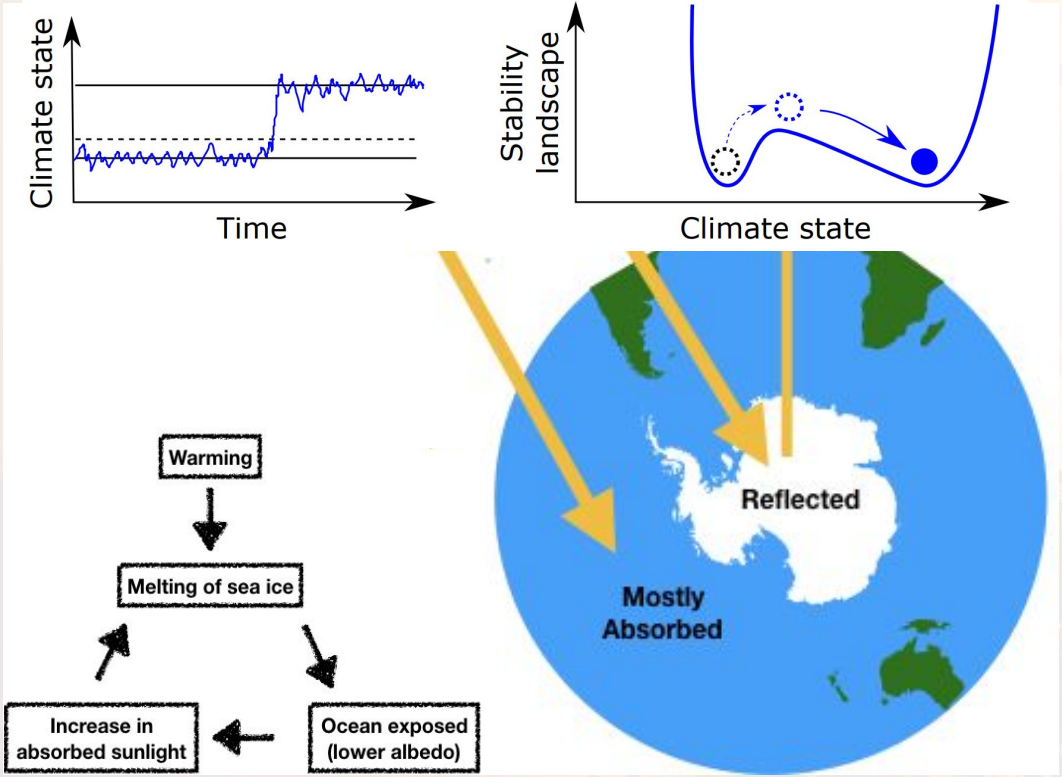


Climate Feedback Loops

feedback loops can be **positive (self-reinforcing)** or **negative (balancing)**



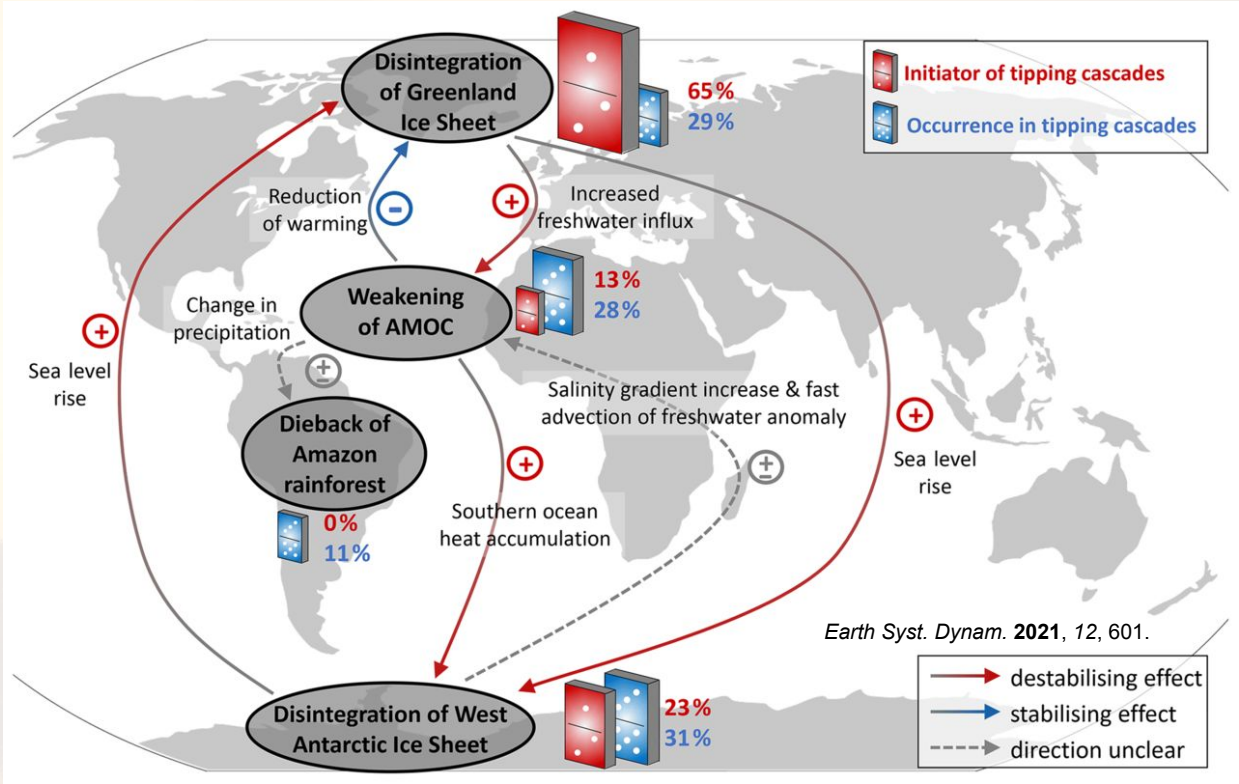
Climate Tipping Points



tipping points are **rapid** and often **irreversible** changes to the planetary system due to **positive feedback loops**

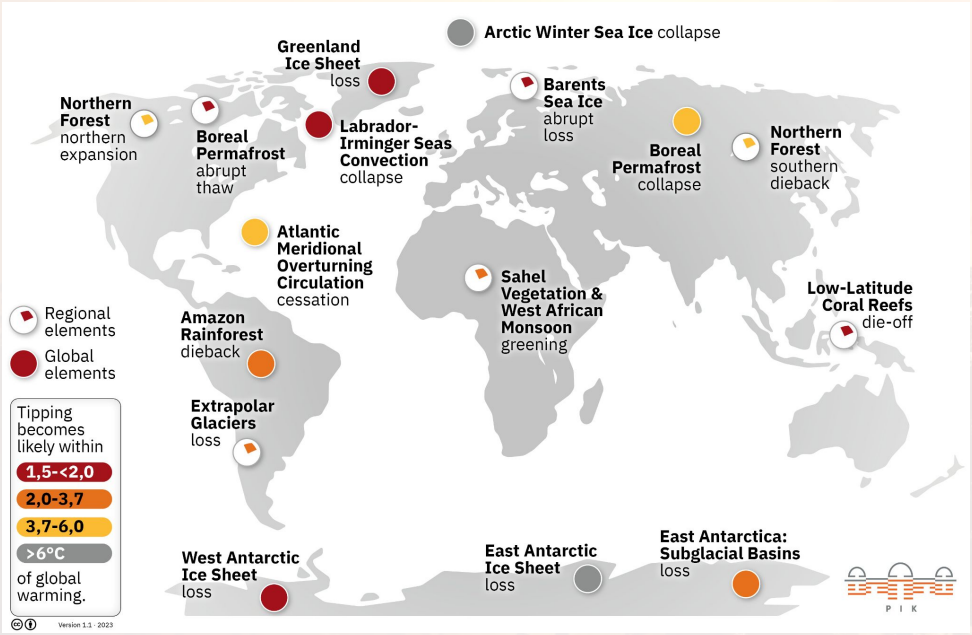
Tipping Point Cascades

passing one tipping point risks a ‘domino effect’ inducing a **cascade** of tipping points



Tipping Point Cascades

there are *so many* possible tipping points

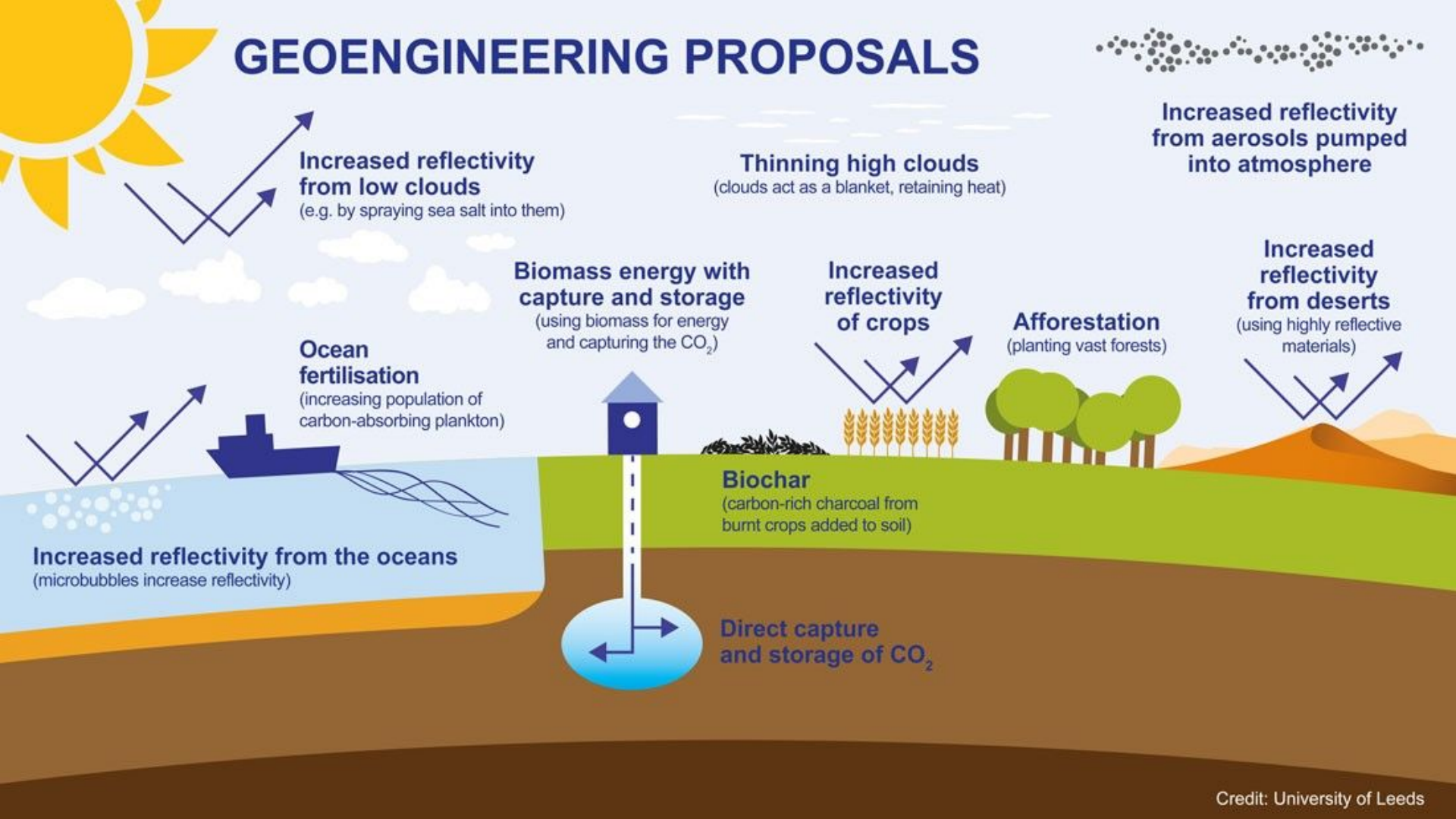


the uncertainty is *ridiculously* high

(almost unquantifiable)

Science **2022**, *377*, eabn7950.

GEOENGINEERING PROPOSALS



Credit: University of Leeds

Geoengineering

Carbon Dioxide Removal

(CDR / “negative emissions”)

- Direct-air capture (DAC)
- Enhanced weathering (EWR)
- Biomass carbon removal (BECCS/BiCRS)
- Pyrolytic carbon removal (biochar, PyCCS)
- Afforestation / desert greening
- Ocean carbon removal (DOC, OAE, etc.)

Solar Radiation Management

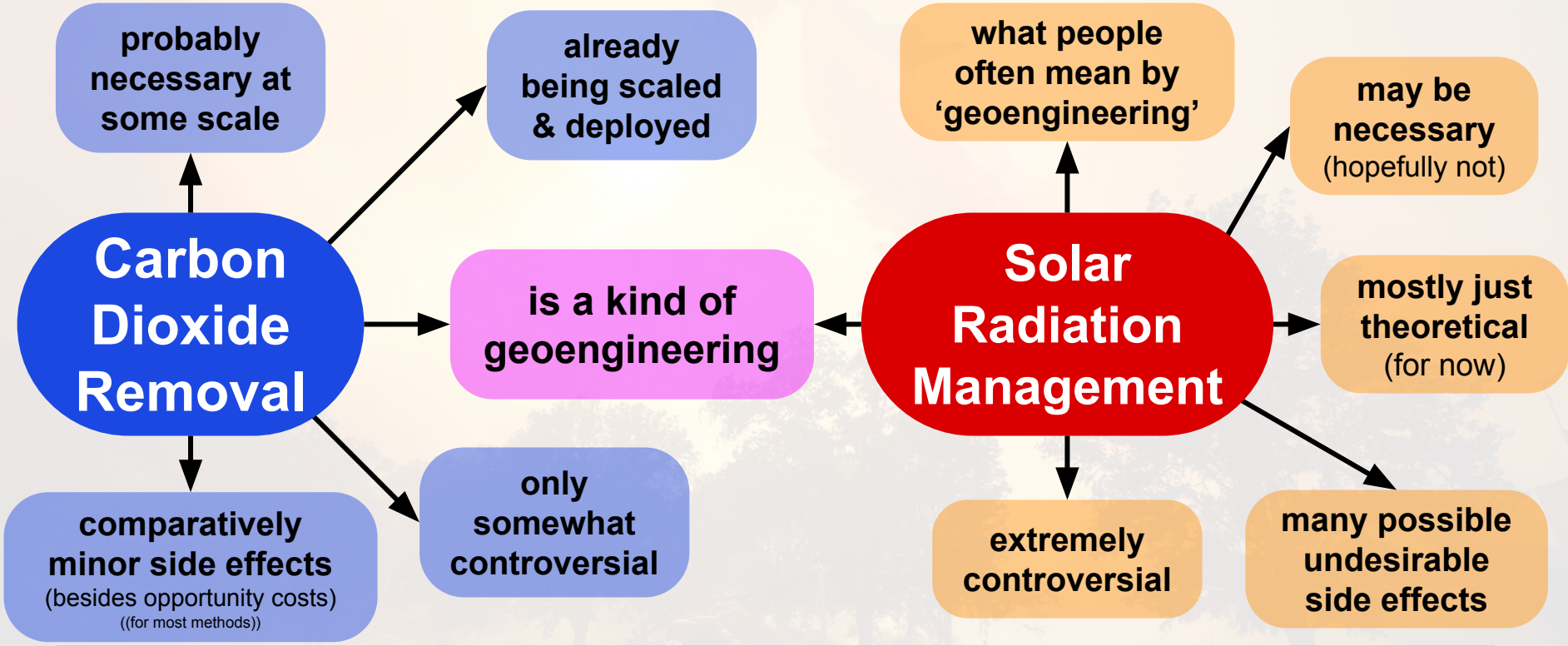
(SRM / “solar geoengineering”)

- Stratospheric aerosol dispersion
- Cirrus cloud thinning
- Marine cloud brightening
- Orbital mirror deployment

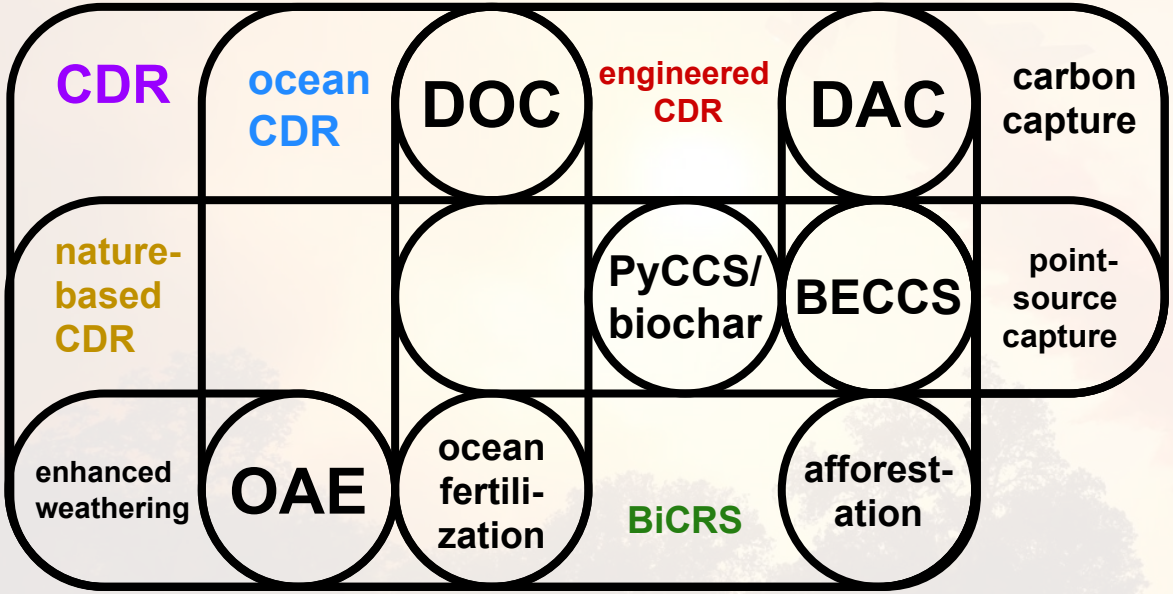
Others

- Surface albedo modification
- Glacier stabilization
- Coastal engineering
- Other, even dumber ideas

i know this is confusing



Every CDR Technology in One Simple Venn Diagram



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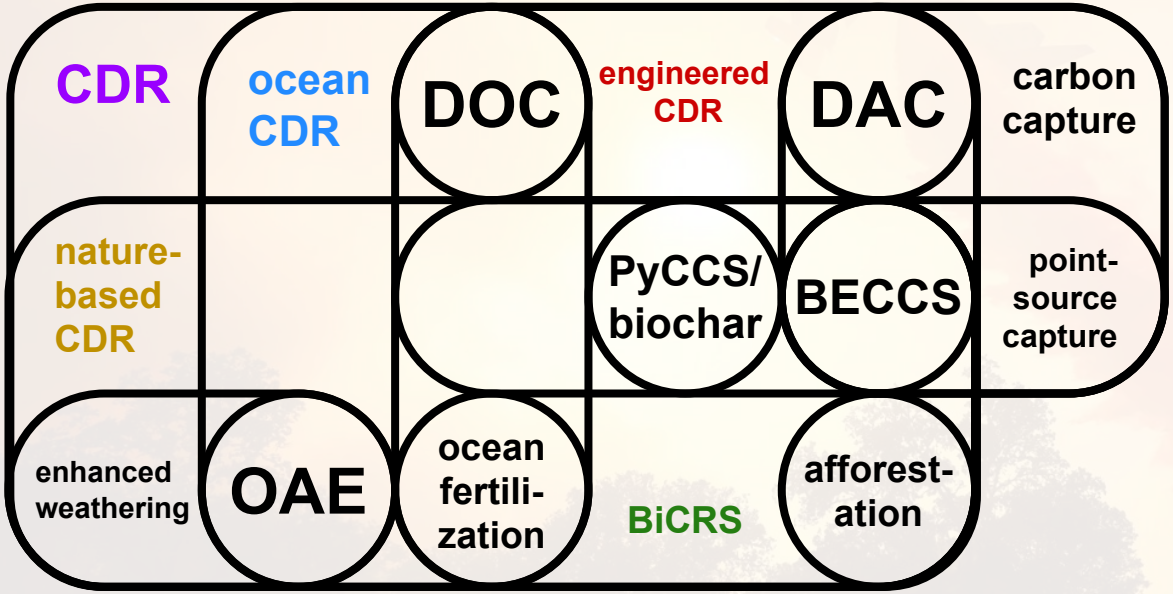

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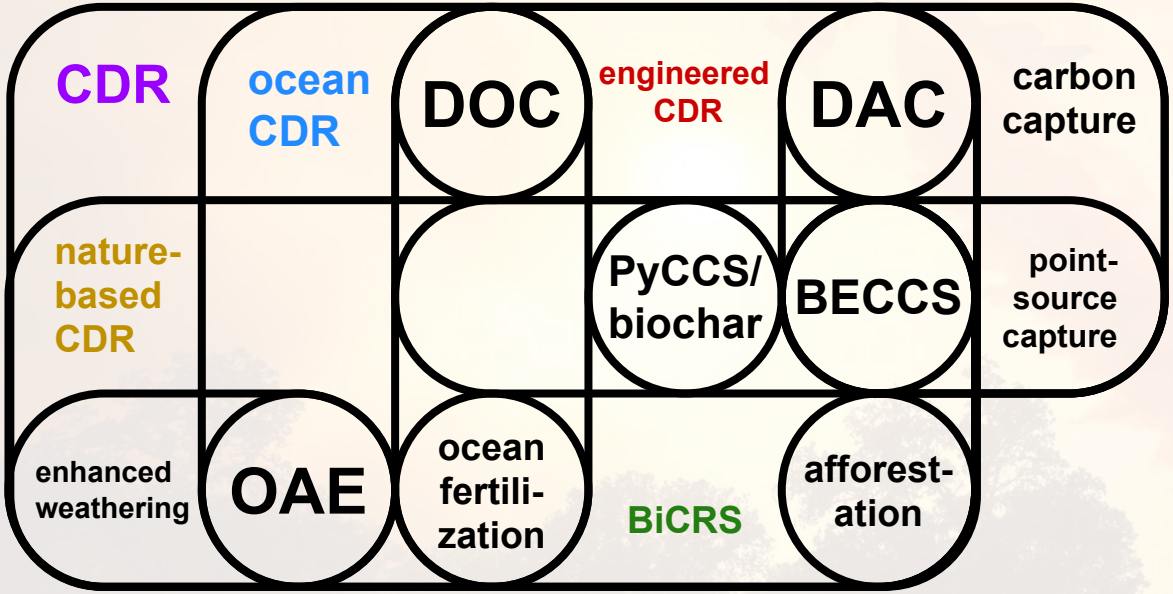

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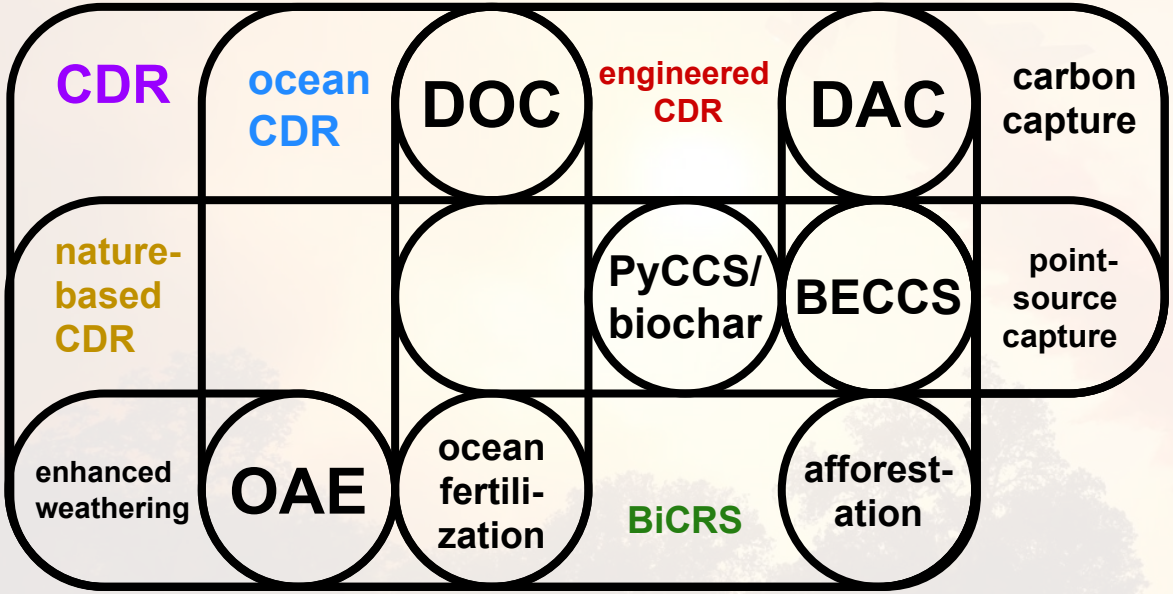

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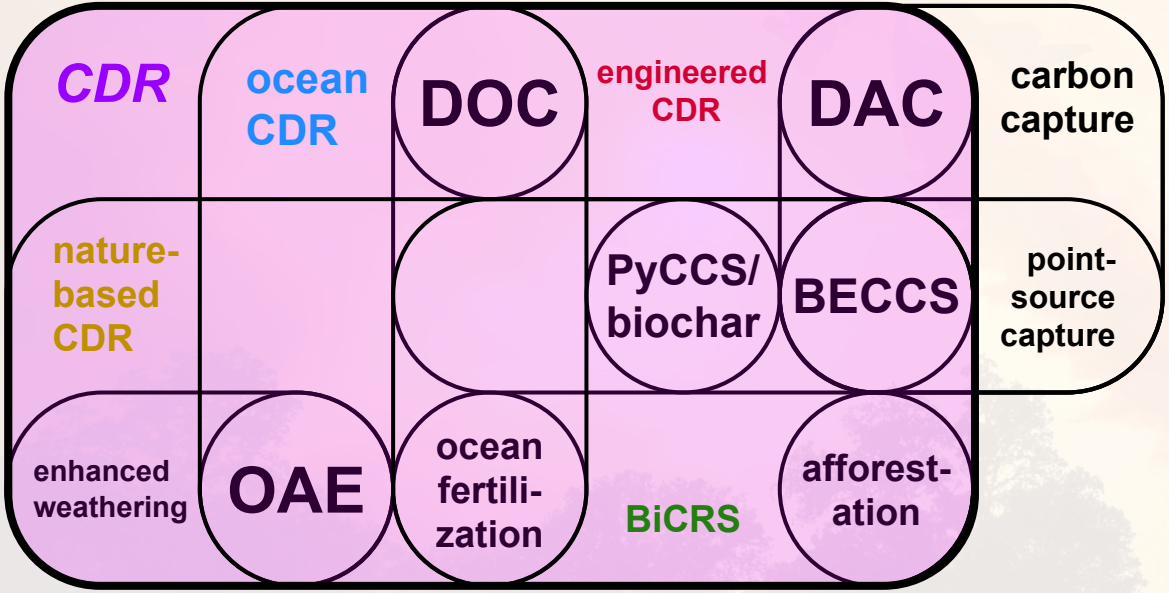

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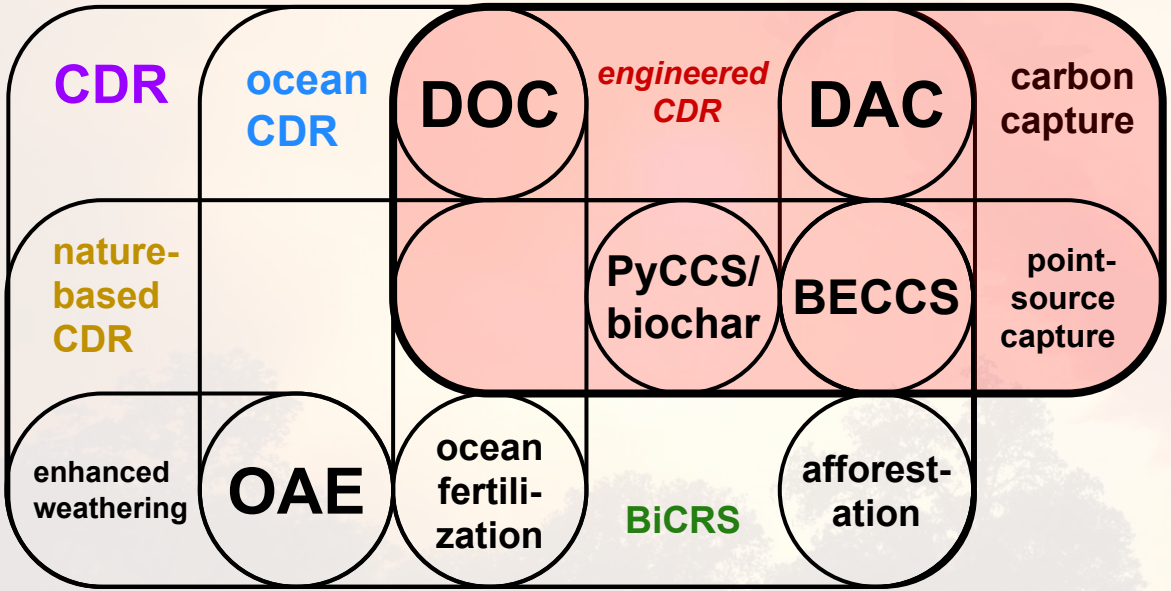

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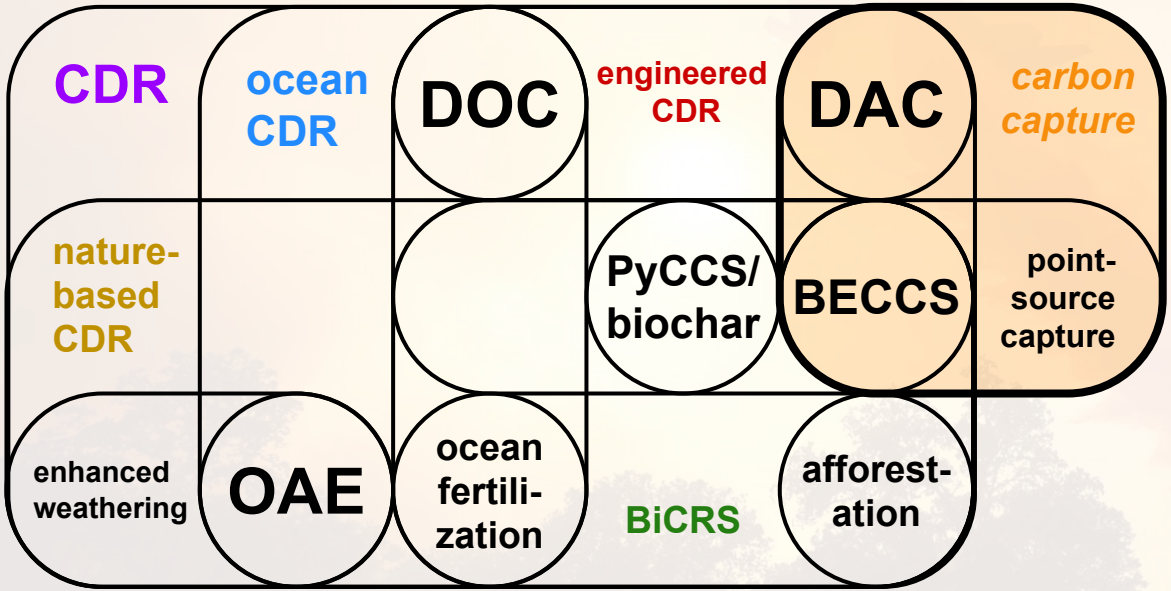

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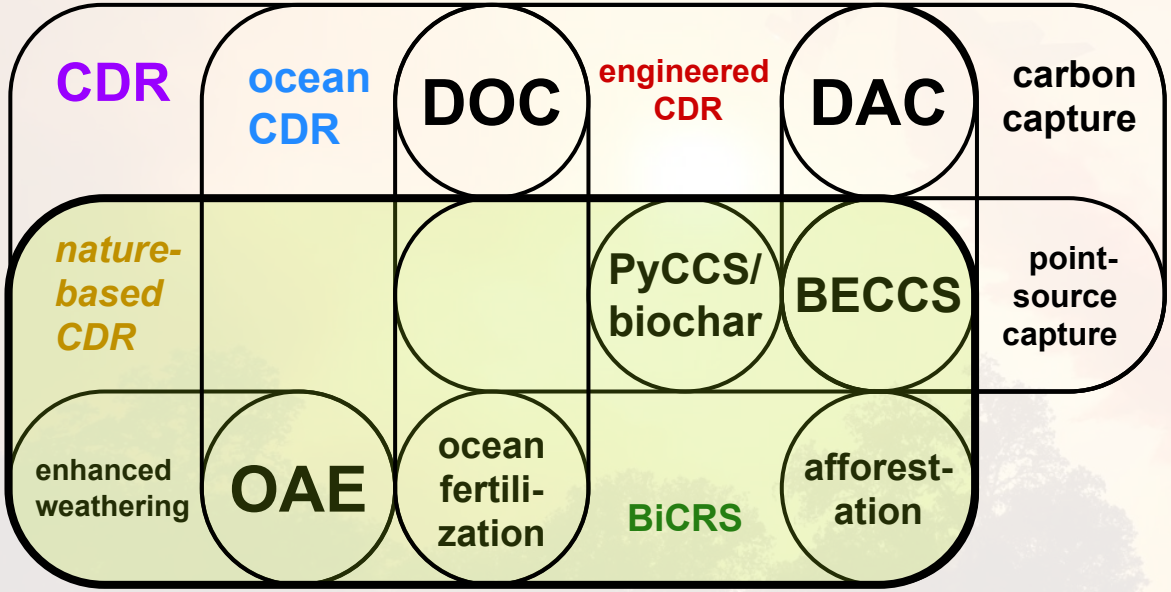

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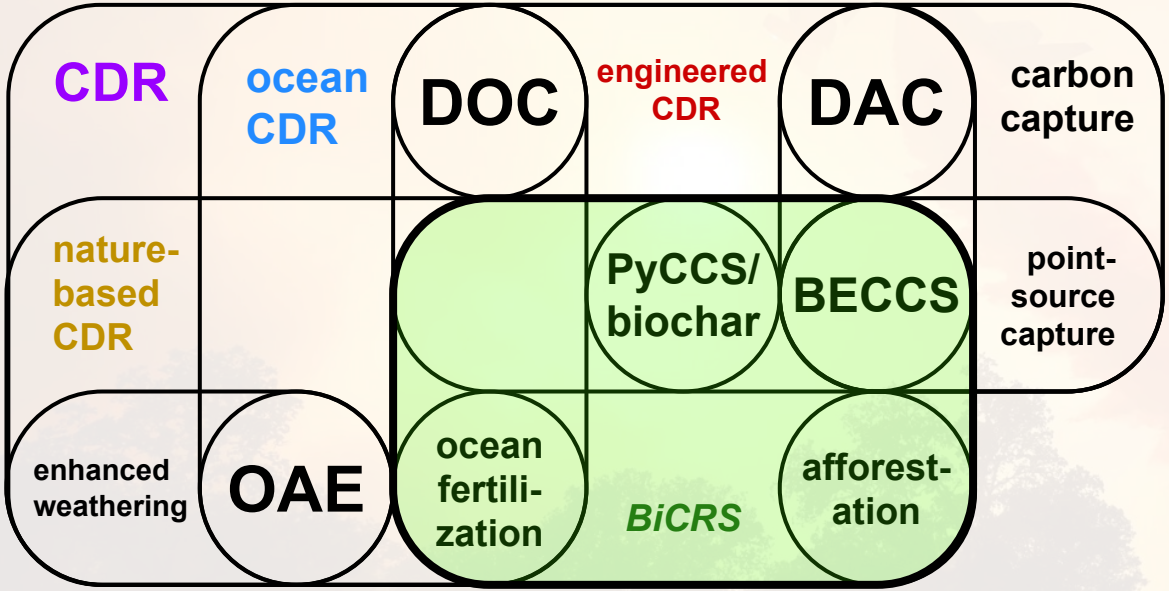

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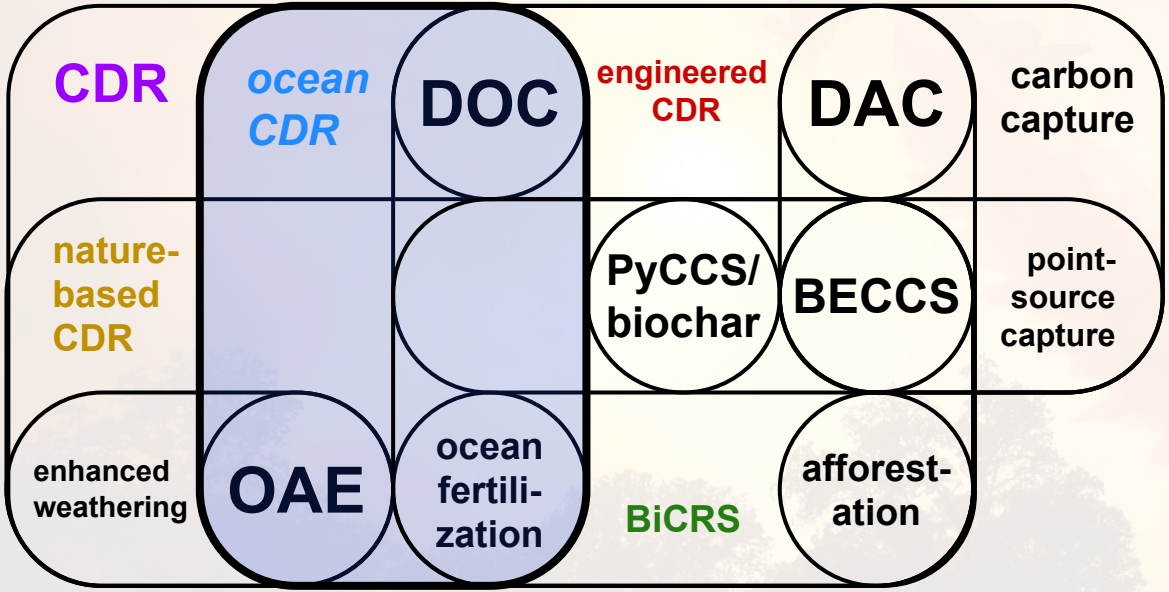

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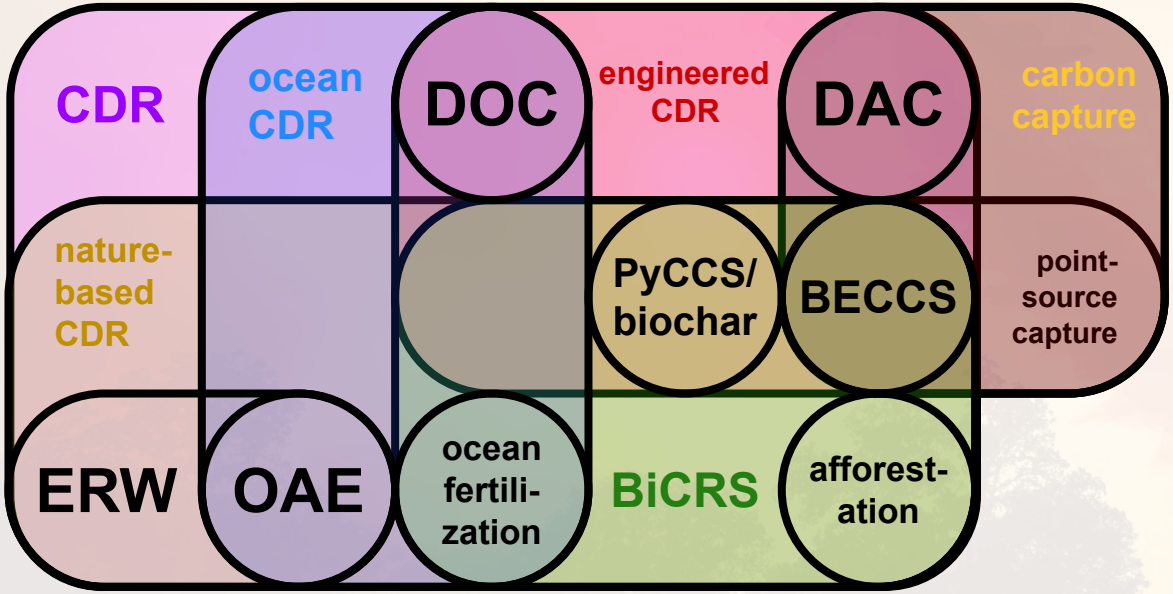

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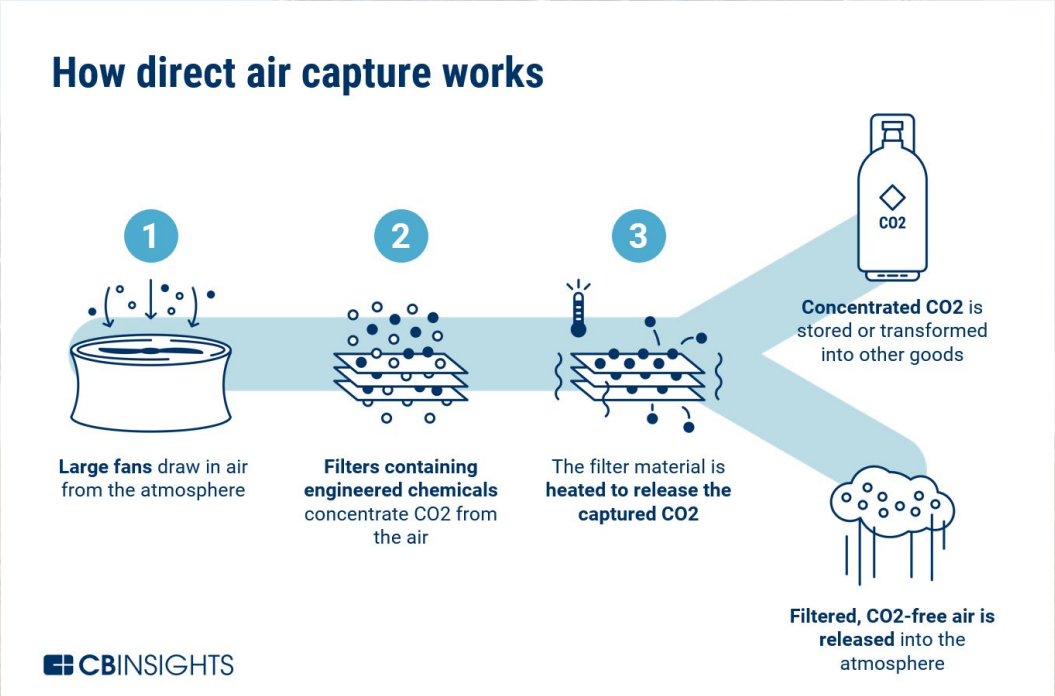
Direct-Air Capture (DAC)

Direct-Air Capture (DAC)

- literally just a big machine to filter CO_2 out of the air
- needs energy ($$$) to run fans, regenerate filters



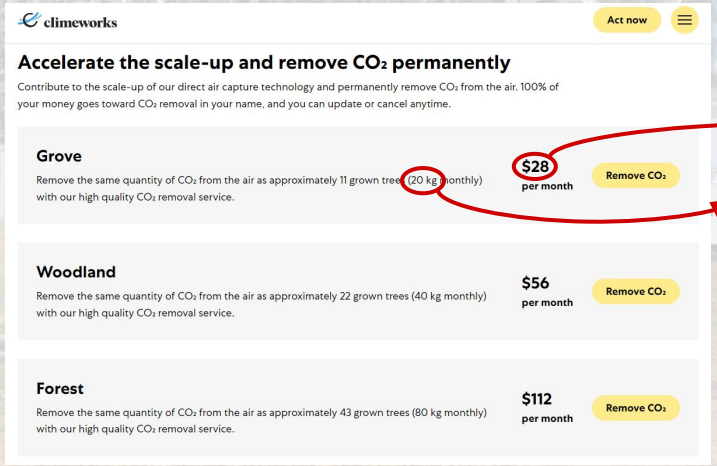
Direct-Air Capture (DAC)

Pros:

+ already being scaled & deployed
+ no real negative side effects
+ it just works!

Cons:

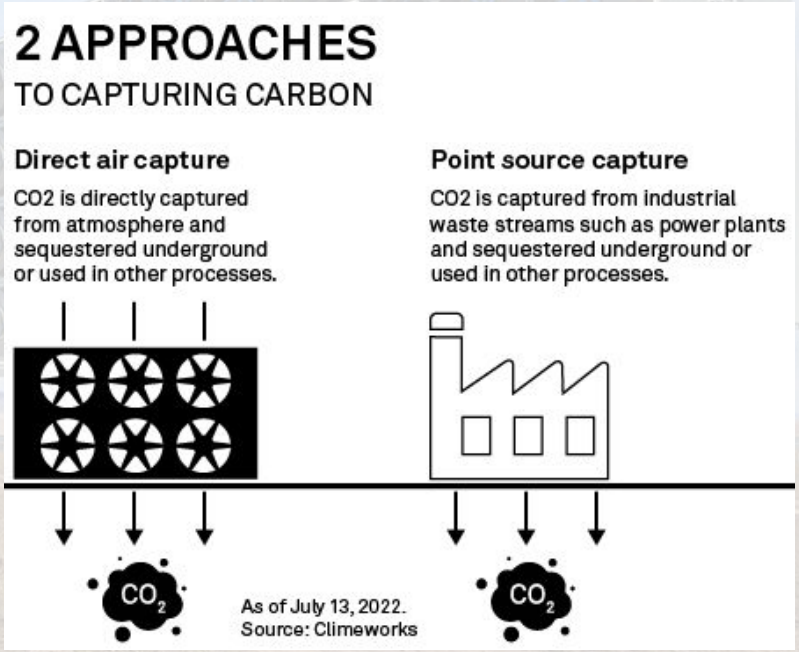
– so expensive!



$$\frac{\$28}{20\ \text{kg}\ CO_2} \times \frac{1000\ \text{kg}}{1\ \text{tonne}} = \frac{\$1400}{tCO_2}$$

Point-Source Capture

- Just like DAC but filters CO_2 from industrial waste streams (i.e. smokestacks)
- More CO_2 from a smokestack than air
  - ➢ easier to capture



Point-Source Capture

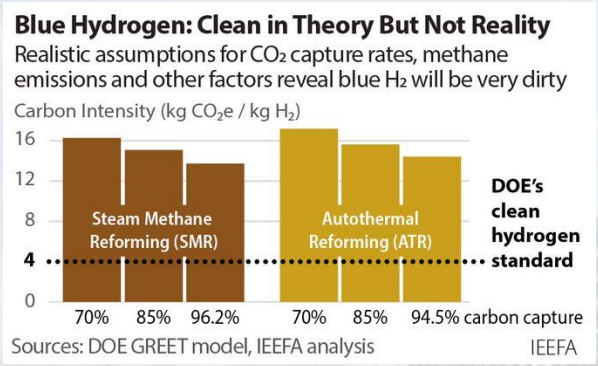
Pros:

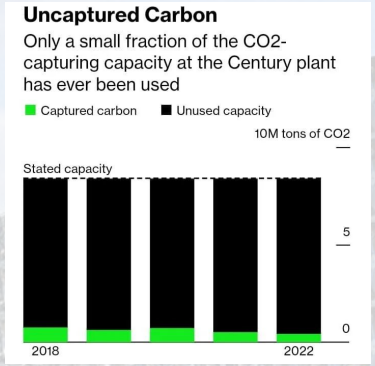
+ cheaper than DAC (per CO_2 molecule)
+ retrofit solution to decarbonize hard-to-abate heavy industries

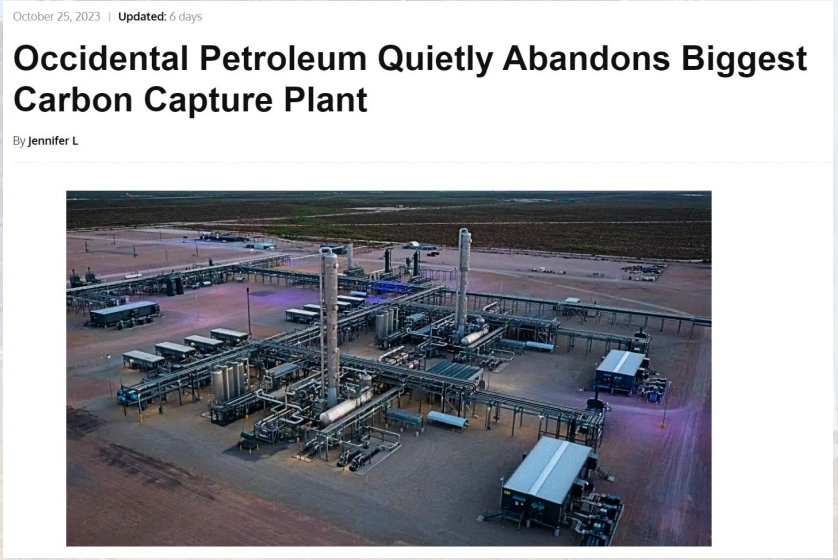
Cons:

− “avoided emissions”, not “negative emissions”
− ~90% efficient at best
− high CapEx, unclear value proposition
− precludes transition from fossil fuels

Point-Source Capture





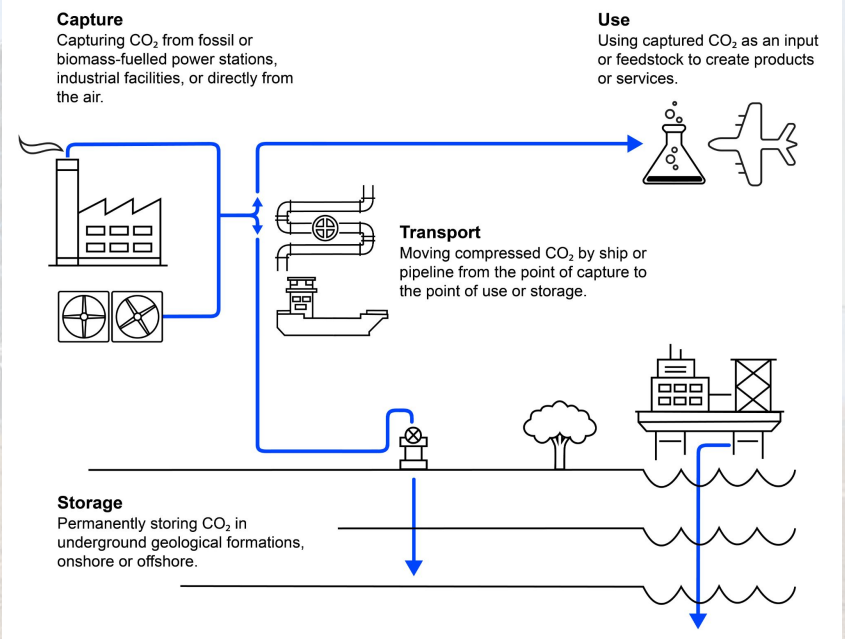


"While carbon dioxide emissions are lower, **fugitive methane emissions for blue hydrogen are higher** than for gray hydrogen because of an **increased use of natural gas** to power the carbon capture."

Energy Sci Eng. **2021**, *9*, 1676.

What Happens to the CO_2?

- **U**tilization / **U**se
  - CO_2 is used directly or converted to products
- **S**equestration / **S**torage
  - CO_2 is injected underground and hopefully stays there



What Happens to the CO_2?

- Inflation Reduction Act § 45Q defines tax credits for CCUS:

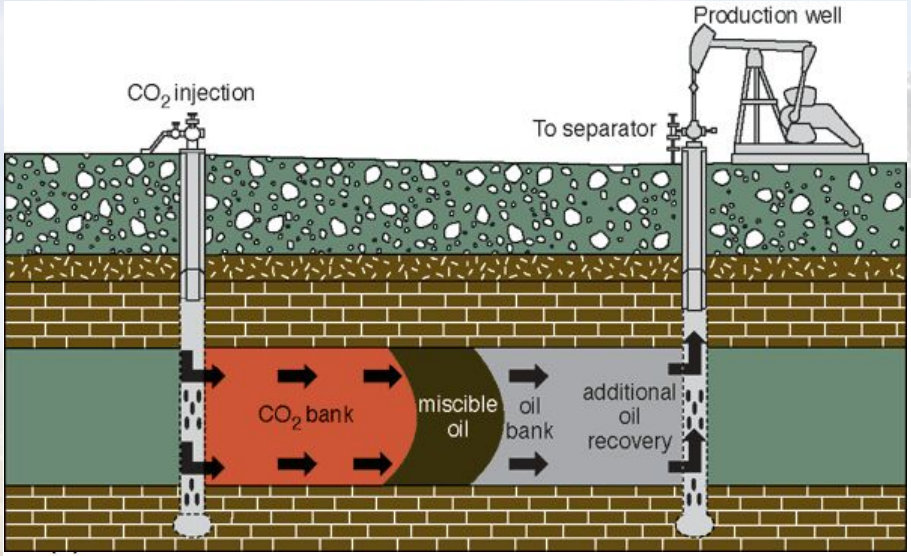
	utilized	sequestered
point-source	$60/tCO$_2$	$85/tCO$_2$
direct-air	$130/tCO$_2$	$180/tCO$_2$

<u>uses for CO_2</u>:

- food & beverage (*e.g.* seltzer, beer)
- synfuels (*e.g.* SAF)

…but that's not the #1 use of captured CO_2:

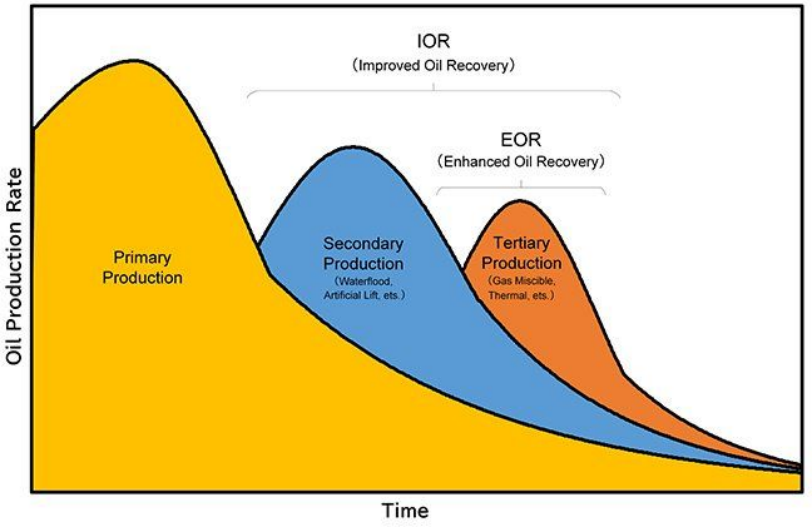
the primary use of CO_2 is drilling oil



(i) used by the taxpayer as a tertiary injectant in a qualified enhanced oil or natural gas recovery project and disposed of by the taxpayer in secure geological storage, or

(ii) utilized by the taxpayer in a manner described in subsection (f)(5).

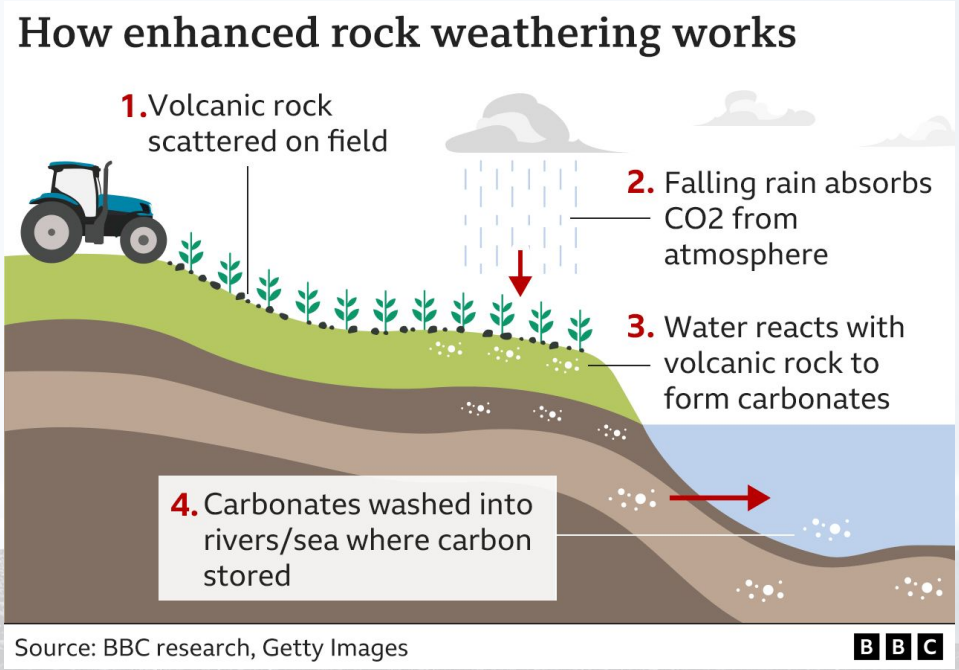
EOR: Enhanced Oil Recovery




Enhanced Rock
Weathering
(ERW)

Enhanced Rock Weathering (ERW)

- some kinds of rock (silicates, basalts, olivine) naturally absorb CO_2 and turn into carbonates
  - mine em, grind em up, let em rip



Enhanced Rock Weathering (ERW)

Pros:

+ comparatively cheap (est. ~$150/t$CO_2$)
+ more than enough silicates in the crust to scale globally

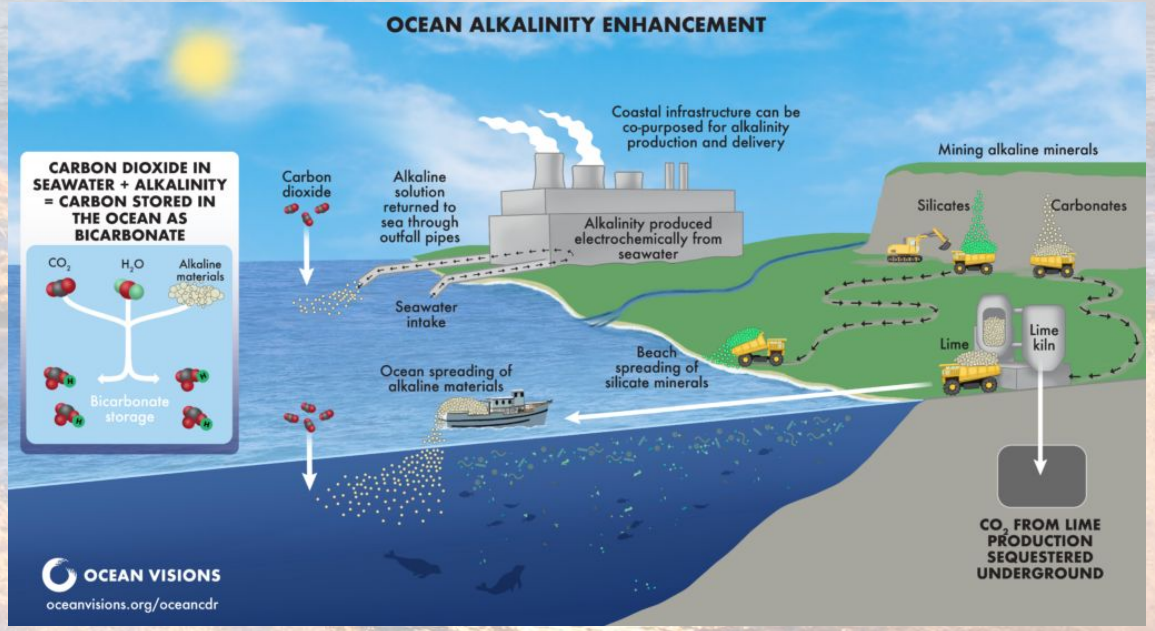
Cons:

− difficult to quantify total carbon removed
− risk of heavy metal leaching into soil, water
− have to mine, grind rock
− can be extremely slow

Ocean Alkalinity Enhancement (OAE)

Ocean Alkalinity Enhancement (OAE)

- grind up the silicates and scatter them in the ocean



Ocean Alkalinity Enhancement (OAE)

Pros:

+ probably even cheaper than ERW (est. ~\$50/tCO_2)
+ could counteract ocean acidification

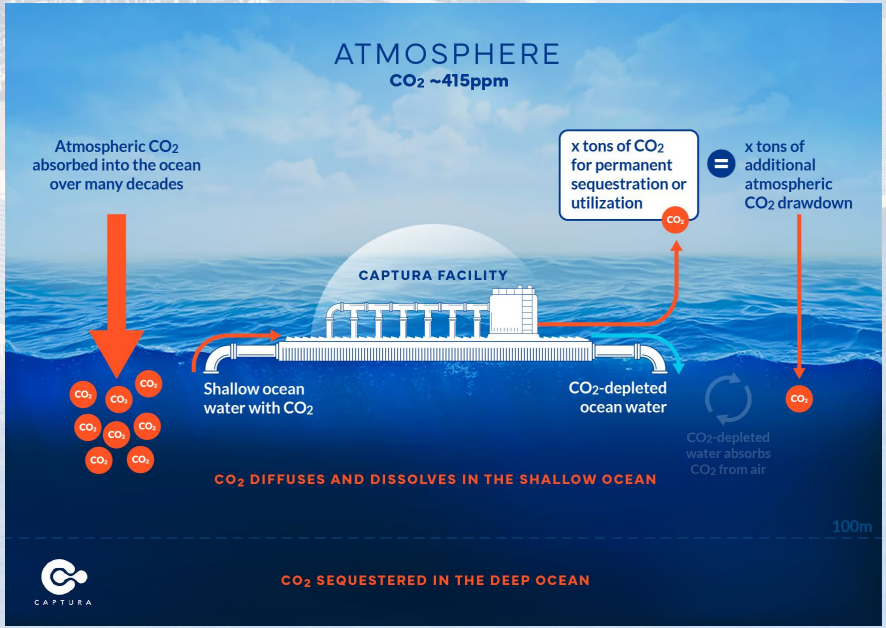
Cons:

− difficult to quantify total carbon removed
− heavy metal leaching directly into ocean
− have to mine, grind rock
− the ocean is big and scary


Direct Ocean Capture
(DOC)

Direct Ocean Capture (DOC)

- extract dissolved CO_2 gas from ocean water
- decarbonized seawater reabsorbs atmospheric CO_2



Direct Ocean Capture (DOC)

Pros:

+ more energy-efficient & cheaper than DAC
+ probably minimal negative side effects
+ CO_2 is a potential revenue stream

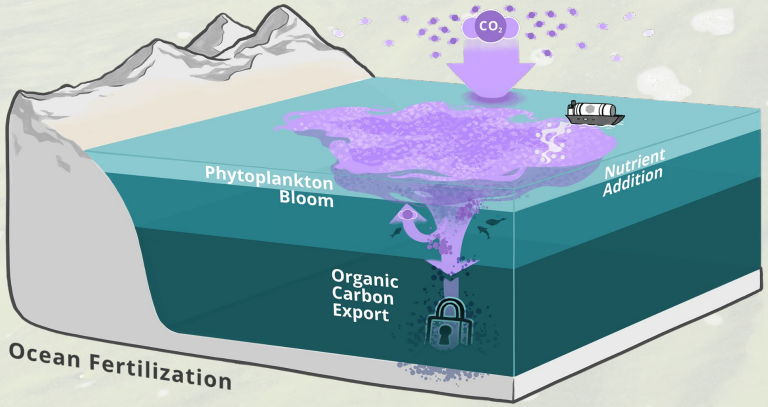
Cons:

– still have to sequester or utilize the CO_2
– remote ocean location makes both more costly


Ocean Fertilization

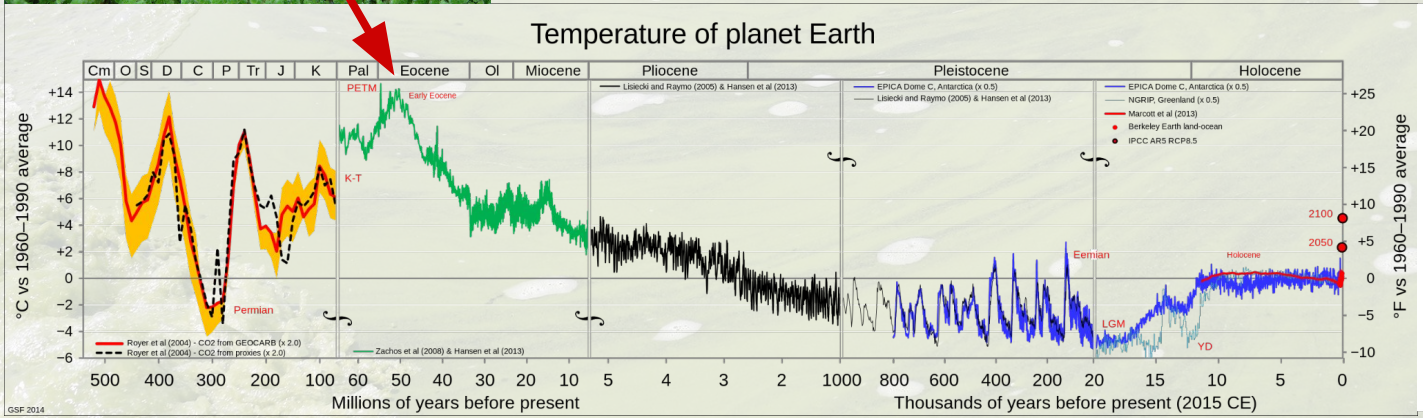
Ocean Fertilization

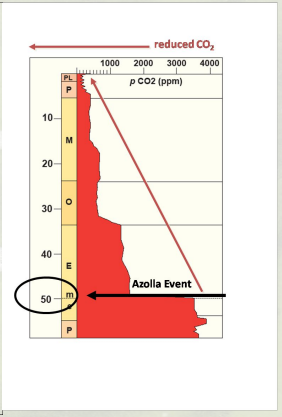
- photosynthetic microalgae (phytoplankton) are often resource-limited in Fe, N, P, etc.
- add nutrients to induce ocean algal bloom (eutrophication)
- plankton suck up CO_2, sink to bottom of sea



Ocean Fertilization: The Azolla Event

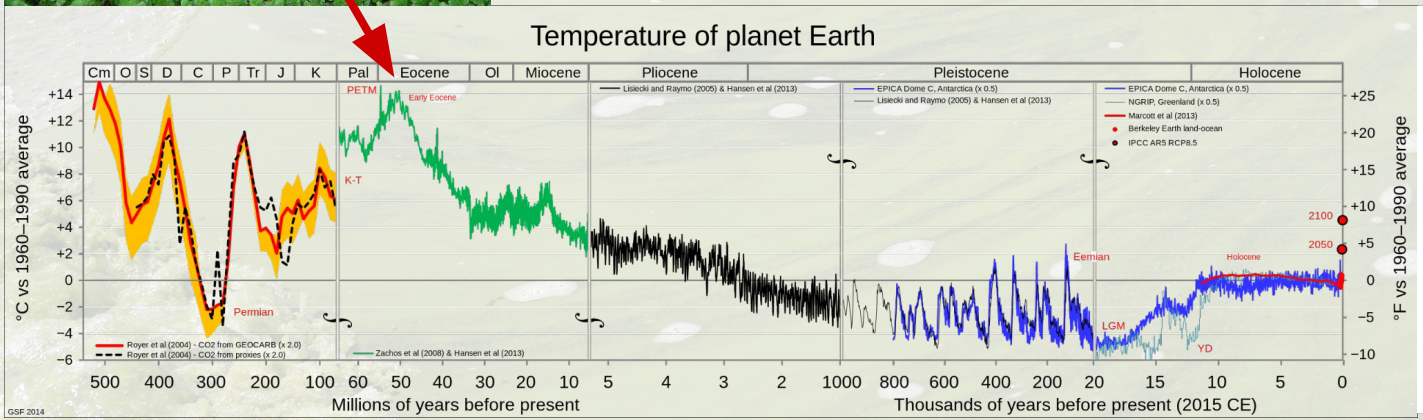
- This has (probably) happened before!

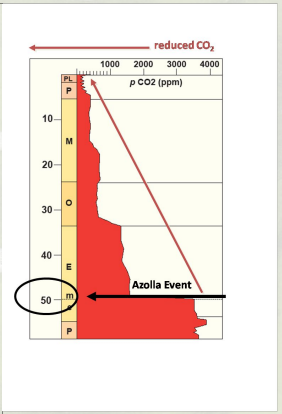




Ocean Fertilization: The Azolla Event

- This has (probably) happened before!
  - 50 m.y.a. the oceans filled up with *Azolla* ferns that sucked up all the CO_2, sunk to the seafloor, and ended hothouse earth





Ocean Fertilization

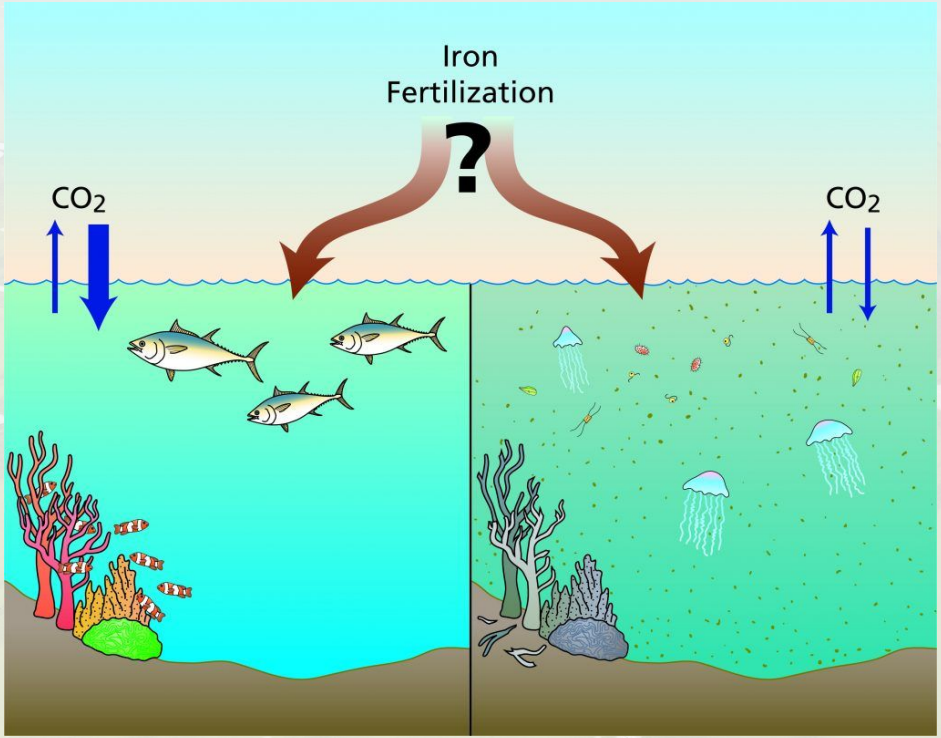
Pros:

+ good enough for the early Cretaceous

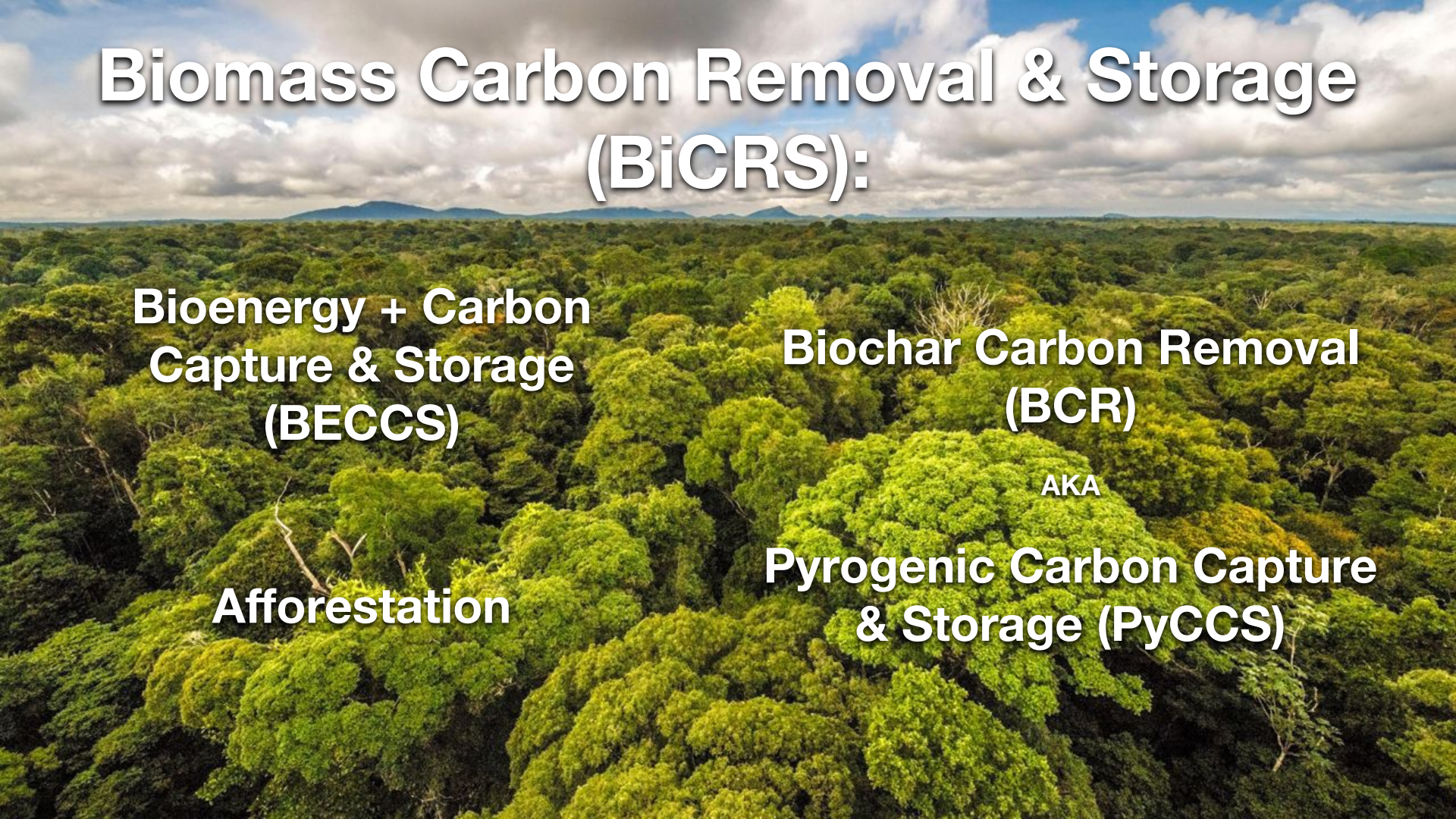
Cons:

− carbon sequestration may be temporary (upwelling)

− might fuck up the entire ocean ecosystem, whoops

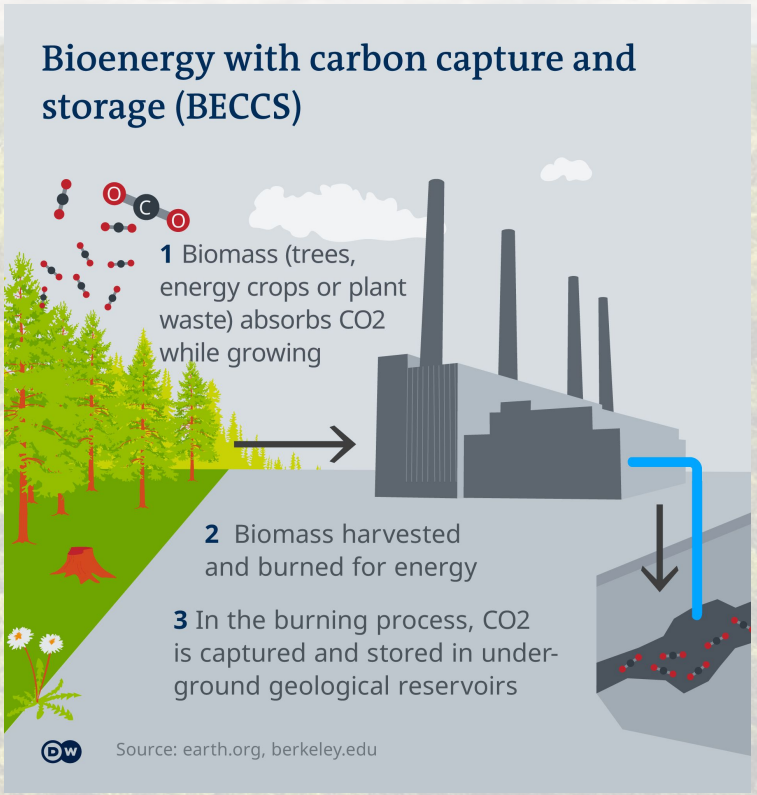


Biomass Carbon Removal & Storage (BiCRS):



Bioenergy + Carbon Capture & Storage (BECCS)

- Combine bioenergy with point-source carbon capture



Bioenergy + Carbon Capture & Storage (BECCS)

Pros:

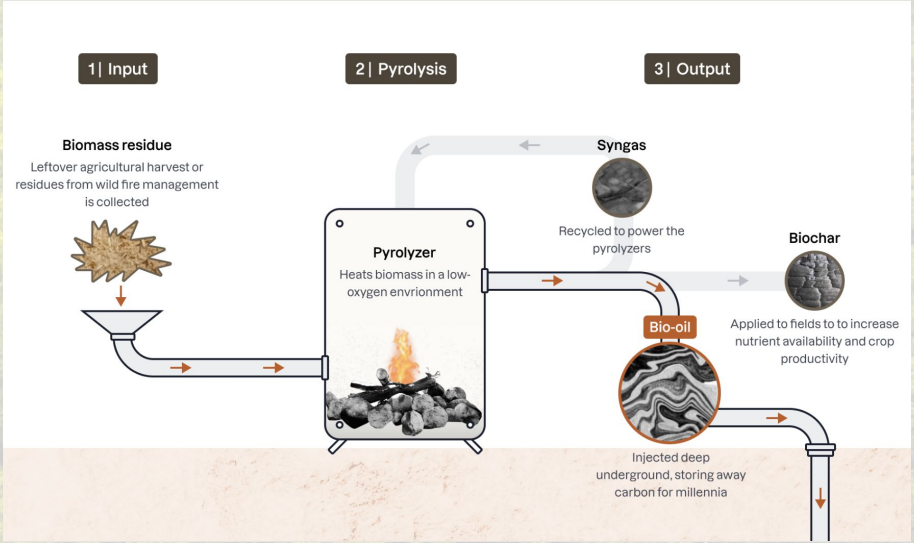
+ carbon-negative energy generation!
+ point-source capture is easier than DAC

Cons:

− high land & water use
− competition w/ food crops
− associated costs & risks of CO_2 sequestration

Biochar Carbon Removal (BCR) AKA Pyrogenic Carbon Capture & Storage (PyCCS)

- pyrolyze plant biomass into solid biochar or liquid bio-oil
- spread biochar on fields, inject bio-oil into ground



Biochar Carbon Removal (BCR) AKA Pyrogenic Carbon Capture & Storage (PyCCS)

Pros:

+ solid, liquid C are much stabler sequestration than CO_2 injection
+ can use waste biomass
+ biochar is probably good for soil health

Cons:

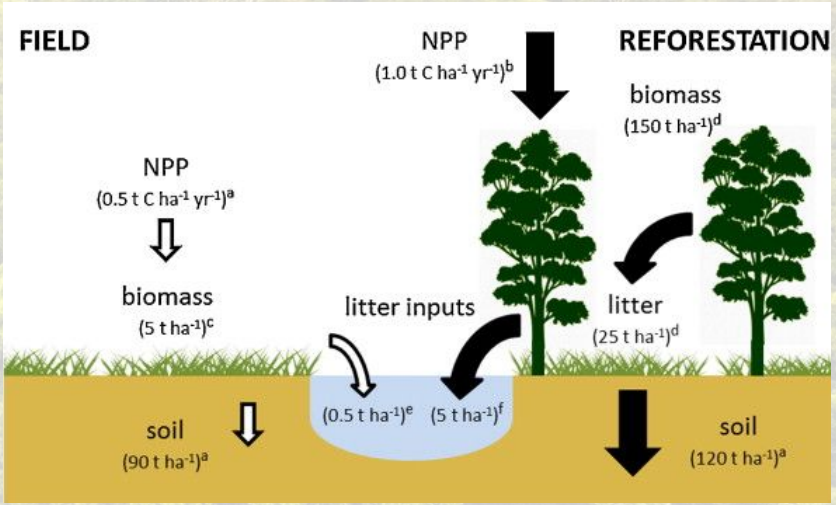
– pyrolysis is inefficient, energy-intensive

– limited scalability to just bio-waste pyrolysis

– bio-oil is not very useful

Afforestation

- what if you grew a forest
- that'd be pretty cool



Perspect. Plant Ecol. Evol. Syst. **2015**, *17*, 301.

Afforestation

Pros:

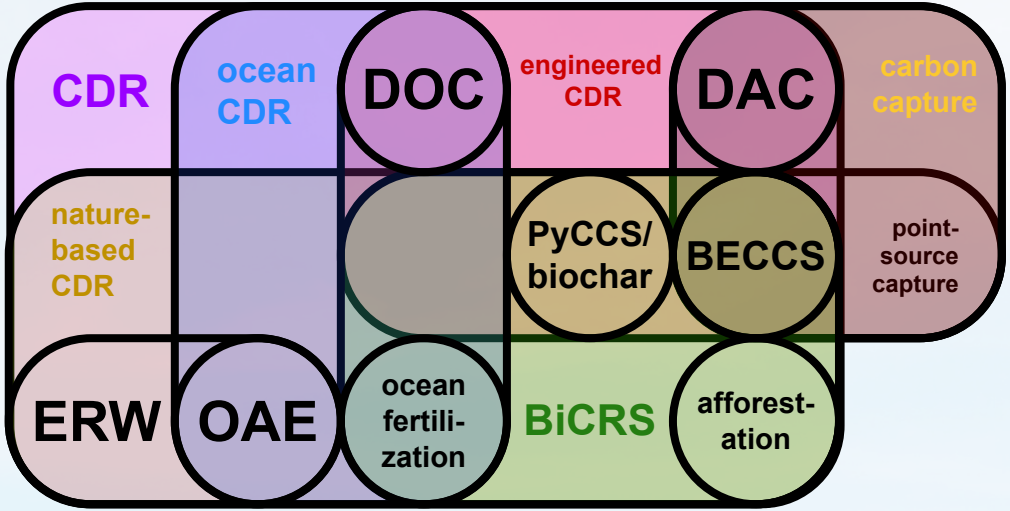
+ it's a forest (:
+ ecosystem benefits
+ fights desertification

Cons:

− not all that land-efficient
− competition w/ food & bioenergy crops
− difficult to quantify total carbon removed

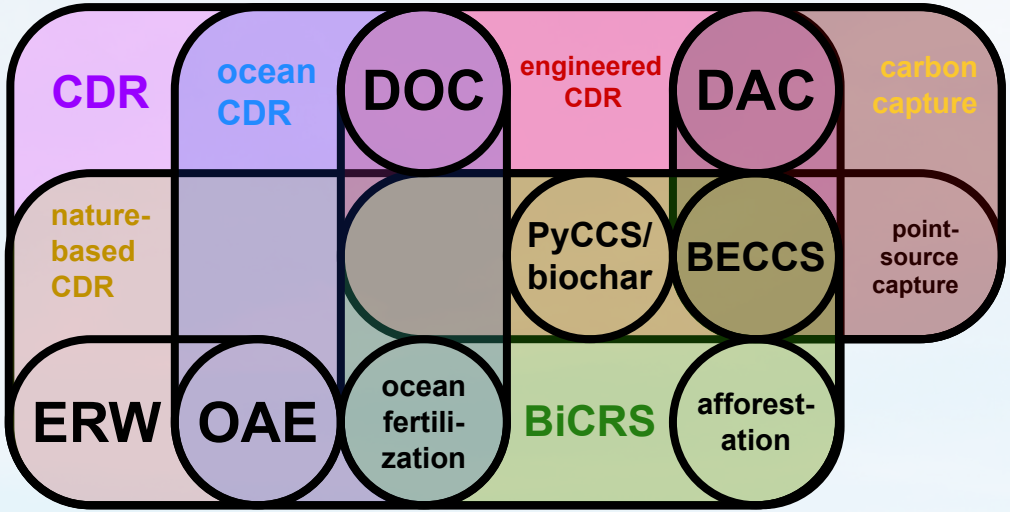
What are the commonalities?

- capturing CO_2 takes energy
  - there are always costs (financial and opportunity)
- the carbon has to go *somewhere*



What are the differences?

- How much does it cost?
- How is the C stored?
- How scalable is it?
- How measurable is the carbon drawdown?
- Are there other risks?



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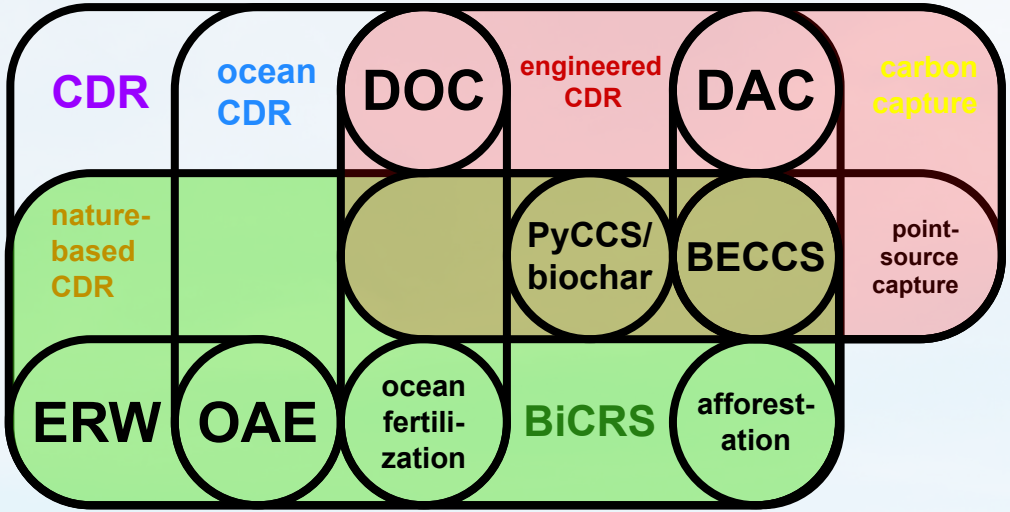
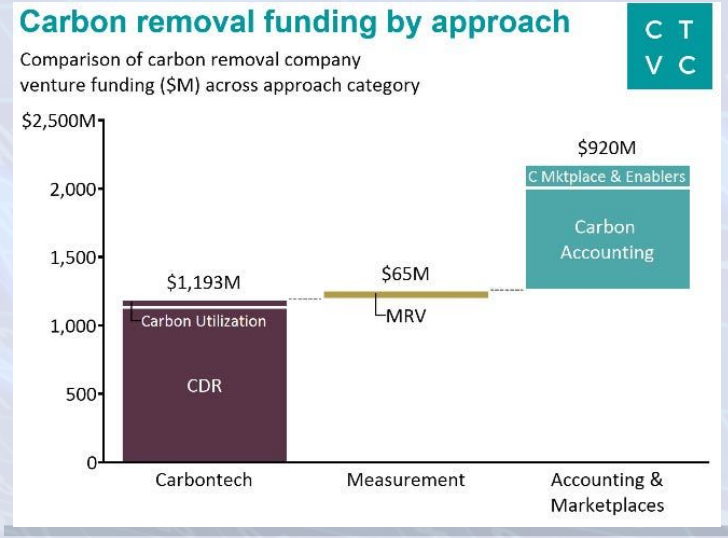
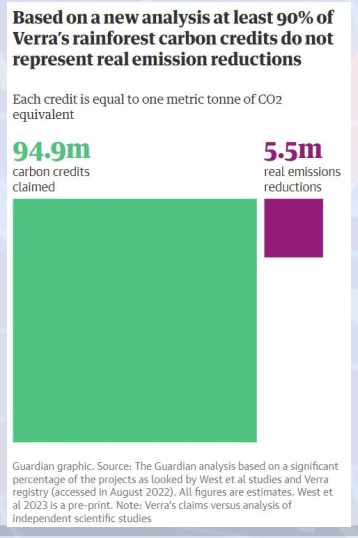
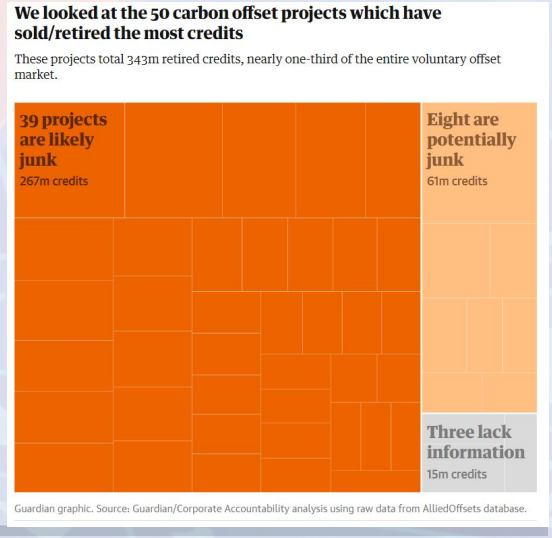


Measurement, Reporting, Verification

- Carbon removal is only as good as the proof that it removed CO_2 from the atmosphere







Geoengineering

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(CDR / “negative emissions”)

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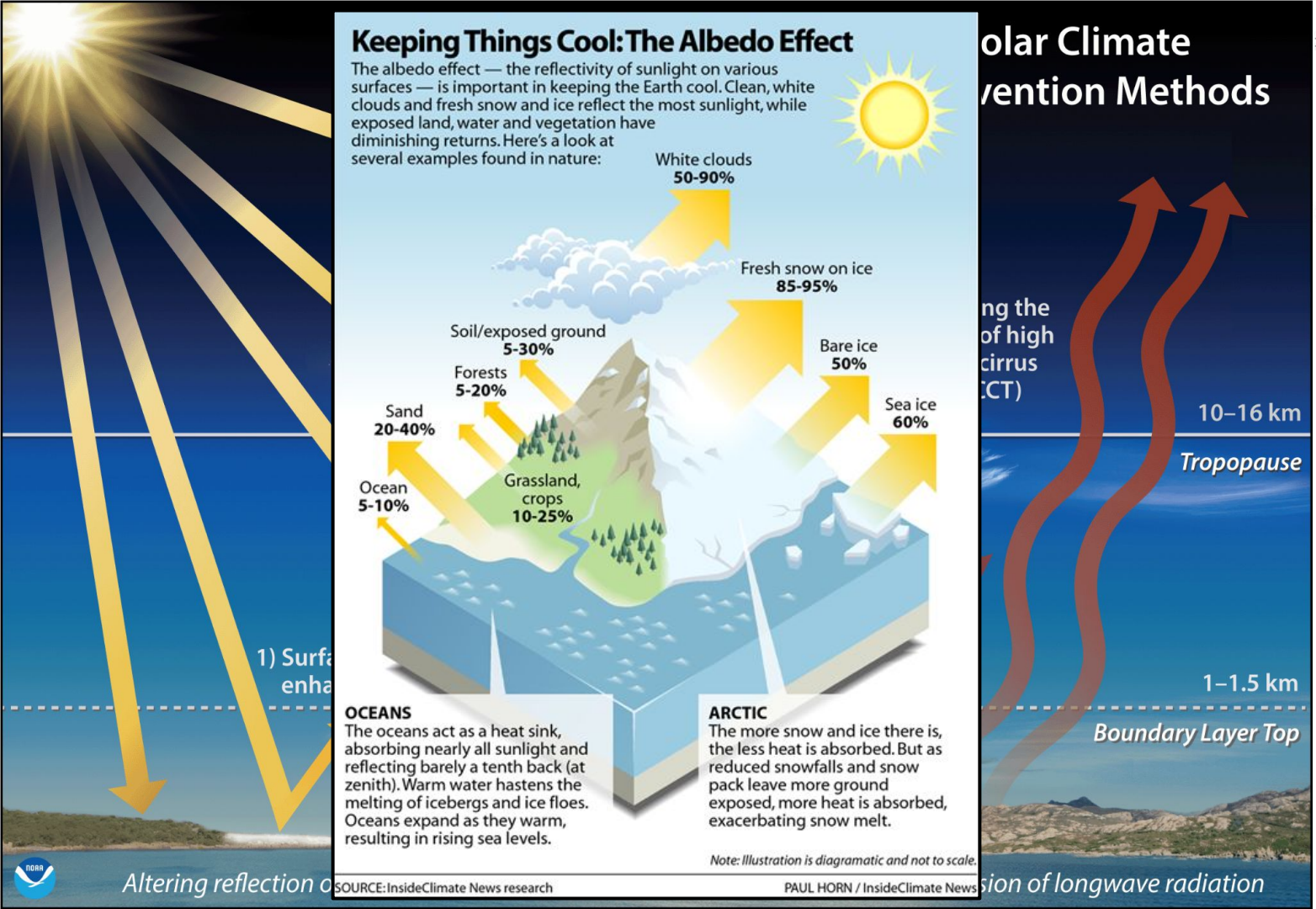


Keeping Things Cool: The Albedo Effect

The albedo effect — the reflectivity of sunlight on various surfaces — is important in keeping the Earth cool. Clean, white clouds and fresh snow and ice reflect the most sunlight, while exposed land, water and vegetation have diminishing returns. Here's a look at several examples found in nature:

White clouds **50-90%**

Fresh snow on ice **85-95%**

Soil/exposed ground **5-30%**

Bare ice **50%**

Forests **5-20%**

Sand **20-40%**

Sea ice **60%**

Ocean **5-10%**

Grassland, crops **10-25%**

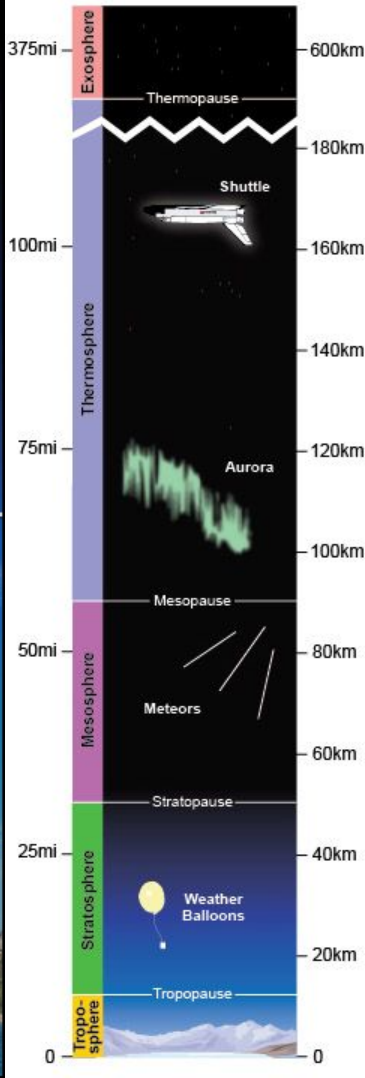
OCEANS
The oceans act as a heat sink, absorbing nearly all sunlight and reflecting barely a tenth back (at zenith). Warm water hastens the melting of icebergs and ice floes. Oceans expand as they warm, resulting in rising sea levels.

ARCTIC
The more snow and ice there is, the less heat is absorbed. But as reduced snowfalls and snow pack leave more ground exposed, more heat is absorbed, exacerbating snow melt.

Note: Illustration is diagramatic and not to scale.

SOURCE: InsideClimate News research

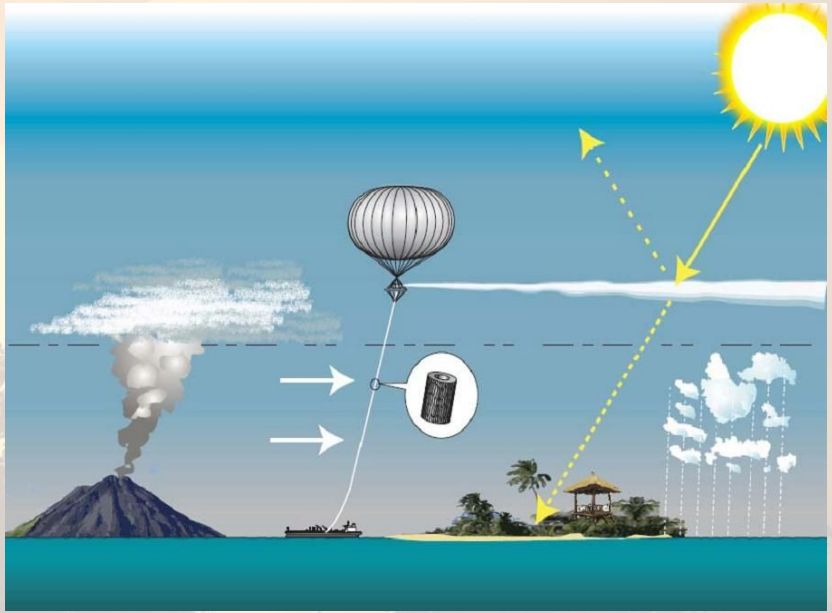
PAUL HORN / InsideClimate News



Stratospheric Aerosol Injection (SAI)

Stratospheric Aerosol Injection (SAI)

- SO_2 is dispersed in stratosphere
- SO_2 forms clouds of sulfuric acid, H_2SO_4
- H_2SO_4 clouds are reflective (high albedo)



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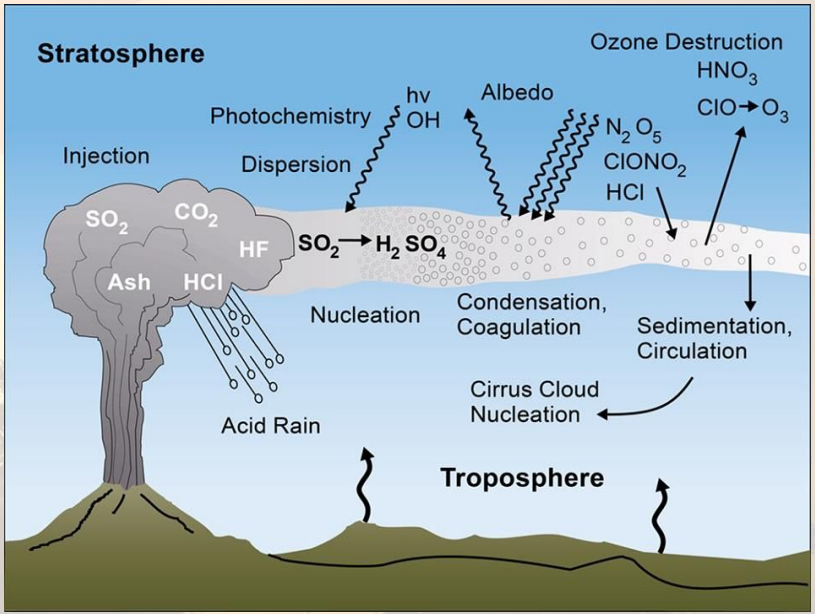
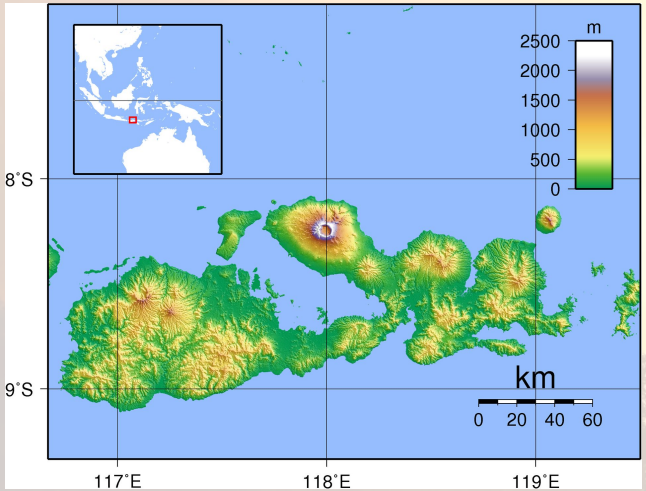


Stratospheric Aerosol Injection (SAI)

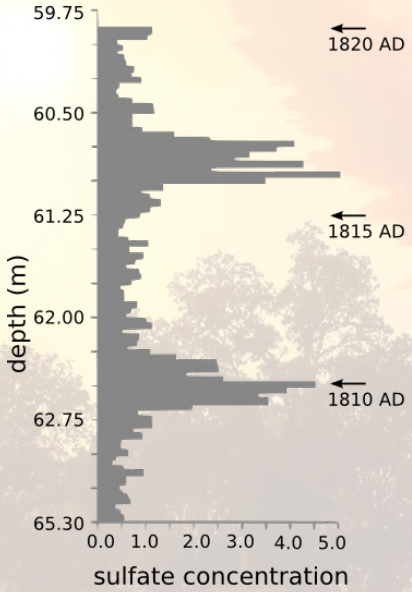
- literally a man-made volcanic winter

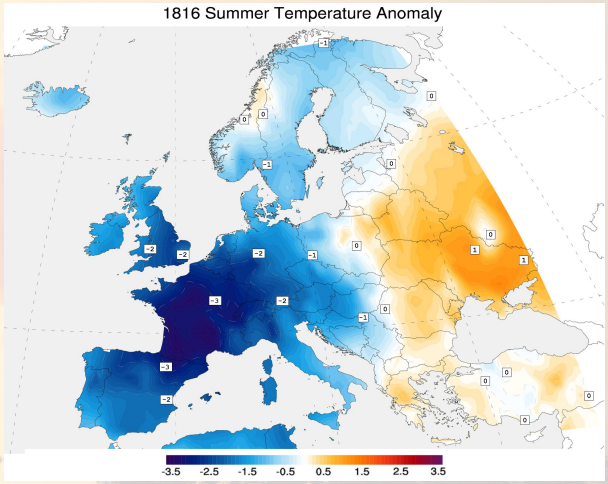


Indonesia

April-July 1815

Mt. Tambora erupts





Europe

1816

"The Year Without a Summer"

Stratospheric Aerosol Injection (SAI)

Pros:

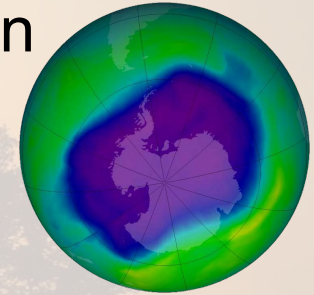
+ comparatively cheap
+ say what you will (and i'm about to) but it will almost certainly lower average global temperatures

Cons:

− many, many undesirable side effects
− exact magnitude of effect is very hard to estimate
− termination shock (it's as bad as it sounds)

Stratospheric Aerosol Injection: Risks

- Asian/African monsoon cycle disruption
  - 1783 Laki eruption (Iceland) caused famines in Japan, Egypt, India
- Sulfate deposition (acid rain)
- Reduced cloudiness → regional warming
- Polar stratospheric ozone depletion
  - Antarctic ozone hole hasn't healed, would reopen

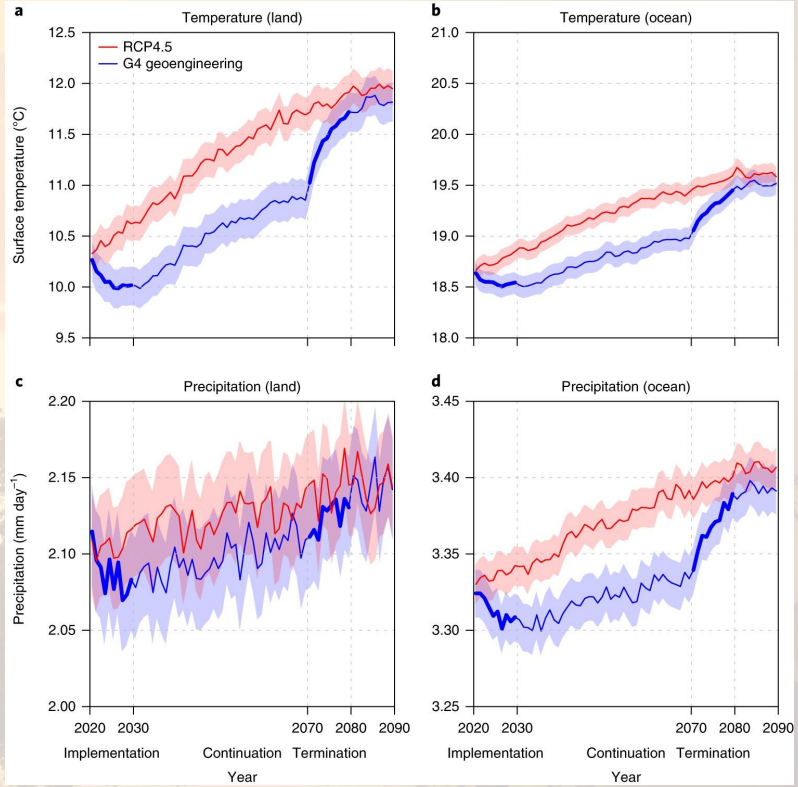


Stratospheric Aerosol Injection: Uncertainties

- Secondary effects on greenhouse gases:
  - Increased lifetime of atmospheric methane
  - Increase in stratospheric water vapor
- Variable effect on cirrus cloud formation
- Nonlinear relationship with injection quantity
  - 2× as much SO_2 ≠ 2× as much cooling
- Very sensitive to latitude/altitude of injection
- Risk of undershooting OR overshooting target

Termination Shock

- if you stop injecting SO_2 *all* the warming you avoided comes back within 1-2 years



Nat. Ecol. Evol. **2018**, *2*, 475.

Make Sunsets

- startup doing unlicensed aerosol injections

Mexico cracks down on solar geoengineering, forcing startup to pause operations

PUBLISHED WED, JAN 18 2023•4:26 PM EST | UPDATED WED, JAN 18 2023•4:41 PM EST

CLIMATE / ENVIRONMENT / SCIENCE

Mexico bans solar geoengineering experiments after startup's field tests

/ The startup tried to launch sulfur dioxide into the stratosphere from Baja California, and now, the government of Mexico is cracking down.

By Justine Calma, a science reporter covering the environment, climate, and energy with a decade of experience. She is also the host of the Hell or High Water podcast.

Jan 18, 2023, 1:59 PM EST | 7 Comments / 7 New

Cowboy Geoengineering

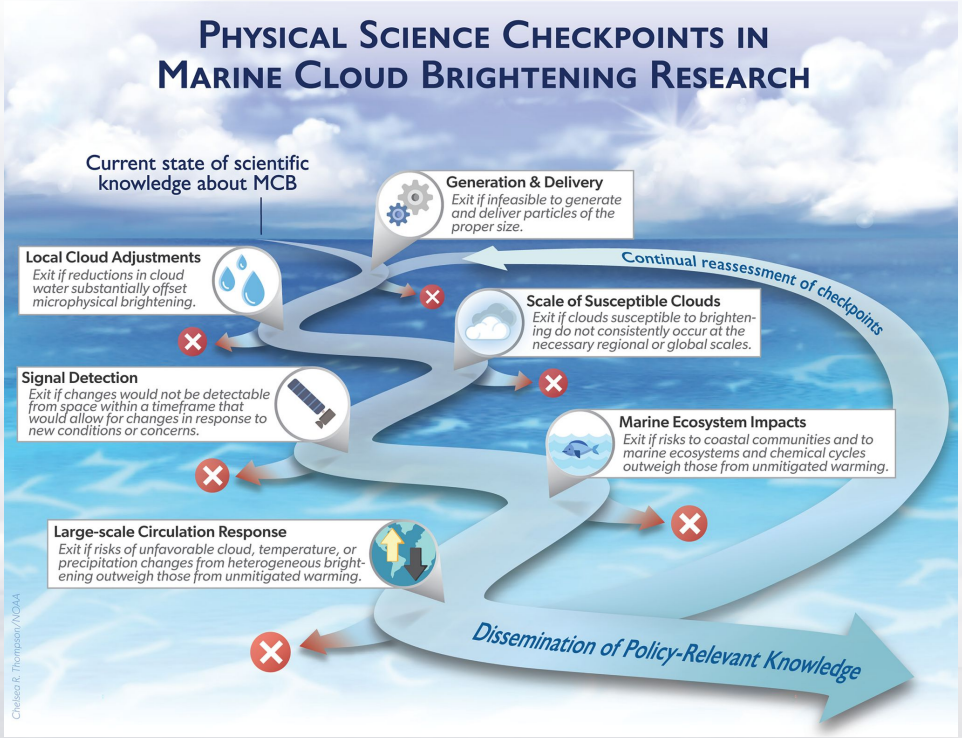
- Make Sunsets is:
  - Luke Iseman
    (BS Economics, Penn)
  - Andrew Song
    (BS Economics, NYU)
- No meteorologists
- No detection or MRV
  - “Our customers don’t care about that”

Luke Iseman and Andrew Song use a grill to burn sulfur powder and capture the smoke in a plastic bag. Balazs Gardi for TIME


Marine Cloud Brightening
(MCB)

Marine Cloud Brightening (MCB)

- have ships spray a mist of seawater into marine clouds
  - sea salt particulate helps condensation
    - ➢ brighter, more reflective clouds



Marine Cloud Brightening (MCB)

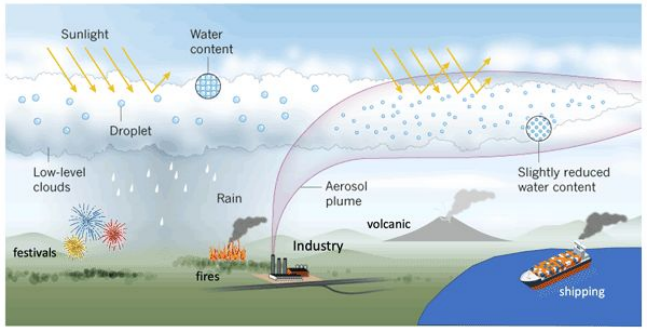
Pros:

+ more benign than SAI
+ rapid climatic response (weeks) vs. SAI (years)
+ quite likely to work (maybe already happening)

Cons:

− not very well-understood
− more expensive than SAI
− effects fairly localized (regional cooling)
− unclear ecosystem effects
− termination shock, still

Accidental Maritime Geoengineering



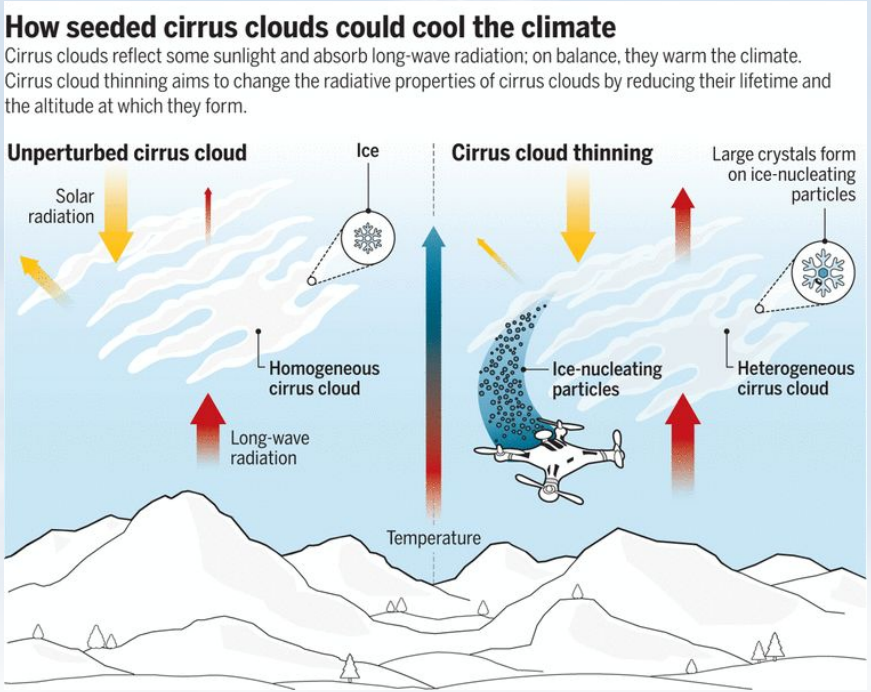
New regulations from the International Maritime Organization (IMO) **limiting sulfur emissions from the shipping industry** are expected to have large benefits in terms of public health but may come with an undesired side effect: **acceleration of global warming as the climate-cooling effects of ship pollution on marine clouds are diminished**. Previous work has found a substantial decrease in the detection of ship tracks in clouds after the IMO 2020 regulations went into effect […] we confidently detect a reduction in the magnitude of cloud droplet effective radius decreases within the shipping corridor and **find evidence for a reduction in the magnitude of cloud brightening as well**.

Atmos. Chem. Phys. **2023**, *23*, 8259.
https://doi.org/10.5194/acp-23-8259-2023

Cirrus Cloud Thinning (CCT)

Cirrus Cloud Thinning (CCT)

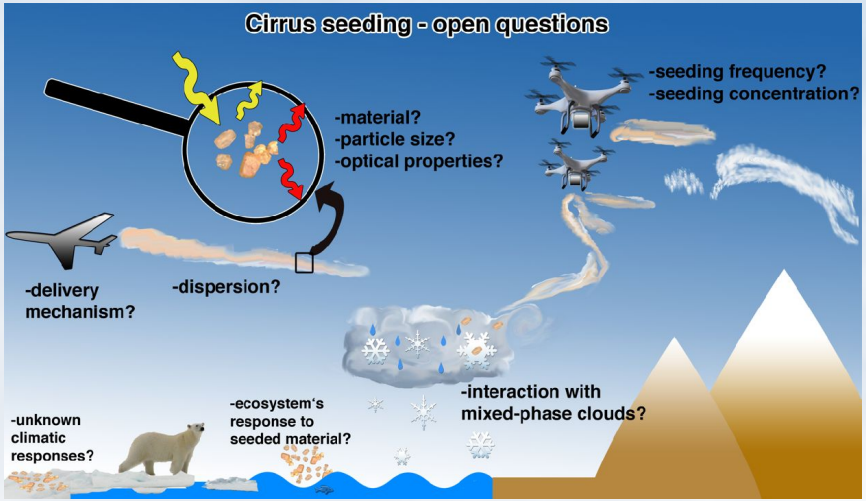
- Cirrus clouds (wispy, high-altitude) have a net warming effect
  - unlike other clouds, trap more heat than they reflect
  - seed cirrus with aerosols to reduce warming effect



Cirrus Cloud Thinning (CCT)

Pros:

+ probably safer than SAI



Cons:

- ...might cause warming lol
  - ➢ really not well-understood
- unclear effects on precipitation (rainfall)
- termination shock is really just kinda intrinsic to SRM


Space
Mirrors

SPACE MIRRORS

- just put a big-ass mirror in orbit?
- stop overthinking it

SPACE MIRRORS

Pros:

+ definitely would work (with enough mirrors)
+ minimal ecosystem risks
+ would be *extremely* funny

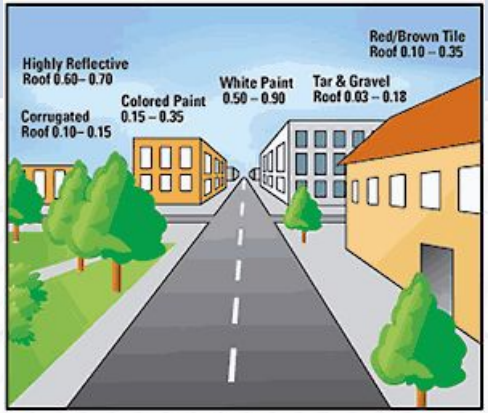
Cons:

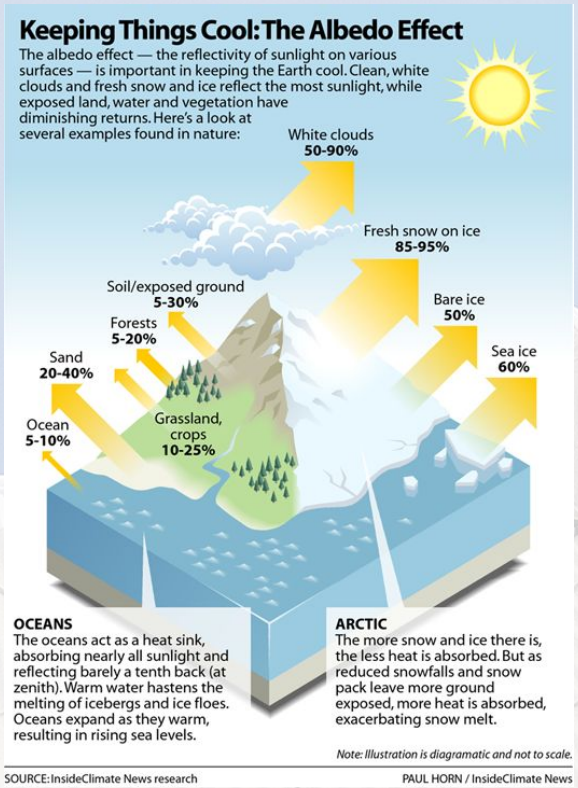
− dear god, how much would this cost
− emissions footprint of launching that many satellites might be large
− do you even hear yourself

Surface Albedo Modification

Surface Albedo Modification

- Just paint your roof white!
- Not geoengineering, according to the IPCC





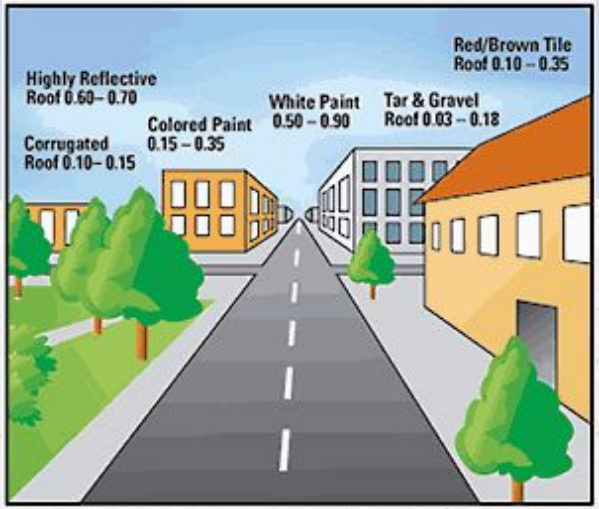
Surface Albedo Modification

Pros:

+ negligible side effects
+ lower heating bills
+ definitely works
+ mitigates urban heat island effect

Cons:

− really not enough by itself



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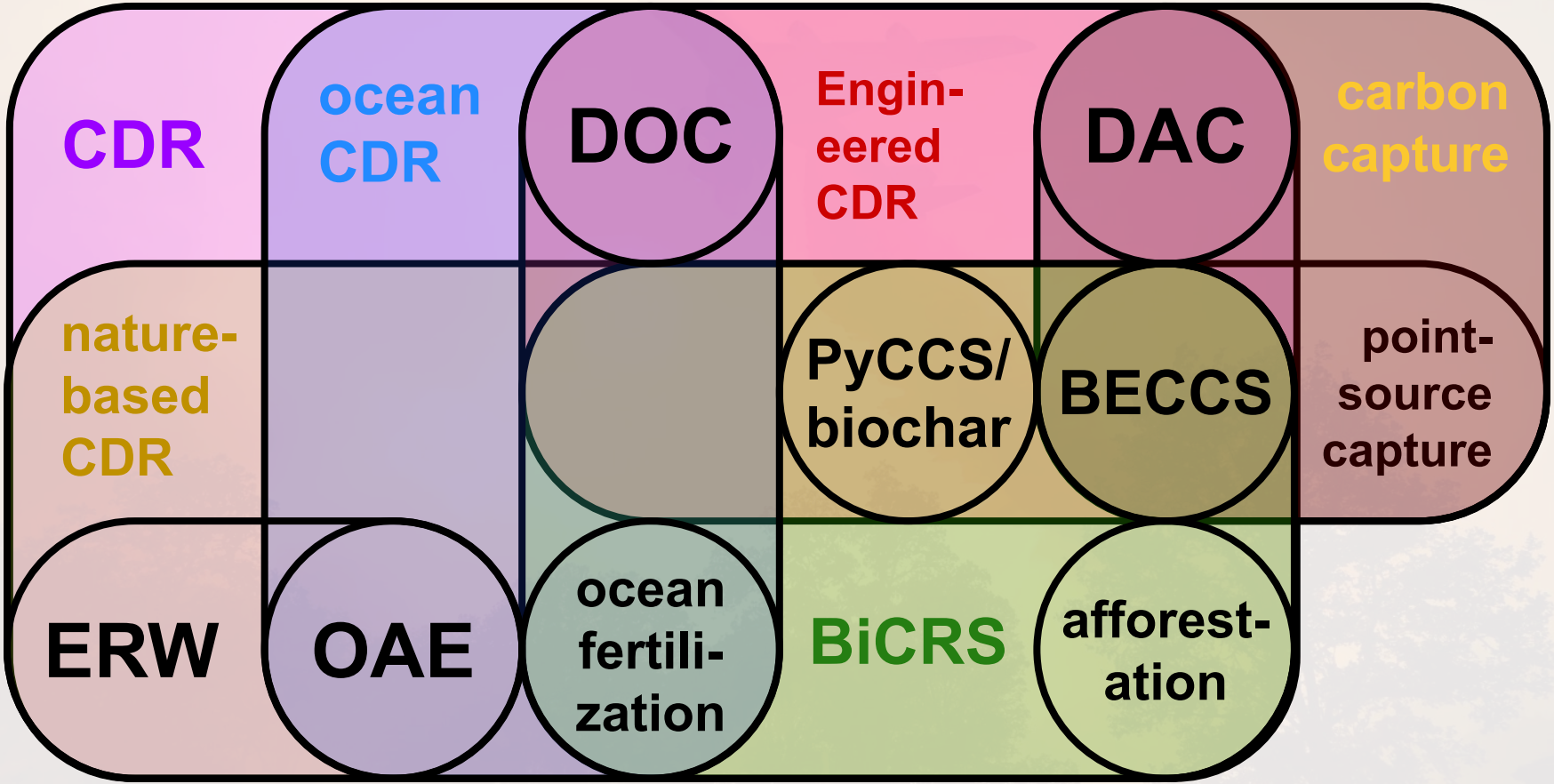
CDR
ocean CDR
DOC
Engin-eered CDR
DAC
carbon capture
nature-based CDR
PyCCS/ biochar
BECCS
point-source capture
ERW
OAE
ocean fertili-zation
BiCRS
afforest-ation

Science **2022**, *377*, eabn7950.

Discussion Questions

- What role does CDR play in reaching net-zero?
  - What metrics should we optimize for?
  - What kinds of CDR should we use?
- Who should decide if/when SRM is deployed?
  - What kinds of SRM are we willing to tolerate?
  - How should a global community regulate / oversee SRM?
- Does climate alarmism / doomerism increase affinity to radical / high-risk solutions?