CARBON DIOXIDE REMOVAL
An Introduction for the Curious

Figure 1: The Petra Nova Carbon Capture Plant, the largest in the world as of 2017 [1]. The carbon capture component of this power plant is the rectangular tower with a scaffolding of pipes in the center-foreground. This facility cost $1billion and will prevent 0.0014 Gt (billion metric tons) of CO_2 per year from entering the atmosphere. Worldwide, about 38 Gt of CO_2 (over 27,000 times more) are emitted annually [2].

What is Carbon Dioxide Removal (CDR)?

Scientists agree that anthropogenic (human-caused) climate change is occurring. Increasing global temperatures exacerbate extreme precipitation events, sea level rise, and cause a variety of other environmental problems [3]. The primary driver of anthropogenic climate change is carbon dioxide (CO_2) gas, which humans emit by burning fossil fuels for electricity, industry, and transportation. CO_2 is a potent greenhouse gas that traps infrared radiation from Earth's surface, causing the planet to heat up [4]. While other greenhouse gases such as methane and nitrous oxide are more potent, CO_2's comparative abundance and residence time (time spent in the atmosphere) makes it one of the most important greenhouse gases [4]. Consequently, reducing the concentration of CO_2 in the atmosphere is an important climate change mitigation strategy.

Since pre-industrial times, atmospheric CO_2 concentrations have risen from 280 to over 400 parts per million (ppm) [5]. While there are several natural carbon sinks (natural systems, such as the ocean and forests, that absorb CO_2) that typically regulate atmospheric CO_2, these processes cannot absorb enough CO_2 to compensate for rapid anthropogenic emissions. Current efforts to mitigate anthropogenic climate change have focused on reducing CO_2 emissions from fossil fuel consumption by transitioning to renewable energy sources like wind and solar. However, overwhelmingly high emissions rates will likely make the transition insufficient to stabilize CO_2 concentrations [2]. Therefore, carbon dioxide removal (CDR)––the deliberate uptake of atmospheric CO_2 through biological, chemical, and/or mechanical processes––could be considered as a supplementary solution to emissions reductions [6].

PRIMARY METHODS OF CDR: CCS, DACS, BECCS

Three primary methods of CDR are carbon capture and storage (CCS), direct air capture and storage (DACS) and biomass energy with carbon capture and storage (BECCS). Each of these approaches captures CO_2 that can then be stored, primarily in deep saline aquifers or through use in enhanced oil recovery. Refer to Table 1 for a comparison of these three methods.

CCS, currently the most common CDR method, involves capturing CO_2 directly from fossil fuel combustion at a point-source of emissions. Rather than removing CO_2 from the atmosphere, CCS prevents the release of CO_2 from power plant or fuel refinery smoke stacks (also known as "flues") [7]. CCS has been in operation for decades, and is primarily tied to enhanced oil recovery.

DACS works by chemically separating CO_2 from the air, ultimately yielding concentrated CO_2. Unlike CCS schemes, DACS works in air with CO_2 concentrations up to 300 times lower than flue gas, thus requiring substantially more energy [6]. Currently, few large-scale examples and little financial backing exist to expand the utilization of this method [8].

BECCS captures and stores the CO_2 released by fermenting biomass into heat, electricity, or usable fuels (like ethanol) through a point-source method similar to CCS schemes at power plants [4]. Because BECCS captures carbon already sequestered by plants during photosynthesis, BECCS can have a net-negative effect on emissions (compared to the net-neutral of CCS) [7, 9]. The combination of energy production and additional atmospheric CO_2 removal makes BECCS promising enough that the Intergovernmental Panel on Climate Change (IPCC) has designated it a critical climate change mitigation strategy [9].

*Figure 2: Climeworks AG facility near Zurich, Switzerland, a **DACS** facility. Constructed in 2017 atop a heat recovery plant, this device is expected to capture 900 tonnes of CO_2 per year at a cost of over \$1000/t CO_2. Rather than being stored, the CO_2 is pumped into a nearby greenhouse [10].*

*Figure 3: Archer D. Midland's Agricultural Processing and Biofuels Plant in Decatur, IL. This **BECCS** plant is an ethanol refinery: it ferments corn into fuel. Some CO_2 from this fermentation is being captured and stored. However, volatile organic compound emissions are high [11, 12]. (Image: US Dept of Energy)*

Strategy	Pros	Cons
CCS: CO_2 is captured directly from fossil fuel combustion in power generation or other processes. One example is the Petra Nova Carbon Capture Plant outside of Houston, TX [13]	• Can be incorporated into existing systems of energy production • Large-scale projects already exist and have been in operation for years, primarily through Enhanced Oil Recovery.	• Net-neutral - does not remove CO_2 that already exists. • Incorporating into energy production inevitably raises the cost of energy.
DACS: CO_2 is separated from the air and captured. Although it has yet to be implemented on a large scale, the first small scale commercial project recently began operating in Zurich, Switzerland [14]	• Removes CO_2 from the atmosphere. • Schemes can be positioned at the point of sequestration, reducing the amount of transport that would be necessary.	• Very expensive • Little existing financial backing/incentive • Not associated with energy production, thus more difficult to create an economic scheme that includes it.
BECCS: CO_2 is captured while fermenting biomass into fuel (such as turning corn into ethanol). One of the first large scale BECCS schemes is the Illinois Basin Decatur Project [15].	• No energy needed from the grid: captures CO_2 taken up by plants during photosynthesis. • Produces consumable energy with net-negative emissions. • More economically viable than DACS.	• Depends on finite resources that are also used for food production • Widespread implementation would possibly displace old growth forests, many of which currently store a large amount of carbon

Table 1: Summary of the CO_2 removal methods discussed above, as well as their advantages and disadvantages [6].

Conventional CO_2 Storage Methods

Deep Saline Aquifers

Numerous deep subterranean or sub-seabed saline aquifers may provide a high-capacity storage space for captured CO_2. In aquifers deeper than 800 meters, the high pressure allows CO_2 to be stored as a supercritical fluid, improving storage efficiency. Several saline aquifers are accessible via pre-existing fossil fuel boreholes. For example, at the Sleipner gas field in the North Sea, CO_2 recovered as a byproduct of natural gas extraction is pumped back down into the sub-seabed aquifer, where it mixes with an existing natural brine solution [16]. Since the CO_2 is less dense than the brine, an impermeable geological "caprock" –– a feature that Sleipner and many other aquifers have –– is necessary to keep CO_2 from rising and re-escaping [16-18]. Though the concept is promising, the aquifer's ability to store carbon for long periods of time remains uncertain.

Figure 4: Sleipner Gas Field Offshore Rig, which pumps CO_2 into a deep saline aquifer. This facility has operated since 1996, and the reservoir beneath appears to be retaining nearly all of the CO_2. [19,20]

Enhanced Oil Recovery

Enhanced oil recovery (EOR) involves pumping CO_2 into oil wells to force new oil to the surface. Historically, CO_2 from natural gas extraction has been used to perform EOR, but CO_2 captured through CDR could be used instead. Drawbacks of EOR include the potential for increased seismic activity from injecting CO_2, and the possibility of CO_2 leaking back into the atmosphere [21]. Leakage impacts can be limited by properly capping wells and monitoring CO_2 release.

Figure 5: Weyburn-Midale Project. Observe the CO_2 injection site (left) next to an oil rig (right). Enhanced Oil Recovery has been conducted at this site in Saskatchewan, Canada since 2000. Many other oil fields in nearby Manitoba and North Dakota also use EOR. [22-23]

The Costs of CDR

One potentially prohibitive aspect of CDR is its high cost. For example, electricity from new power plants employing carbon capture (CCS) will cost at least 50% more than normally-generated electricity [24-30]. Based on recent estimates, 1 megawatt-hour of electricity (enough to power the average US home for a month [31-32]) costs about $84 if generated from coal and $54 if generated from natural gas. With CCS technology, those respective prices will grow by $51 and $27 (see Figure 2, caption explains LCOE) [33-38].

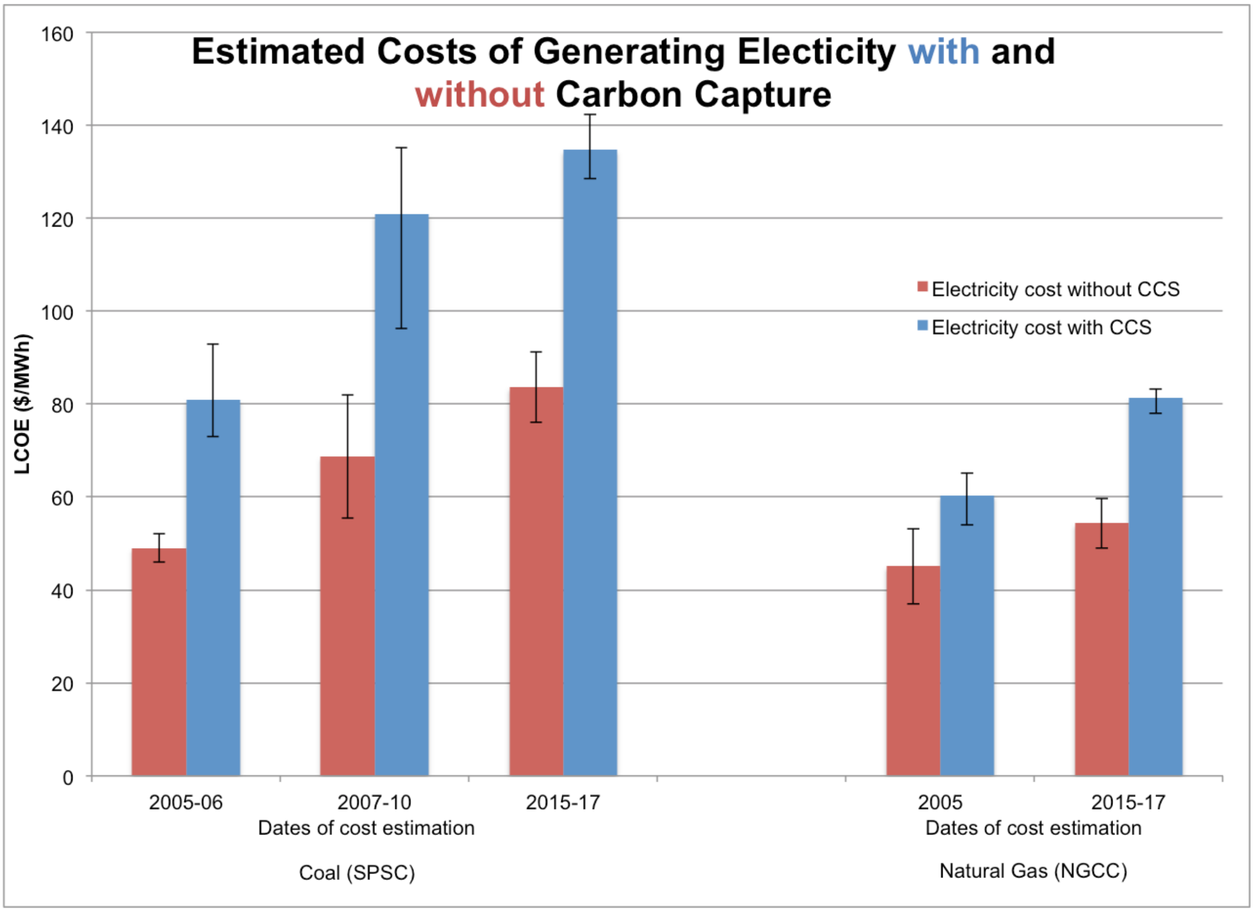

Figure 9. Additional cost to generate electricity using carbon capture [24-30,33-38]. The levelized cost of electricity (LCOE) refers to the money needed to generate 1 MWh of electricity, factoring in both operational costs and the initial plant construction costs spread over the plant's expected lifespan. Colored bars represent the averaged estimate and error bars represent the full range of estimations (3 included per time period). Note that natural gas is a more energy-dense fuel source than coal: it is cheaper to generate electricity from natural gas and build a carbon-neutral natural gas plant because natural gas requires less carbon to produce the same energy. The levelized cost of electricity is rising with more recent estimations because coal and natural gas are becoming more expensive (due to increased demand, decreased supply, renewable alternatives, stricter regulations on emissions and mining-related pollution).

The main reason for this added expense is the high energy-demanding process of concentrating and compressing diffuse CO_2 in flue gas [39]. For every unit of electricity generated by the CCS plant, 30-50% additional energy (and thus fossil fuel) is required to capture carbon. [36-38, 40]. Additionally, building CCS-specific equipment adds 50% to the cost of building a power plant. These increases are even larger for retrofitted power plants which were not initially built to support CCS [30, 41]. Alternative carbon capture solutions such as DACS and BECCS, which are still being developed, are estimated to cost 2-10 times more than CCS [6: Table 2.2].

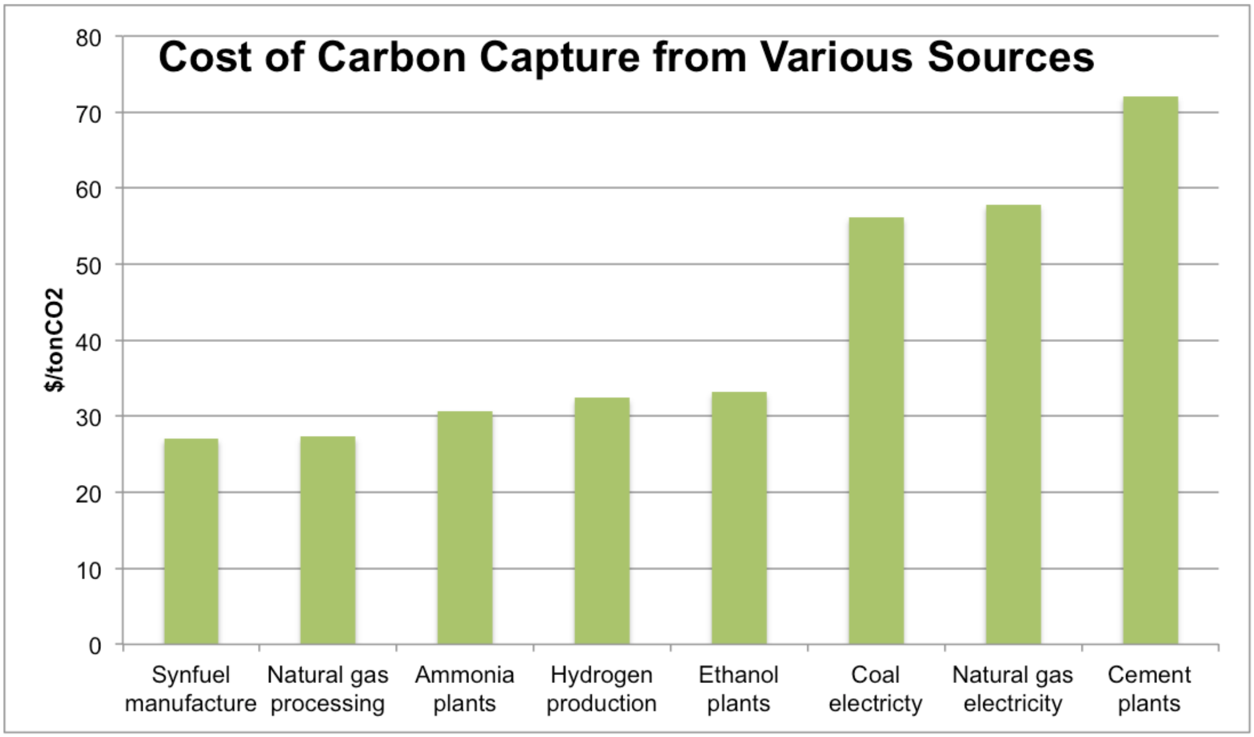

Figure 10. Cost to capture carbon from various sources [33-38, 42-43], using most recent estimates. Some processes take place in certain locations (e.g. cement plants should be close to cities where the cement is needed) and thus incur greater transportation costs.Transportation cost has been assumed to be a uniform \$9/ton CO_2 (middle of \$3-15 range [44]) in order to make comparisons between various sources, so any additional transportation costs are represented as carbon capture costs. It costs about the same to capture a given mass of carbon from either coal or natural gas. This may appear to contradict the previous figure, but recall that natural gas requires less carbon than coal to generate 1 MWh of electricity.

Once carbon has been captured, costs associated with sequestration are smaller. The total transportation, injection, and monitoring cost is about \$15/t CO_2 [45] (range: \$10 [8] - \$28/t CO_2 [25, 45, 46]). As an example, captured CO_2 is sold to EOR companies for less than 20% of the capture cost [47]: the \$15/t CO_2 sequestration expense becomes a \$10 profit.

Alternative Carbon Dioxide Removal Methods

Reforestation / Afforestation

Figure 6: A coniferous forest in southern Oregon with many planted saplings. This land was previously logged. Many other types of forest can also be regrown. [48]

Among the better-understood carbon sequestration approaches is reforestation, which involves repopulating deforested areas, and afforestation, which refers to establishing a forest on previously barren land. Both approaches would increase carbon capture from the atmosphere by an estimated maximum of 4-6 $GtCO_2$/yr [6]. There is high confidence that re/afforestation will sequester carbon and can be implemented immediately with current technologies. However, reforesting in potential areas such as tropical rainforests would compete with land and water resources needed for agriculture.

See section Why not just grow trees? for more information.

Peridotite Carbonation

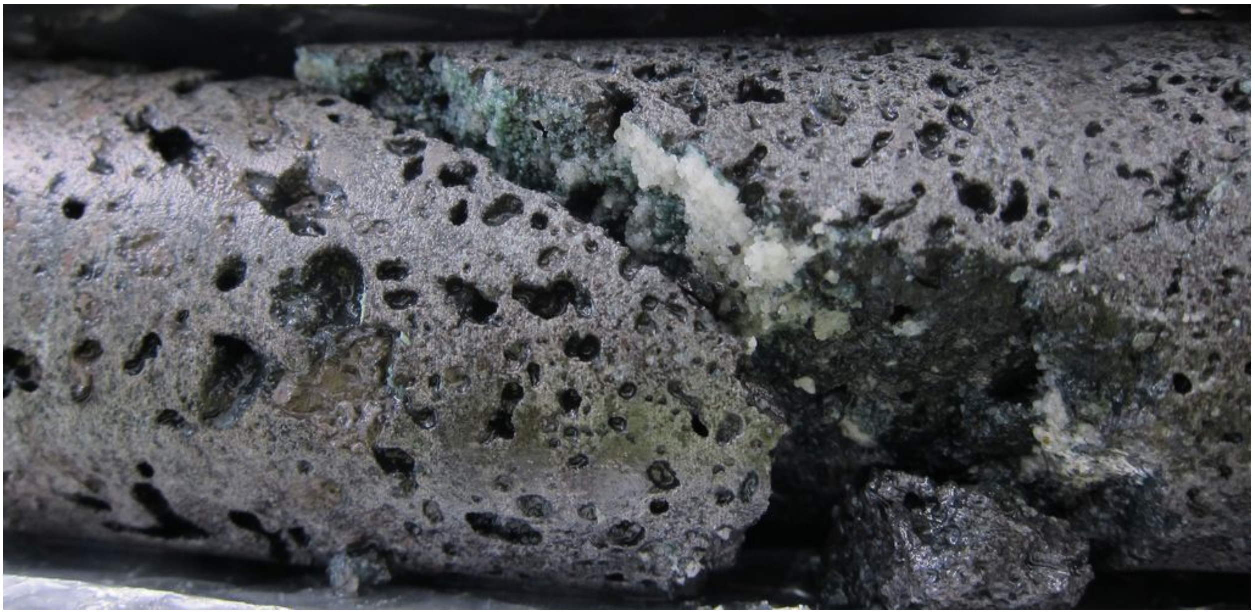

Figure 7: Calcium carbonate rock (white) in a core sample taken in Iceland. This limestone was formed due to a CO2 injection project. [49]

Peridotite, a rock normally found in the Earth's mantle layer, reacts with near-surface CO_2 to form stable forms of carbonate rock in a weathering process called "carbonation" [50]. Large peridotite-rich areas such as the Samail Ophiolite in Oman sequester 10,000 - 100,000 tons of CO_2/year through this process [50]. The rate of peridotite carbonation could be increased by performing hydraulic fracturing (or "fracking") in the ophiolite and pumping in a CO_2-rich fluid. The reaction mechanism can be enhanced by heating the reaction surface to 185 °C, allowing the reaction to become self-sustaining [50]. Since the reaction products, magnesite and calcite, are stable, there is little risk of sequestered carbon re-escaping into the atmosphere. No large-scale field tests of accelerated carbonation have yet been attempted.

Ocean Fertilization / Seabed Sediment Storage

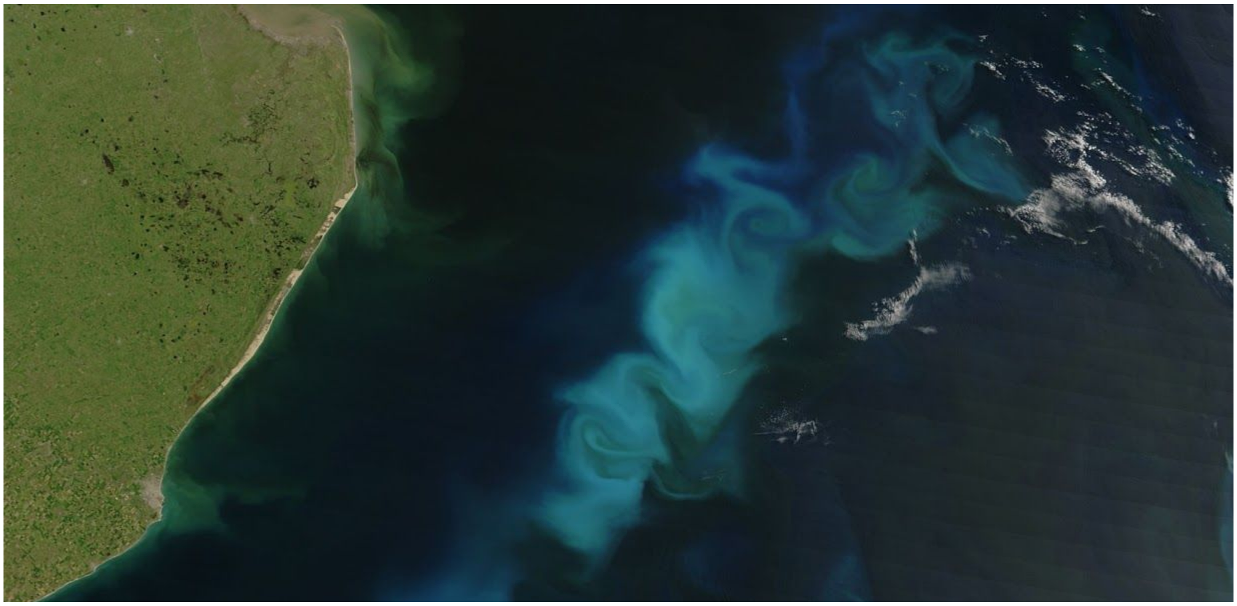

Figure 8: Natural phytoplankton bloom in Southern Ocean eddy currents, off coast of Argentina. [51]

Ocean iron fertilization proposes releasing large quantities of iron into the Southern Ocean to stimulate phytoplankton blooms, thereby increasing CO_2 removal from the upper ocean [16, 52, 53]. Twelve iron fertilization experiments since 1993 suggest that dissolved iron, a critical nutrient, is the limiting factor for phytoplankton growth in the Southern Ocean [52]. Through photosynthesis, phytoplankton convert atmospheric carbon into carbon-rich organic structures, some of which sink upon the planktons' death. If the organic matter sinks deep enough, it can turn into seabed sediment, sequestering the carbon for long time periods [52, 54]. However, mixing dynamics and seabed sedimentation are still poorly understood, making this sequestration method highly controversial.

Frequently Asked Questions

Why not invest in renewables instead of CDR?

Although renewables are now arguably less expensive than fossil fuels, and are needed to transition towards a less carbon-intensive society, we have not yet completely embraced green technologies [41]. Renewables are dependent upon fluctuating natural processes, and current power grids are not designed to handle irregular power flow. As a result, standby natural gas generators supply the grid during periods of low wind or sunlight [55]. Renewable sources can only operate at 20%-30% capacity: they provide full power only occasionally, partial power most of the time, and no power some of the time [56, 57]. Renewable energy alone cannot solve this problem: greener backups need to be invented, energy storage means (such as battery farms) need to be improved, and/or the grid needs to be redesigned. However, these new technologies are still very expensive and in development [58, 59].

Societies have delayed the transition to renewables for so long that climate change mitigation will be significantly more challenging without CDR technologies [6].

Why stop burning fossil fuel now (if we take back CO_2)?

CDR is expensive, technologically challenging, and has not been studied thoroughly enough for large-scale implementation. These knowledge gaps make it difficult to predict the time required to implement CDR schemes and whether they can sequester enough carbon to mitigate the effects of global warming.

It is important to consider the release and capture rate of carbon when dealing with CDR methods. According to the 2013 IPCC Technical Summary, 38 ± 3.8 $GtCO_2$ was emitted from fossil fuels in 2010. By contrast, Sleipner-type deep storage projects are currently only capable of sequestering 0.9 $MtCO_2$/year per plant. It would take over 130,000 Sleipner-type projects just to cancel out our current emissions rates [2].

Will CDR destroy ecosystems or create earthquakes?

CDR does have the potential to disrupt ecosystems and induce seismicity [6]. However, the magnitude of these effects depends largely on which CDR method is being considered [6].

Since the 1930s, oil companies have been injecting fluid CO_2 into the ground as part of the [Enhanced Oil Recovery (EOR)] process [6]. Studies have shown that injecting fluids into porous ground rock could create or increase local seismic hazards by expanding cracks in rock and/or propagating existing fractures [21, 61]. This phenomenon is illustrated in the USGS Earthquake Hazards map for the USA [62]. The figure shows earthquake hazards not only in areas with active faults but also in areas not normally associated with seismic activity––these areas have been subjected to fluid injections (EOR CO_2 fluid or wastewater from local fracking) and now suffer from induced seismic activity [62].

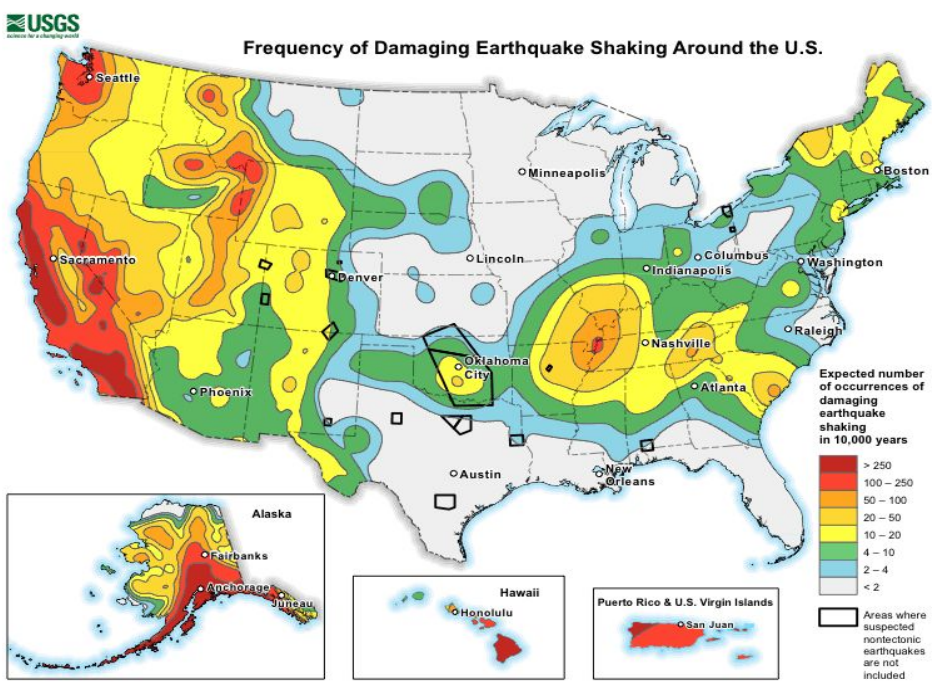

Figure 11. USGS Map of Earthquake Hazards in the United States [62]. *This map shows seismic activity and intensity in the continental United States. Seismic activity is present in non-tectonically active regions such as Oklahoma, which also has high fracking activity.*

Inducing seismicity can have many unintended consequences, such as destabilization of the ground, mudslides, or destruction of human infrastructure. Updating building codes in areas with “new” seismic hazards will be expensive [63], but placing CDR injection sites far from major population centers could help mitigate the human and economic costs.

Other CDR proposals, such as the Pleistocene Park project, rely on fundamentally altering a current ecosystem [64]. Pleistocene Park aims to restore the mammoth tundra steppe ecosystem to prevent the release of methane from the now-thawing ground [64]. The researchers argue that, since humans hunted mammoths to near-extinction, Pleistocene Park is restoring an anthropogenically-disrupted ecosystem rather than disrupting the current one [64].

Since humans have been reshaping ecosystems to suit their needs for millennia, it can be very hard to select a baseline for what is “natural” or to establish what ought to be “preserved” [65]. However, it is virtually certain that climate change is globally disrupting the Earth’s current “natural” ecology [66]. Thus, CDR cannot be considered in isolation: the impacts of climate change might be more damaging to ecosystems than the localized hazards associated with CDR [67].

Why not just grow trees?

While trees do store CO_2 in their biomass tissue through photosynthesis, this CO_2 is released as plants decay, so living plants do not have a net impact on atmospheric CO_2 concentration over their lifecycle [68]. However, *changes* in the average amount of tree biomass are important, as those changes force the land-atmosphere CO_2 exchange out of equilibrium [68]. Due to the natural exchange of carbon resulting from plant growth and decay, growing more trees (or any biomass) will have a measurable but finite impact on atmospheric CO_2 concentrations [69].

In order to make a large carbon sink, vast areas of deforested land would need to be reforested. Unfortunately, the size of this carbon sink is limited by available growth area. Since many of the earth’s forests were replaced by agriculture, large-scale reforestation could create food shortages [70]. There is also a chance that reforestation schemes could significantly reduce biodiversity and threaten natural ecosystems [71]. Finally, the pollution and emissions created by fertilizer manufacturing could negate the carbon sequestration benefits of reforestation [72].

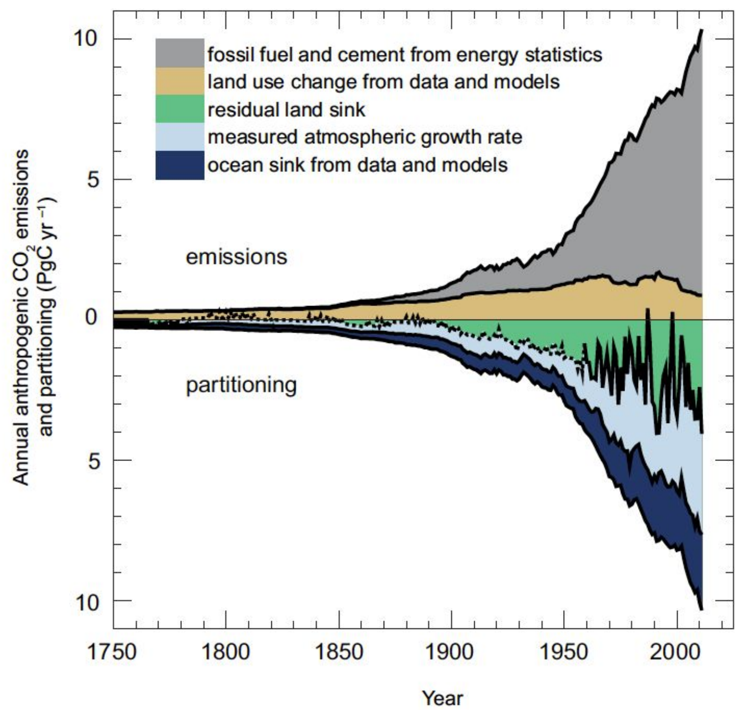

Figure 12. The diagram above illustrates the sizes of land (brown and green) carbon flux and carbon pollution (grey) due to fossil fuels. Forests worldwide are still shrinking, causing net emissions, but reforesting land could reabsorb these emissions. However, total fossil fuel emissions far surpass emissions impacts of land use: forests simply do not have the capacity to absorb all the CO_2 humans have released [2]. Note: 1 PgC is equivalent to 3.8 Gt CO_2.

Conclusion

Confronting climate change will require a multifaceted approach. The transition from fossil fuels to renewable energy sources has been insufficient in speed and volume to be effective at mitigating climate change. CDR provides another tactic to fight climate change, one with the ability to maintain and reduce current atmospheric CO_2 concentrations. Although additional research into CDR technologies is necessary to further understand potential risks and hazards, the benefits of CDR for mitigating climate change may outweigh its associated risks.

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